Risk analysis of the disruption to urban transport networks from pluvial flooding

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ABSTRACT

Cities are increasingly vulnerable to damage and disruption from adverse-weather events, due to their high concentration of people and assets. To improve engineering and planning decisions in the face of complex interactions between climate hazards, infrastructure and actors within the urban system requires novel analytical tools and methodologies. This research therefore takes a systems approach to developing an integrated framework to model the impact of surface water flooding on the transport network before using this to explore the effectiveness of potential adaptation options to increase urban resilience.

The framework calculates delays in travel times by coupling a hazard model to both a hydraulic model and traffic network simulations. The hazard model was approximated for current climate by obtaining intensities for rainfall events with different return periods using the Flood Estimation Handbook (FEH methodology). These rainfall intensities were converted to flood depths over the region of interest using a dynamic flood model (CityCAT). Spatial flood footprints obtained from the model were integrated over the road network to identify affected transport corridors. To calculate the reductions in vehicle speeds due to standing water on these corridors, a new depth-disruption function (*i.e*. relates depth of flood water to safe vehicle speed) was developed. This was used to estimate reductions in the speeds of individual vehicles which drive a macro-transport network model that has been developed to calculate city-wide travel times and subsequently how these change due to flooding. Pre-event and post-event travel times of commuters are compared, in order to quantify the impact of flooding on network performance, and assess the effectiveness of urban interventions at managing this risk.

The framework has been demonstrated in Newcastle-upon-Tyne (UK) using publicly available data and verified through available historical data. With no adaptation of the transport system, a 1 in 200 year rainfall event increases travel times by more than 50%, with an associated economic impact of over £220,000. Adaptation measures contribute significantly to flood alleviation. Application of a risk-based 'criticality assessment' has been shown to enable effective targeting of grey (traditional engineering) adaptation, and in this case installation of flood management measures at the top six most 'critical' locations can reduce net present flood risk by 41% over a 10 years timeframe. This compares to similar reduction (38%) for a green adaptation strategy. The green strategy provides a city-wide flood depth reduction, and it does not represent an economically-feasible option. Green infrastructure also provides additional co-benefits, such as enhanced biodiversity and air quality improvements, deployment of green infrastructure at a city-wide scale would require an unprecedented scale, and high cost, of intervention. Balancing grey and green interventions offers the most effective strategy to manage flood risk to transport disruption.

Combining flood modelling and transport network analysis is shown to improve engineering decision-making and enable the prioritisation of adaptation investments in urban areas. The findings and the methodology are of interest to transport policy analysts, planners, economists and engineers, as well as communities affected by disruptive events.

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LIST OF PUBLICATIONS

Analysis and results of this research have been published within several peer-reviewed journal papers, reports and conference papers. The main thesis chapters (Chapter 2, 3, 4, 5 and 6) are based upon these publications.

Peer-reviewed Journal Papers

Pregnolato, M., Ford, A., Glenis, V., Wilkinson, S., and Dawson, R. (2017). "Impact of flooding and urban adaptation in a changing climate". *Journal of Infrastructure Systems*, Special Issue "Infrastructure Resilience to Climate Change", 23(4). DOI: 10.1061/(ASCE)IS.1943-555X.0000372

Pregnolato, M., Ford, A., Wilkinson, S., and Dawson, R. (2017). "The impact of flooding on urban transport sector - an integrated depth-disruption function". *Transport Research Part D: Transport and Environment*, 55, 67-81. DOI: doi.org/10.1016/j.trd.2017.06.020.

Pregnolato, M., Ford, A., Robson, C., Glenis, V., Barr, S., and Dawson, R. (2016). "Assessing Urban Strategies for Reducing the Impacts of extreme Weather on Infrastructure Networks". *Royal Society Open Science*, Special Issue "City Analytics" 3(5), 1-15. DOI: 10.1098/rsos.160023

Conference Papers

Pregnolato, M., Dunn, S., Ford, S., Dawson, R. and Wilkinson, S. (2017). "A Next Generation of CAT (NG-CAT) models". *International Symposia For Next Generation Infrastructure (ISNGI) 2017.* London, UK, 11th-13th September 2017.

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Pregnolato, M., Ford, A., Vassilis, G., and Dawson, R. (2015). “Analysis of the risk of transport infrastructure disruption from extreme rainfall”. *12th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP)*. Vancouver, Canada, 12th-15th July 2015.

Pregnolato, M., Galasso, C., and Parisi, F. (2015). “A Compendium of Existing Vulnerability and Fragility Relationships for Flood: Preliminary Results”. *12th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP).* Vancouver, Canada, 12th-15th July 2015.

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Reports

Ford, A., Dawson, R., Pregnolato, M., Glenis, V., Walsh, C., Goodman, P., and Namdeo, A. (2016). “D3.2: Extension of detailed systems-based risk analysis” *RAMSES Rep*ort, WP3: Small-scale vulnerability and risk assessment for cities and sectors. Newcastle, UK.

iBUILD (2015). “Are you being served? Alternative infrastructure business models to improve economic growth and well-being” *iBUILD manifesto and mid-term report*. Newcastle, UK, ISBN: 978-09928437-1-7.

Database repository

The output data underpinning this research can be found here:

- https://rdm.ncl.ac.uk/landing/pages/10.17634/154300-16;
- https://rdm.ncl.ac.uk/landing/pages/10.17634/121736;
- https://rdm.ncl.ac.uk/landing/pages/10.17634/121736-3.

ABBREVIATIONS

BAU	…………………….	Business As Usual
BC	…………………….	Betweenness Centrality
BCR	…………………….	Benefit-Cost Ratio
BGI	…………………….	Blue-Green Infrastructure
CAT	…………………….	Catastrophe (model)
CBA	…………………….	Cost-Benefits Analysis
CEA	…………………….	Cost-Effectiveness Analysis
CI	…………………….	Critical Infrastructure
CityCAT	…………………….	City Catchment Analysis Tool
COBA	…………………….	COst Benefits Analysis (programme)
DDF	…………………….	Depth-Duration-Frequency (curves)
DEFRA	…………………….	Department of Environment, Food and Rural Affairs
DEM	…………………….	Digital Elevation Model
DTM	…………………….	Digital Terrain Model
EA	…………………….	Environment Agency
EAD	…………………….	Expected Annual Damage
EMA	…………………….	Emergency Management Australia
EP	…………………….	Exceedance Probability
FEH	…………………….	Flood Estimation Handbook
FEMA	…………………….	Federal Emergency Management Agency
FHWA	…………………….	Federal Highway Administration
FRA	…………………….	Flood Risk Assessment
FRM	…………………….	Flood Risk Management
GIS	…………………….	Geographic Information System
IDF	…………………….	Intensity-Duration-Frequency (curves)
IM	…………………….	Intensity Measure
IPCC	…………………….	Intergovernmental Panel on Climate Change
JtW	…………………….	Journey-to-Work
LLFA	…………………….	Lead Local Flood Authorities

LSOA	…………………….	Lower Layer Super Output Areas
MCA	…………………….	Multi-Criteria Analysis
MCM	…………………….	Multi-Coloured Manual
NCC	…………………….	Newcastle City Council
NFIP	…………………….	National Flood Insurance Program
NPV	…………………….	Net Present Value
OD	…………………….	Origin Destination
ONS	…………………….	Office for National Statistics
PHD	…………………….	Person Hour Delay
ROI	…………………….	Return On the Investment
SRN	…………………….	Strategic Road Network
SPRC	…………………….	Source-Pathway-Receptor-Consequence
SuDS	…………………….	Sustainable Drainage System
TADU	…………………….	Traffic and Accident Data Unit
USACE	…………………….	United States Army Corps of Engineers
VOC	…………………….	Vehicle Operating Cost
VoT	…………………….	Value of Time
WebTAG	…………………….	Web Transport Analysis Guidance

EQUATION VARIABLES

a	………………………	The distance coefficient.
AS	………………………	Adaptation Scenario.
b	………………………	The time coefficient.
B_{ij}^{AS}	………………………	The benefit for an adaptation scenarios AS with respect to the disruption scenario.
C	………………………	The estimated cost of traffic disruption due to a flood (£).
C_L	………………………	The additional cost of travel per km per vehicle type, given road disruption due to flooding (£/km).
C_p	………………………	The cost per person delayed by road disruption due to flooding per person.
C_{veh}	………………………	The additional cost due to delays per vehicle, given road disruption due to flooding (£/hr).
D	………………………	The distance travelled by vehicles (km).
$D(w)$	………………………	The disruption associated to a certain event *w.*
D_p	………………………	The delay in the journey time per person (hr).
D^s	………………………	Delay in time using the network characteristic of the scenarios S, in comparison to the baseline.
f	………………………	The duration of the considered flood (hr).
$I_{net}(x)$	………………………	The total disruption cost for an event (£).
JL^s	………………………	Journey Length using the network characteristic of the scenarios S.
JT^s	………………………	Journey Time using the network characteristic of the scenarios S.
L	………………………	The diversion length due to rerouting per vehicle (km).
m	………………………	The number of recorded occurrences of a certain event.
n	………………………	The number of recorded years.
NPV_r	………………………	The Net Present Value of the benefits in terms of risk reduction.
PHD_{net}	………………………	The overall impact on the network by aggregating the Person Hour Delay across the network.

PHD^S	………………………	Person Hour Delay, considering the number of delayed users for a certain journey for the scenario S.
q	………………………	Number of commuters for a certain OD trips.
R	………………………	The expected annual disruption from flooding (£).
r	………………………	Discount rate for infrastructure (%).
S	………………………	Scenario for the simulation.
T	………………………	The recurrence interval or return period.
t_w	………………………	The water-film thickness on roads (mm).
v	………………………	The vehicle speed allowed by transport regulations (km/h).
v^S	………………………	The disrupted speed for the scenario S (km/h).
$v(z)$	………………………	The vehicle speed as a function of flood depth (km/h).
veh	………………………	The number of vehicles delayed due to a flood.
VoT	………………………	The average Value of Time for commuters (£/hr).
v_p	………………………	The hydroplaning speed (km/h).
w	………………………	Rainfall event.
z	………………………	The water depth due to flooding.
$\rho(w)$	………………………	The probability of occurrence of a given rainfall event w.
l	………………………	Loading hazard.

MAIN DEFINITIONS

Adaptation	Adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.
Catchment	The drainage area whose runoff drains into a stream network.
Commuting time	Travel time for all journeys with non-work purposes, including travelling to and from work.
Free flow speed	Speed of vehicles in free flowing conditions of traffic on roads.
Green adaptation	Alternative strategies of flood alleviation that incorporate nature into the design (*e.g.* rain gardens, green roof, ponds).
Grey adaptation	Man-made and invasive interventions designed to alleviate the impact of flooding (*e.g*. levees, drainage improvement).
Hazard	The exceedance probability of potentially damaging flood situation in a given area and within a specified period of time.
Hotspot	Geographic area more likely to be exposed and susceptible to flooding.
Outlet	The lowest point along the boundary of a catchment, at which water flows out.
Repayment time	The timeframe within which the benefits due to an intervention exceed the cost of the initial investment.
Resilience	The ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event.
Risk	The product of the probability of flooding and the consequential damage, summed over all possible flood events.
Urban Core	The ward(s) of a city in which the major number of jobs is located.
Vulnerability	The propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events.
Watershed	Natural division line along the highest points in an area, which divides the whole catchments into sub catchments.

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CHAPTER 1: INTRODUCTION

1.1 IDENTIFICATION OF THE PROBLEM

Cities are becoming increasingly vulnerable to adverse-weather events. This is because global urbanisation is leading to higher concentrations of people who are increasingly dependent on an expanding array of infrastructure assets (HM Government, 2016). In addition, with global megatrends such as climate change, ageing populations and an ever increasing level of complexity of urban environments, the exposure and vulnerability of assets will continue to increase and therefore losses and impacts from adverse weather will consequently increase as well (Garschagen and Romero-Lankao, 2013).

Infrastructure (water supply, railways, etc.) is usually considered the backbone of cities, underpinning the economic, social and technical functioning of cities. Transport networks play a key role in the overall infrastructure system, connecting people, businesses and services, in both everyday and emergency conditions. A small and seemingly localised event could disrupt cities and their surroundings due to the interconnections between multiple infrastructure assets.

Among all the possible incidents, natural hazards are the most dangerous to infrastructure services (Cabinet Office, 2011), and in particular flooding represents the most frequent natural hazard in cities where alteration of the land surface has reduced permeability (CRED and UNISDR, 2015). The transport sector is particularly vulnerable to flooding and at risk of regular inundation, amplified by aging drainage system assets, and pressure from climatic change (Doll and Sieber, 2011).

Ensuring the robustness (which includes the system integrity, safety, reliability, and resistance) of transport networks is key to enhancing a city's resilience and smooth functioning to such event. Yet, despite the considerable progress made on flood impact assessment in the last decades, more knowledge is needed for effective risk-based decisions (Dawson *et al.*, 2011).

Although urban environments need to be, and are indeed designed to cope with natural hazards on a regular basis, currently infrastructure protection strategies are designed in isolation and for a particular magnitude of hazard with little thought as to what may happen if the design event is exceeded. This latter point is of particular significance in the face of a changing climate, given that current measures may be inadequate for the future, and other interventions may make the problem worse in the case of design exceedance (Dawson, 2007; IPCC, 2012; Aerts *et al.*, 2013a). Therefore, adaptation of urban areas and infrastructure can be seen as an urgent requirement for decision-makers to minimise the potential effect of hazards.

One urban system particularly affected by climate impacts is transport, which is essential for a city's businesses, employees, and economic competitiveness, since transport networks represent the main driver of development (Jaroszweski *et al*., 2010; Chen *et al*., 2016). The urgency of adaptation interventions has driven the development of tools and techniques for risk and impact assessment from natural hazards, such as flooding. However, current policies often still prove inadequate, and decisions about the type of interventions to improve transport resilience is far from straightforward (Merz *et al.*, 2010). Such decision-making is made particular difficult by the prohibitive cost of upgrading all roads and drains, and the necessity to define critical locations and prioritise investment.

This thesis develops an integrated risk model for transport networks to assess the impact of city-wide disruption as a result of surface water flooding. The model couples hazard scenarios from a high-resolution hydrodynamic model and network analysis, in order to appraise city-scale flood intensities. Current assumptions are that a road is either 'wet' and impassable, or 'dry' and fully operational, yet this binary view is not reflected in observations of transport systems during flood events (Penning-Rowsell *et al.*, 2013). Therefore, a new depth-disruption function was developed to translate predicted flood depths into changes in vehicle speed, which are then incorporated into a macro-transport model to make estimates of traffic disruptions, in terms of total delays. The individual components of the framework have been validated. The framework has been used to study potential impacts of a range of rainfall events on an urban road network. Subsequently, the efficacy of different green and grey adaptation strategies are tested to assess how they reduce flood risk from transport disruption.

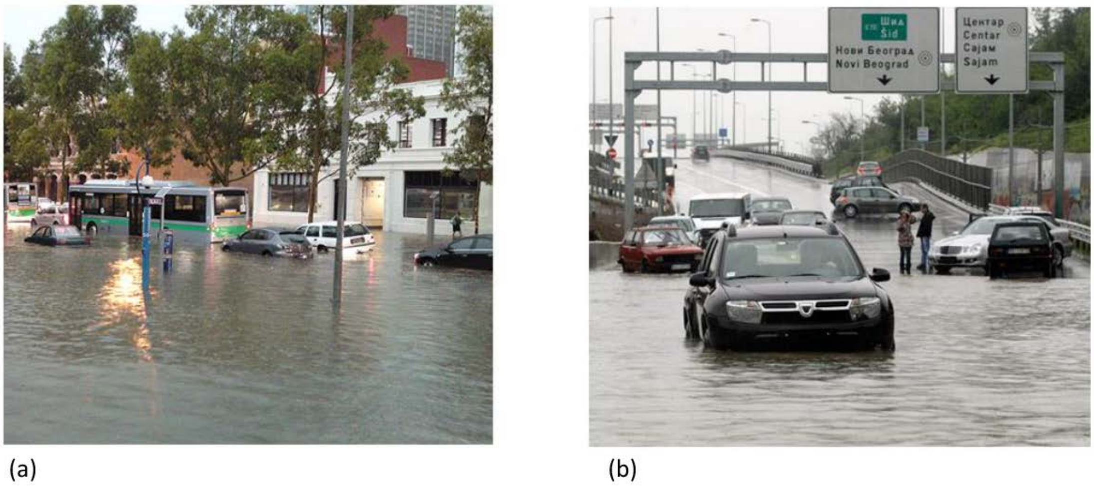


Figure 1-1: Example of flooding and disruption of transport sector: (a) Australia 2010 (Spencer, 2010) and (b) Serbia 2014 (EPA, 2014).

1.2 MOTIVATION

According to Swiss RE (2014) 40 major catastrophic events took place in Europe in 2013, including two of the costliest in the world (£10.6 billion of damage for the Germany/ Czech Republic floods; £3 billion for hailstorms in France and Germany). In the last decade the UK suffered multiple extreme events, with £3.2 billion of economic losses in 2007 for floods in England and £276 million for the Cumbria floods in 2009 (Pant *et al*., 2014). Considering all the possible sources of flooding (fluvial, coastal, surface and groundwater), floods today are responsible for approximately £1.3 billion of annual damages in the UK alone (Sayers *et al.,* 2015). Additionally, such damages are projected to increase in the future due to changes in climate pattern and population increase (Schweighofer, 2014).

These facts underline an urgent need to adapt urban areas to reduce the risk from adverse weather events; however, we currently have limited understanding of how the complex relationships and interactions between the built and natural environment can impact on society. In addition, most contemporary urban environments are characterised by a high percentage of impermeable surfaces (Houghton *et al.,* 2009). This directs surface runoff along roads and other impermeable surfaces during rainfall events, rapidly filling often out-dated drainage systems.

Of all the infrastructure networks, the transport sector is the most affected by flooding (Pyatkova *et al.,* 2015). This is important as the effective operation of the urban transport systems is essential for the economic competitiveness, businesses, and employees of a city (Mattsson and Jenelius, 2015). Any damage to the above mentioned systems could lead to severe and far-reaching consequences as well as further exacerbating effects, such as congestion, leading to even greater economic costs (Demuzere *et al*., 2014). In addition, transport networks are of fundamental importance during crises, with the resilience of such networks being vital for communication and emergency movements of people and material as well as the primary means of delivering aid.

A number of recent studies have examined the impact of weather events on urban transportation. However, they focus on the effect on traffic speeds due to ice and snow (Kyte *et al.*, 2001, Agarwal *et al.*, 2005, Tsapakis *et al.*, 2013), precipitation (that hampers driver visibility as opposed to flooding; Kyte *et al.*, 2001, Agarwal *et al.*, 2005, Koetse and Rietveld, 2009; Jaroszweski *et al.*, 2010; Tsapakis *et al.*, 2013; Hooper *et al.*, 2014), and wind (Kyte *et al.*, 2001; Agarwal *et al.*, 2005). Traffic safety and travel times for road transport have been investigated for many weather-related phenomena (*e.g*. fog, wind, rain, snow, ice), but flooding is generally missing from this literature (Koetse and Rietveld, 2009), apart from analysis of water forces on parked vehicles (*e.g*. Shu *et al.*, 2011; Xia *et al.*, 2011). Investigations into the impact of floods on road networks are limited to road closures or car accidents, without considering traffic speed and travel time (Suarez *et al.*, 2005; Chang *et al.*, 2010; Penning-Rowsell *et al.*, 2013).

Advances in flood risk analysis have predominantly focused on improved modelling of the hazard, with most assessment of damages limited to direct economic losses (Stewart and Deng, 2014). Very few studies include indirect damages that result from reduced infrastructure performance, *i.e.* the "accomplishment of tasks set for the system by the society that builds, operates, uses, or is neighbour to that infrastructure"(NRC, 1996). Indirect damages include interruption to flow and services as a result of capacity restrictions, damage, or network failures. Moreover, there is a paucity of data regarding flooding disruptions on traffic flows and no well-established models are currently able to provide them (Merz *et al.*, 2010). Flooding poses significant challenges to urban planners, and the limited financial resources of local councils makes it crucial to understand the nature and vulnerabilities of road networks for current and future climate hazards, in order to prioritise investments. However, understanding the effectiveness (*i.e.* value of economic losses that are avoided) of potential adaptation options is far from straightforward, due to the complexity and multi-disciplinarity of the topic (Doll *et al.*, 2014b; Levina and Tirpak, 2006).

This research has taken a systems approach to tackling these challenges, and led to the development of an integrated framework that considers the dynamic relationship between surface water flooding and the transport networks, alongside potential adaption options, in order to reduce the impacts on these systems. It investigates how urban environments can be impacted by extreme rainfall events and the strategies which could help to better protect them from present and future flooding in terms of transport network performance.

Newcastle-upon-Tyne (North-East of England) is susceptible to surface water flooding and is representative of a highly-impermeable UK city of medium size and has been the primary case study for this research. The value of the case study has been further enhanced by the availability of data and strong stakeholder relationships with Newcastle City Council, Northumbrian Water and other local stakeholders.

1.3 AIM AND OBJECTIVES FOR THE RESEARCH

This research aims to develop a practical tool that can assess system-scale impacts of surface water flooding on transport networks, and evaluate potential adaptation strategies to enhance urban resilience to current and future climatic conditions.

The following objectives are proposed to accomplish this aim:

OBJ1| understand the broader issues of flooding in urban environments, and review the gaps in current capabilities of flood risk assessment of urban transport systems.
This objective is functional to assess the current landscape on the topic and identified gaps to be covered.

OBJ2| develop an integrated modelling systems framework to quantify the impact of flooding on transport systems.

The integrated framework will overcome current silo-based approached in the transport-flood modelling

OBJ3| quantify the relationship between flood characteristics and transport system performance.
Existing approaches adopt a binary consideration of flooded roads (either open or closed), without examining the actual driving on flooded roads.

OBJ4| apply the framework to a representative urban case study, and validate the model using historic flood events.
The application of the framework will demonstrate the utility of this work and how can be used to assess cost-benefits for a flood-prone city.

OBJ5| assess the effectiveness of green and grey adaptation interventions to manage flood risk to transport disruption.
This analysis will provide a method to provide risk-based information regarding the efficacy of adaptation in flood impact alleviation.

The main outcome of this PhD is a framework to assess flood impact on transport networks, in order to prioritise adaptation options based on different scenarios and decision criteria. As infrastructure has long-term implications for a city's functioning, any future adaptation must be both effective and sustainable.

1.4 THESIS OUTLINE

An overview of the thesis is shown in Figure 1-2. Following this introduction, Chapter 2 reviews flood risk practice in the UK and at an international level, and describes the main elements of flood risk assessment. Chapter 3 defines the innovative methodological approach adopted by this research, and determines which modelling approaches and relationships are most suitable to incorporate into the framework by looking at the combination of hazard and impact modelling techniques. Chapter 4 introduces a new flood depth-transport disruption function, and its implications for transport modelling. How the curve was obtained and why represents significant progress with respect to the current state-of-the-art is described in detail. Chapter 5 presents the application of the methodology to the case study of Newcastle-upon-Tyne (UK). The techniques presented are used to assess the best adaptation options in the context of different flood scenarios. Chapter 6 summarises the results from the case study, and critically discusses the implications and impact of the findings. Finally, Chapter 7 summarises this body of work and considers the implications for transitioning to flood resilient cities.

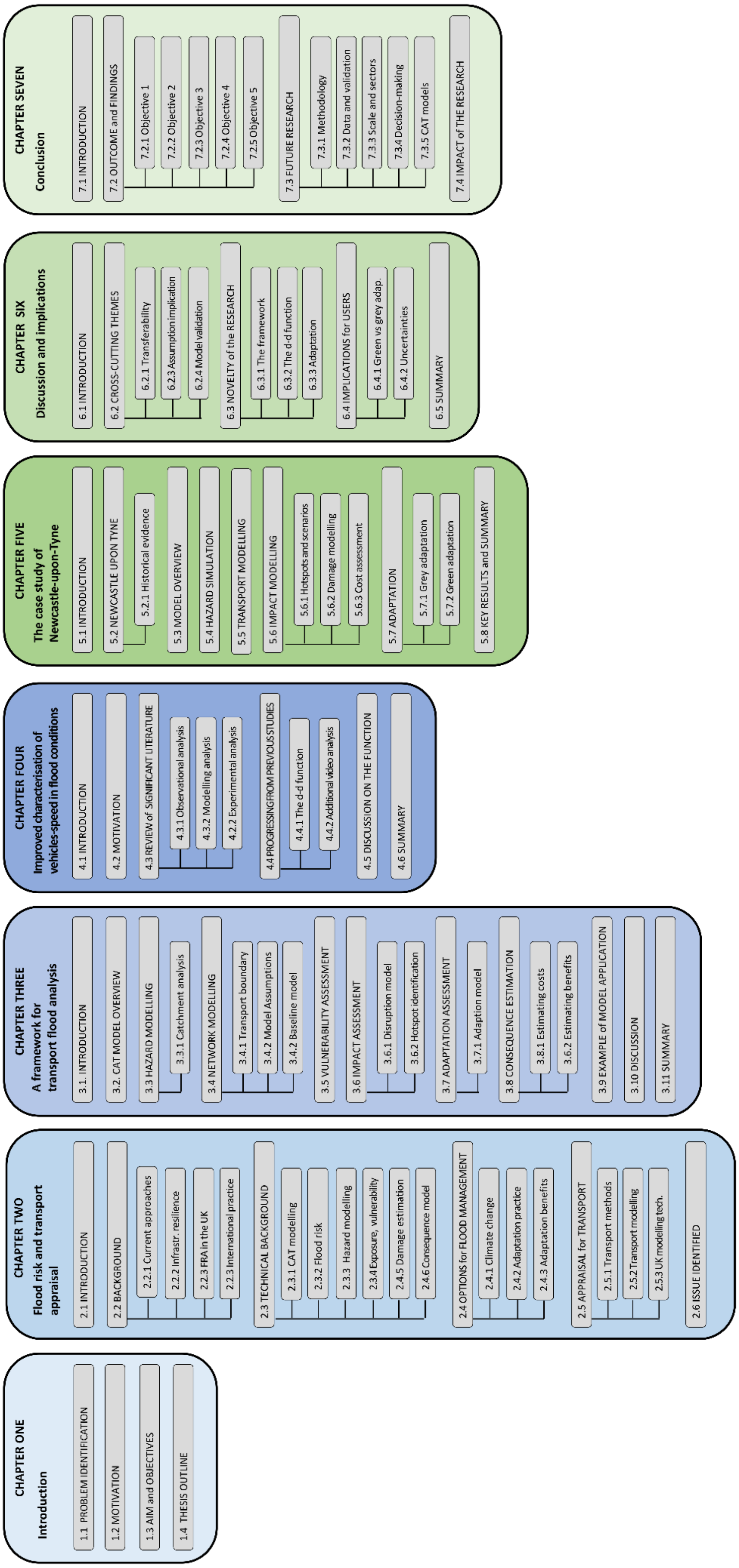


Figure 1-2. Overview of this thesis. Some sub-section titles have been shortened for graphical issues.

CHAPTER 2: FLOOD RISK AND TRANSPORT APPRAISAL

2.1 INTRODUCTION

In Chapter 1 it was argued that a new modelling framework that can integrated flood and transport modelling is required. Chapter 2 reviews current UK practice in flood risk management and best practice of flood risk management from around the world, describes existing modelling approaches and discusses what modifications need to be made to them so they can be applied to this problem. In addition, scientific research that can plug the gaps in the existing models is described. A technical background of risk assessment is described, illustrating the Catastrophe (CAT) modelling approach in its component: risk, hazard, exposure and vulnerability. Finally, options for flood management regarding urban strategies of adaptation and existing transport appraisal methods are identified.

The chapter addresses objective no. 1 of this thesis.

2.2 BACKGROUND OF FLOOD RISK MANAGEMENT IN THE UK

Water has always been a vital resource for communities, driving the establishment of cities close to rivers. Since ancient times communities have faced flooding and applied basic flood risk management principles, such as draining or structure elevation (Bekker, 2014). The government was not involved in flood protection, until the Sewers Act (1427) established drainage rates (Watson *et al*., 2009). In the 19th century, public money was appointed to fund drainage and the role of government continued to rise, as confirmed by the first Planning Act passed in 1909, followed by additional acts decades later (Bowers, 1988).

During the 20th century regulations developed further; in the 60s hard engineered solutions such as drainage and flood defences were in common use, although small attention was given to the natural environment. Moreover, planning and water authorities were established and organised at regional level. It was the Town and Country Planning Act in the 1968 that introduced a new system of local plans (Delafons, 1998), giving some freedom to local institutions.

By the end of the century until nowadays, responsibilities relating to the environment protection and enhancement, including flood risk, have been managed by different agencies at national level, namely: the Environment Agency (EA) in England, the Scottish Environment Protection Agency (SEPA), the Natural Resources Wales and the Northern Ireland Environment Agency (NIEA). These agencies are co-ordinated across the EU Water Framework Directive (2000), although the implementation of the measures could differ. Particular emphasis has been given to issues such as the development of flood risk maps, the consideration of the natural and built environments as "systems", and climate change.

Since 2000, numerous heavy rainfall and flooding events were recorded, as shown in Figure 2-1.

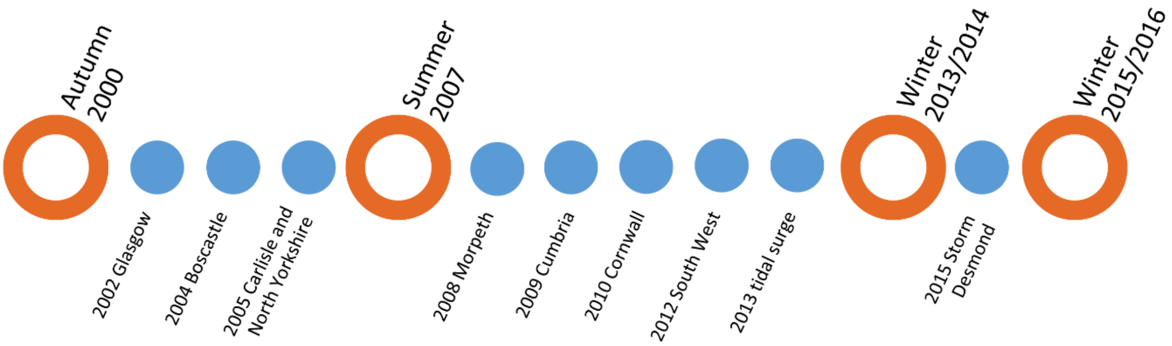


Figure 2-1. Main flooding events since 2000 in the UK.

In the last decades, increased concerns about the limits of structural flood defences and future uncertainties led to the development of the adaptation agenda, which is currently applied in the UK (Figure 2-2).

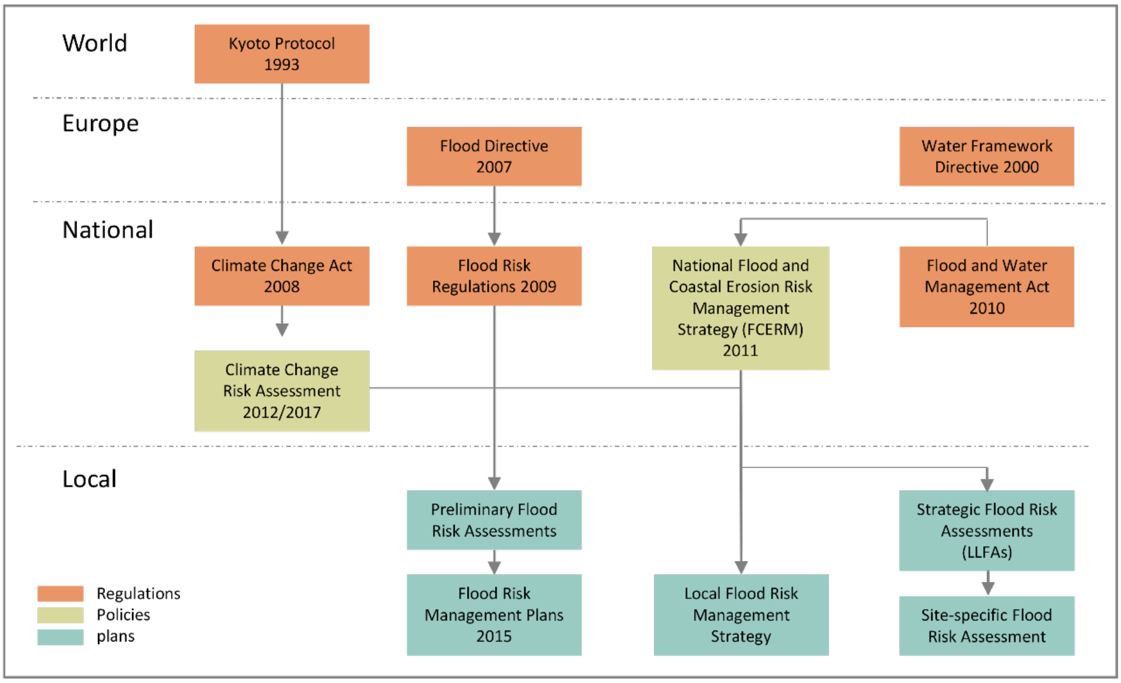


Figure 2-2. Current Flood Risk Management in the UK, modified from Bekker (2014).

After severe widespread flooding in 2007, The Pitt Review (Pitt, 2008) influenced the national approach to flood management by identifying the needs of an effective response to flood risk. The Flood and Water Management Act 2010 complemented it (see Section 2.2.1), by giving city councils the role of Lead Local Flood Authority (LLFA).

Although these actions set the right priorities, their implementation still needs research and tools to rethink flood protection and resilience across the country (Creutzig *et al.*, 2016). For example, households and businesses were hit by the winter floods of 2015/16 for a total cost of £5bn, of which £250m was infrastructure damage, notwithstanding the preparedness plans for facing floods (The Guardian, 2016).

Currently in the UK, the organisational framework for dealing with floods is considered "unfit", especially in the light of climate change and the increased environmental risk (Harrabin, 2016). The Government is undertaking major reforms of the system for managing flood risk, looking for long-term plans and new approaches to protect from the "domino effect" of infrastructure.

2.2.1 CURRENT APPROACHES

The flood events of the last decades emphasised the danger that flooding poses to communities. Recent approaches of risk management facilitate the assessment and mitigation of flooding impact on the basis of a methodological framework of five elements (HM Treasury, 2013). Risk assessment is encompassed in the process, together with options appraisal, decision-making and intervention; monitoring is the last stage (Figure 2-3).

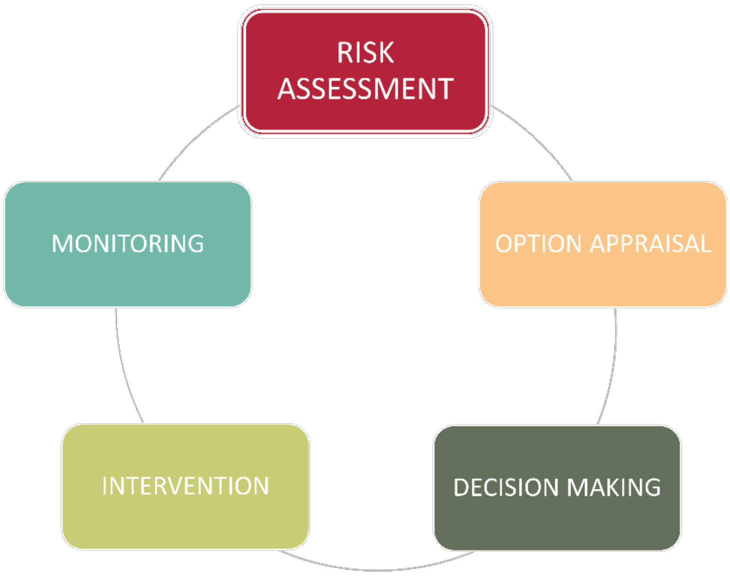


Figure 2-3. Risk assessment flowchart, adapted from HM Treasury (2001).

Flood simulations are an indispensable strategic planning tool when assessing flood risk. The new emphasis on the representation of uncertainties (*e.g.* variation in the simulation output) has been a relevant achievement in the field, considering the many unknowns of future scenarios (*e.g*. climate patterns, socio-economic factors) (Begum *et al.*, 2007).

Taking into account principles and methods of risk-based processes, probabilistic approaches for flood risk assessment have emerged as an extension of more consolidated methods used in seismic risk assessment. Probabilistic catastrophe loss models are becoming increasingly popular tools for estimating potential loss, linking a range of hazard intensities to the expected level of loss.

Catastrophe modelling can be applied to many natural events (perils), such as hurricanes or earthquakes, and it is particularly successful in addressing the challenge of flooding assessment. By combining hazard, exposure and vulnerability, the methodology allows to compute losses *via* damage functions.

2.2.2 INFRASTRUCTURE RESILIENCE

Protecting the infrastructure facilitates the reduction in urban flood risk and enhances their level of resilience to natural hazards (Pregnolato *et al.*, 2016; Zio, 2016). Infrastructure resilience is a necessary condition for resilient cities, since lifelines (critical infrastructure assets) underpin the functioning of the society. However, infrastructure systems are vast in size, interconnected and complex, which leads to a poor understanding of their resilience and consequently makes them vulnerable to potential disruptions (Cuthbertson, 2010).

In the urban context, infrastructure resilience can be defined as the "ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event" (Cabinet Office, 2011). It includes four components (Figure 2-4):

i) resistance, the capacity to withstand a hazard;

ii) reliability, the ability to operate in a range of conditions, including the adverse ones;

iii) redundancy, the designed capacity of the system concerning back-up installation for providing an alternative when normal operations are diverted; and

iv) response and recovery, the ability to quickly restore the service provision

Figure 2-4. The four components to be considered when evaluating infrastructure resilience, according to the Cabinet Office (2011).

The framework "Triple Resilience Target" (Wang and Yu, 2014) expressed the concept of resilience engineering by setting the timeframe of a resilient response (Figure 2-5).

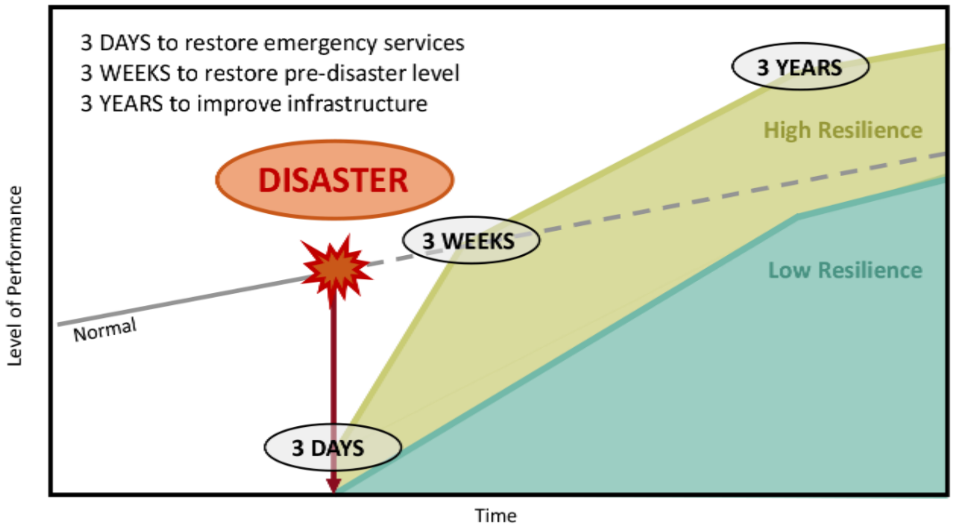


Figure 2-5. The Triple Resilience Target (adapted from Wang and Yu, 2014).

Where ideally disaster effects are contained by an emergency response in three days, the recovery activities are completed in three weeks and the improvement are developed after three years.

The capacity to manage crises and to recover after adverse weather plays a fundamental role in reducing the potential impact of flood on human and economic activities. Lifelines are crucial as their failure can amplify the impact, rather than enable emergency and repairing operations. Given the long life span of transportation assets, planning for system preservation and safe operation under current and future conditions constitutes an advisable approach to risk management.

Decision-makers can facilitate these operations through a range of structural and non-structural measures, driven by risk-based information.

2.2.3 FLOOD RISK ASSESSMENT IN THE UK

In the policies domain, Flood Risk Management (FRM) and Flood Risk Assessment (FRA) are the latest approaches to tackle the impact of flooding. Within this direction, the traditional focus of defending against floods has been transformed into a new vision of managing flood risk (Begum *et al.,* 2007). The concepts of risk involve different factors, not limited to rainfall or discharge, but inclusive of socio-economic and physical characteristics. This can be pragmatic only if a system perspective is applied, considering dynamics of processes and uncertainties.

Arising from devastating floods across the country, various documents and organisations have been set by the Government to assess how the territory could be best protected from future flood events and extreme weather, together with definitions, regulations and concepts.

This sub-section and the following one (Section 2.2.4) will respectively review *(i)* the main institutions, acts and policy documents that characterise the FRM and FRA landscape; (ii) the best practice worldwide adopted to tackle flooding.

INSTITUTIONS

Centre for Protection of National Infrastructure (CPNI)

CPNI protects UK's national critical infrastructure (assets, facilities, systems and networks). These assets are considered crucial components and include water, energy, waste and transportation systems. CPNI highlights the importance for a business to be operational after/during any disruption (such as a major fire, flooding or power fault) and to return to 'business as usual' in the quickest possible time.

Department of Environment, Food and Rural Affairs (DEFRA)

DEFRA is the ministerial department with lead responsibility for flooding, which promotes more integrated solutions to urban flood risk management. Together with the Environment Agency, it manages the Flood and Coastal Erosion Risk Management Research and Development Programme (FCERM R&D Programme), synthesising the best practice emerging from academia and operational practice from all over the world. To better deliver the implementation of the Floods and Water Management Act, in 2013 it established the Thematic Advisory Group (TAG), to help identifying and prioritising research needs.

Environment Agency (EA)

EA is an executive non-departmental public body, sponsored by DEFRA to protect the environment. It is responsible for managing the risk of flooding from main rivers, reservoirs, estuaries and the sea. It provides flood warnings, however they are limited to riverine and coastal flooding, whereas surface water flooding is missing (*e.g*. flash floods).

POLICY CONTEXT

Climate Change Act 2008

It is a Parliament act to ensure that the Kyoto protocol will be respected by the year 2050 (cutting greenhouse gases emissions by 80%), trying to avoid more dangerous consequences of climate change. An independent Committee on Climate Change (CCC) has been created under the Act (see Section 2.4.1).

Pitt Review (Pitt, 2008)

The report can be considered one of the widest ranging policy UK reviews and was commissioned by DEFRA after the UK widespread flooding of summer 2007, which left over 500,000 people without water or electricity. The focus is on resilience and vulnerability of critical infrastructure, as key for an effective flood risk management.

Flooding in England: national assessment of flood risk (NAFRA) (EA, 2009)

As first national assessment, the report analyses the risk of flooding in England, mainly from rivers and the sea (major area of responsibility of the EA). Indeed, most analysis are not surface-flooding focused, but riverine or coastal. A strategic overview of flooding in urban areas is missing at the moment and likely to be addressed in the future (Dawson *et al.*, 2008).

Flood and Water Management Act 2010

It provides a more comprehensive management of flood risk for the built environment, especially associated with extreme weather. The act gives power to LLFA and the Environment Agency regarding their FRM functions. It encourages the design of sustainable developments, using for example Sustainable Drainage Systems (SuDS).

Keep the country running: natural hazards and infrastructure (Cabinet Office, 2011)

Cabinet Offices' guide to support infrastructure stakeholders and government departments. The reduction of societal vulnerability to natural hazards is strongly related to the resilience of infrastructure, seen as a complex interconnected system. It defines the concept of infrastructure resilience (see Section 2.2.2) and presents "Reasonable worst case scenarios for natural hazards in the UK". Inland flooding is related to loss of primary transport routes, blocked roads and emergency services assets.

Flood and coastal erosion risk management: A Manual for Economic Appraisal (Penning-Rowsell et al., 2013)

Better known as the Multi-Coloured Manual (MCM), it defines the more established method in the UK for the estimation of flood losses and appraisal of flood hazards. The methodology includes direct damage assessment to urban properties (residential and non-residential), and indirect effects of floods, such as disruptions to utility services and transportation. However, flooded roads are considered either closed or fully operational, using a typical binary approach.

The State of the Nation (ICE, 2009; ICE, 2014)

This report series aims to identify the actions needed to improve the UK's infrastructure and associated services. In particular, findings underline that flood management and local transport are two sectors of particular concern. Major interruptions in infrastructure networks due to flooding cause impact on society and the economy, likely to increase under a growing population and changing weather patterns in both the short and long-term. A set of criteria from the Government are advocated for the improvement of urban resilience, alongside an efficient investment of the limited available funding for infrastructure.

National Risk Register (NRR) (Cabinet Office, 2015)

The National Risk Register provides an assessment of the likelihood and impact of a range of risks (*e.g.* natural and malicious hazards) potentially affecting the UK over the next five years. These hazards include coastal and, with a lower impact score, inland flooding, with just a mention to the dangers of flash flooding.

National Flood Resilience Review 2016 (DEFRA and Cabinet Office, 2016)

The Review committed £2.3 billion for reducing flood risk and coastal erosion, £12.5 million to be invested in temporary defences; however, extreme rainfall events and the vulnerability of assets require further improvements to assure the urban system resilience. Risk-based information is indicated as functional for giving guidance for investment.

CCRA 2017 (DEFRA, 2016)

The report assesses the need of actions to tackle current and future risks related to climate changes, particularly high for communities and infrastructure. The chapter of CCRA 2017 dedicated to infrastructure evidenced that adaptation is required to decrease flooding risk and how adaptation investments could contribute to such reduction (Dawson *et al.*, 2016).

2.2.4 INTERNATIONAL PRACTICE

The catastrophic aftermath of floods all around the world during the past decades shows that the exposure to flood risk is constantly increasing and that flooding is a global problem. To respond to these observations and implement renewed policies for flood management, similarly to the UK many countries are setting out national strategies and risk management plans, highlighting directions and priorities. International best practice is identified for inclusion into this study, in order to make the model globally compatible.

EUROPE

In Europe, the EU Floods Directive (2007/60/EC) appointed risk management as the leading direction to cope with flooding, demanding a preliminary assessment of the river basins and associated coastal areas at risk of flooding. For such zones, flood risk maps and relative FRM plans were required. The Directive attempted to set a common minimum standard of FRM in Europe; however, the requirements are not specific, and characterised by large flexibility. The Directive is supposed to be carried out in coordination with the previous Water Framework Directive (2000/60/EC).

European countries have mobilised relevant technical and financial sources to answer the call of the Directive, with the priority placed on probabilistic approaches and riverine floods (European Commission, 2003). Current policies still suffer from a lack of awareness of the overall vulnerability of territories, especially in considering direct and indirect impacts of flooding (Thieken *et al.*, 2008). Regarding pluvial floods, few countries seem prepared, given that maps of vulnerability to pluvial floods have not been introduced (Falconer *et al.*, 2009). In fact, additional sources of risks are likely to be added in the next years, together with climate change and adaptation, trying to refine risk assessment.

UNITED STATES of AMERICA

Catastrophic events, like Hurricane Katrina or Sandy, have stirred a new interest in developing more rational approaches to flood damage reduction in the USA. Following the results of several recent studies and government actions, risk analysis methodologies started to support decisions through flood risk management and away from floodplain management (Galloway, 2008). However, studies showed that government's decisions are mainly based on economic costs and benefits, with little consideration of social and environmental consequences of flooding (NRC, 2004). Analyses currently involve costs and benefits limited to the ones that can be easily quantified in economic terms, whereas they disregard non-quantifiable impacts of flooding.

The United States Army Corps of Engineers (USACE) is the lead flood control agency, responsible for planning and designing infrastructure and water defences (McKay *et al.*, 1999). They also actively research and apply damage assessment techniques (USACE, 1985; Davis *et al.*, 2008; USACE, 2008).

Regarding loss estimation, the most used and developed US software is HAZUS-MH. It quantifies various measures of impact (*e.g.* human, property, financial, social) from multiple natural hazards, in particular floods under existing conditions and given any possible mitigation measures (Scawthorn *et al.*, 2006a; Scawthorn *et al.*, 2006b). HAZUS Flood Model uses damage functions developed by USACE and is based on the rational of Catastrophe Modelling (Grossi and Kunreuther, 2005); it is largely applied for coastal and riverine flooding.

The Federal Emergency Management Agency (FEMA) coordinates the response to disasters, managing funding during declared emergencies. Additionally, it manages the National Flood Insurance Program (NFIP), which offers national rates of flood insurance to homeowners, renters, and business owners.

The Federal Highway Administration (FHWA) is the U.S. Department of Transportation, supporting States and local governments in the design. Through the Order 5520 "Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events" (2014), they stated that considerations of climate and extreme weather risks should be integrated into planning, operations, policies and programs of the transport sector.

AUSTRALIA

Australia is another flood prone region where major flood episodes have recently caused billions of dollars in damage to public infrastructure and private property (Fitzgerald *et al.*, 2010).

Geoscience Australia is the national public sector acting as advisor on the geology and geography of Australia. The National Flood Risk Advisory Group (NFRAG) is a working group of the Emergency Management Australia (EMA), and provides guidance on the responsibility of government regarding flood risk management.

Currently, two national guidelines are available. The first is the national guideline for the estimation of design flood characteristics, the Australian Rainfall and Runoff (ARR) (Ball *et al.*, 2016). Given the increasing concern about safety of people and vehicles in floods over the past two decades, vehicles stability criteria have been recently updated and are still a matter of revision (Shand *et al.*, 2011). The second is the handbook “Managing the floodplain: a guide to best practice in flood risk management”, which provides in four sections best practice for managing the flood threat to communities inhabiting floodplains, discussing how to apply information. The overarching goal is to deliver flood protection that includes sustainable and long-term benefits for the environment, and to improve community resilience (EMA, 2013).

Finally, many academic studies contributed to analyse and improve the assessment of flood damages based on Australian case studies (Smith *et al.*, 1990; Gissing and Blong, 2004; Middelman-Fernandes, 2009; Middelman-Fernandes, 2010; Mason *et al.*, 2012).

From the review of FRM practice around the world, it is clear that there is need for more sophisticated modelling approaches and various countries are starting to develop them. All countries either require or are very likely to introduce the assessment of adaptation related flooding and the quantification of economic consequences. Currently, one of the most sophisticated methods of calculating losses due to natural hazard is Catastrophe Modelling. This is a sophisticated tool that requires data from a variety of sources, including expertise in multiple fields (Grossi and Kunreuther, 2005). Natural hazard, engineering and economics lay the basis of catastrophe models. They consist in probabilistic analyses that estimate likelihood and severity of loss, together with financial impacts of catastrophes.

2.3 TECHNICAL BACKGROUND OF RISK ASSESSMENT

Risk models for risk assessment are usually made of four components: the hazard (key metrics of the hazard like flood depth), exposure (*e.g*. land use), vulnerability (*e.g.* damage-loss functions), and consequence (Hall *et al.*, 2003; Apel *et al.*, 2004; Grossi and Kunreuther, 2005; De Moel and Aerts, 2011).

In assessing flood risk, most attention is focused on the hazard stage, dedicating less analysis to the other components (Koks *et al.*, 2015).

In a context of uncertain changes, risk-based approaches are best-suited to advance adaptation measures. Most models are limited to stationary climate, whereas there is a need to evaluate infrastructure performance within costs and benefits of adaptation measures (Stewart and Deng, 2014).

2.3.1 CAT MODELLING

Flood is probably the most challenging hazard to model among all the natural perils because of the complexity at each stage of the flooding process. Insurance and reinsurance industries (such as AIR Worldwide or Risk Management Solutions) were the first to adopt catastrophe models in the late 1980s, to predict potential insured losses to properties from theoretical events. Nowadays flood damage functions are extensively used for loss estimation in the residential sector (*e.g*. MCM), for insurance and research purposes.

The general framework for modelling the impact of natural catastrophes can be broken down into the four primary components or modules, as shown in Figure 2-6. The main output of a probabilistic catastrophe (CAT) model is the exceedance probability (EP) curve, which illustrates the annual probability of exceeding a certain level of loss.

Figure 2-6. Overview of the catastrophe modelling framework, with the four main components: hazard, exposure, damage and consequences (Grossi and Kunreuther, 2005).

The *hazard* module deals with: (1) simulating thousands of representative catastrophic events in time and space (*i.e.* a range of scenarios); (2) assessing the resulting hazard intensity (*e.g.* level of ground motion, wind speed, flood depth, etc.) across a geographical area at risk. Each event is defined by a specific intensity measure (IM *i.e.*, its severity), location and probability of occurrence based on historical data.

The *exposure* module contains details of the location and characteristics of the "asset at risk", *i.e.* a property at risk of damage or a business/service at risk of interruption.

The *vulnerability* is the susceptibility to damage of elements, or other forms of loss, because of the hazard impact. The vulnerability can be defined as "the propensity of exposed elements, such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events", in other words it is the potential susceptibility of being damaged by adverse events (IPCC, 2012).

The *consequence* module estimates monetary losses by applying generalised cost functions to the total loss estimates. The estimates of insured loss can be validated using loss data from actual (historical) events.

CAT modelling has been extensively applied to buildings in both public and private sector. In this case, the information may be very specific, including geo-coded location, detailed engineering and architectural drawing, retrofit and replacement cost estimates.
However, in the context of transportation infrastructure modelling, detail flood assessment is rare, and models for estimating losses to infrastructure sector are scarce (Merz *et al.*, 2010; Kellermann *et al.*, 2015). Few established flood damage models (*e.g.* the Rhine Atlas damage Model, RAM) roughly assess direct flood damages in the

transport infrastructure sector, whereas indirect losses due to traffic disruptions are estimated by the MCM by considering the impact of road closure.

The extension of CAT modelling to the indirect losses resulting from infrastructure failure, such as traffic disruptions of transport systems, has, after an extensive search, not been found in the literature and represents a novel contribution of this study.

2.3.2 FLOOD RISK

Flood risk can be defined as "the product of the probability of flooding and the consequential damage, summed over all possible flood events", which "it is often quoted in terms of an expected annual damage" (EAD) (Hall *et al.*, 2003).

After Dawson and Hall (2006), the disruption risk due to flooding is given by Equation 2-1:

$$R = \int \rho(w) D(w) dw$$

Equation 2-1

where *ρ(w)* is the probability of a given rainfall *w*, and *D(w)* is the disruption associated with it.

Given *N* simulations of the loading hazard l, the expected annual disruption from flooding *R*, can be computed as a function of the disruption of each event $D(l_k)$, and the probability of occurrence $P(l_k)$, as shown in Equation 2-2:

$$R = {}^{1}\!/_{N} \sum_{k=1}^{N} D(l_k) P(l_k)$$

Equation 2-2

Given this definition, the flood risk depends upon:

- the characteristic of the hazard trigger, that is the intensity measure (IM) of the flooding event (*e.g.* flood depth, flood duration);
- the characteristics of the exposure (land use, assets value);
- the vulnerability of the exposed elements to the hazard.

Therefore, catastrophe modelling can be applied to flooding, and the modular approach (explained in Section 2.3.1) can be modelled alongside a flood hazard (Figure 2-7).

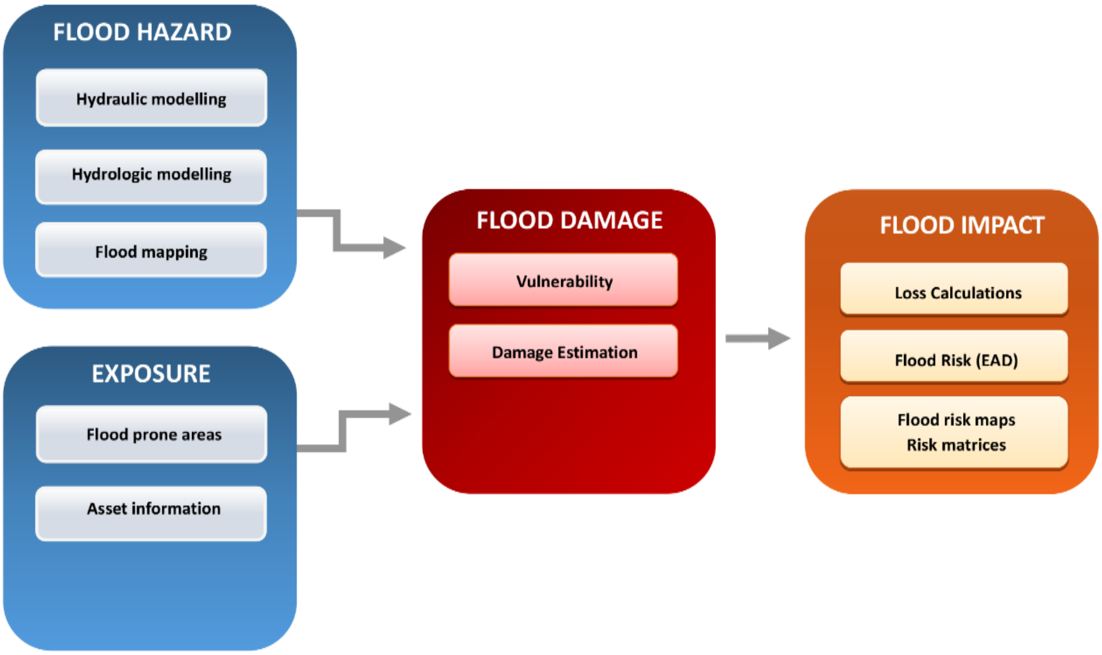


Figure 2-7. Flood model sub-components.

The starting point for flood loss assessment is the quantification of flood hazard in order to produce any relevant IM in the area of interest (Galasso and Senarath, 2014). Although different types of flooding (*e.g.* riverine, flash, coastal) behave differently, flood-related damage fundamentally results from the depth and duration of inundation as well as the water velocity.

For each flooding event, the runoff per catchment area is calculated, accounting for topographic features, by implementing a hydrologic model that converts precipitation to discharge. Next, a detailed hydraulic model is used in conjunction with the hydrologic model output to define a flow versus depth relationship, *i.e.* a rating curve, for each location of interest. Typically, one-dimensional or two-dimensional hydraulic-hydrological models are used for producing flood hazard maps, which spatially represent the IM. There are a wide variety of models that accounts for varying degrees of physical complexity and offer subtly different solutions to a given problem (*e.g.* Neal *et al.*, 2012; see Section 2.3.3).

The damage module estimates losses and downtime caused by flood to assets of interest, including vulnerability and exposure. The extent of damage depends on many factors, which change according to the sector considered (*e.g.* debris load, house location and its orientation to the flow for properties; type of roads, number of users for transport).

When assessing the consequences, monetary losses are calculated alongside the expected risk. Risk matrices of the event likelihood and relative consequences can be an appropriate method of showing low (L), medium (M) and high (H) risk, as shown in Figure 2-8 (CIRIA, 2001; Larsen *et al.*, 2010; Naso *et al.*, 2016).

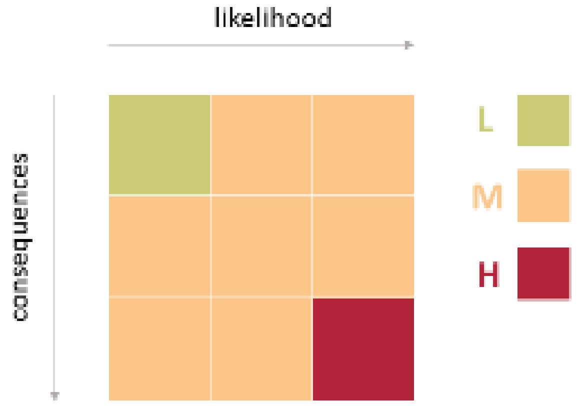


Figure 2-8. An example of risk matrix; green represents a lower risk, whereas red represents a higher risk.

The matrices can be then associated with flood risk maps, showing the spatial distribution of potential losses to the areas expected for certain scenarios (*e.g*. 200-year flood event), as shown in Figure 2-9.

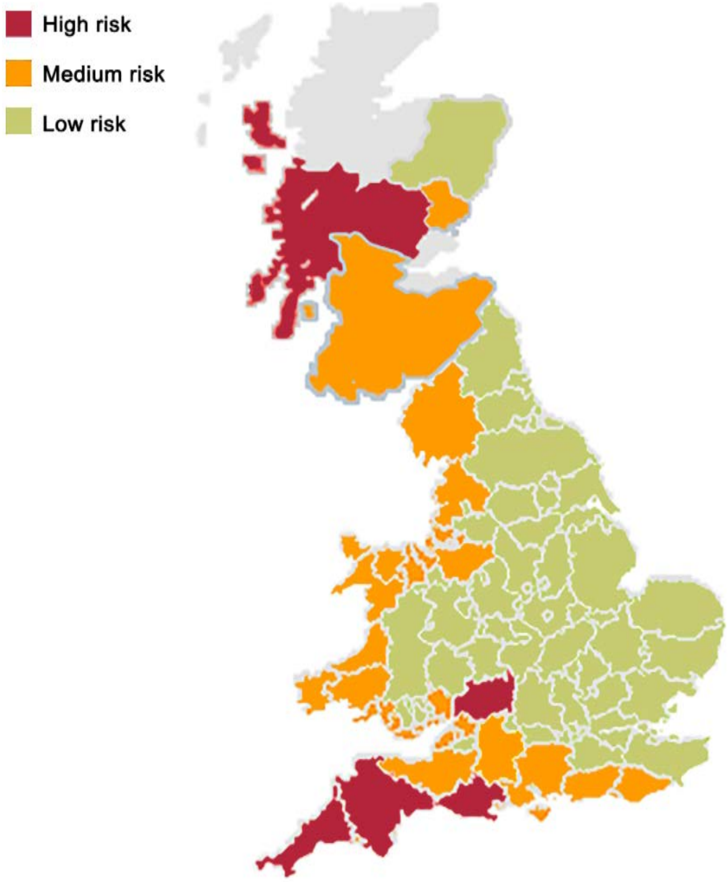


Figure 2-9. Example of flood risk map, showing the areas at risk of flooding for England, Wales and Scotland produced by the Environment Agency for the 3rd of January 2014 (from BBC News, http://sarr.tk/map-uk-floods-2014/).

Risk matrices and flood maps give a simple and graphical risk assessment, strategically functional for multiple purposes (urban planning, information, insurance, emergency preparedness, societal awareness).

2.3.3 HAZARD MODELLING

Floods can derive from multiple sources, namely coastal, riverine, and surface floods, or they can be due to failure of a man-made defence structure (*e.g.* dam-break floods). Among these events, flash floods due to excessive surface runoff and riverine floods are the most common and most damaging in urban environments (Kvočka *et al.*, 2016).

The flood hazard can be defined as "the exceedance probability of potentially damaging flood situation in a given area and within a specified period of time" (Begum *et al.*, 2007). The flood extent and intensity are usually related to a particular scenario, *i.e.* return period or design flood event. The return period estimates the likelihood of a hazard, such as a flood, to occur. It denotes the average recurrence interval over a given period of time (Equation 2-3):

$$T = \frac{n+1}{m}$$ **Equation 2-3**

where T is the recurrence interval or return period, n the number of recorded years, m the number of recorded occurrences of the event. The return period is the inverse of the probability that the event will be exceeded in a year. For instance, in a year a 10-year flood has a 1 on 10 (0.1) or 10% probability of being exceeded, whereas a 50-year flood has a 1 on 50 (0.02) or 2% chance of being exceeded (Mays, 2010). Example of typical design flood frequencies for pluvial floods are in the range of 2 to 500 years alongside durations of 60-90 minutes (Tyrna *et al.*, 2017).

The choice of appropriate flood metric to assess impact varies according to sector: one parameter might be significant for damage evaluation of residential buildings, but less important for agricultural crops or infrastructure (Merz *et al.*, 2010). A number of indicators can be taken as intensity measures (IMs), including: flood duration, flow velocity, rate of water rise, flood preparedness, sediment, pollution, and others (Smith, 1994; Merz *et al.*, 2004; Kreibich *et al.*, 2009; Merz and Thieken, 2009; Merz *et al.*, 2010; Mason *et al.*, 2012). Isolation of the influence of each variable is challenging because of insufficient data on their spatio-temporal dynamics during a flood. However, depth and velocity are considered to be the key metrics for flood damages (Merz *et al.*, 2010). Moreover, for indirect impacts (such as service and business interruption) most of these parameters have no significant influence, and it is considered reasonable to use water depth and flood duration as key measures for the magnitude and timeframe of impact respectively (Kreibich *et al.*, 2009).

The relationship between rainfall intensity and water depth for various return periods can be expressed through the Depth-Duration-Frequency (DDF) or Intensity-Duration-Frequency (IDF) curves, as shown in Figure 2-10. By focusing on design peak flow only, flood frequency curves can be produced through the Flood Estimation Handbook (FEH) methodology (Robson and Duncan, 1999). The FEH methodology is an accepted method in the UK and it is widely adopted in practice (Kjeldsen, 2007) to estimate design rainfalls from DDF curves.

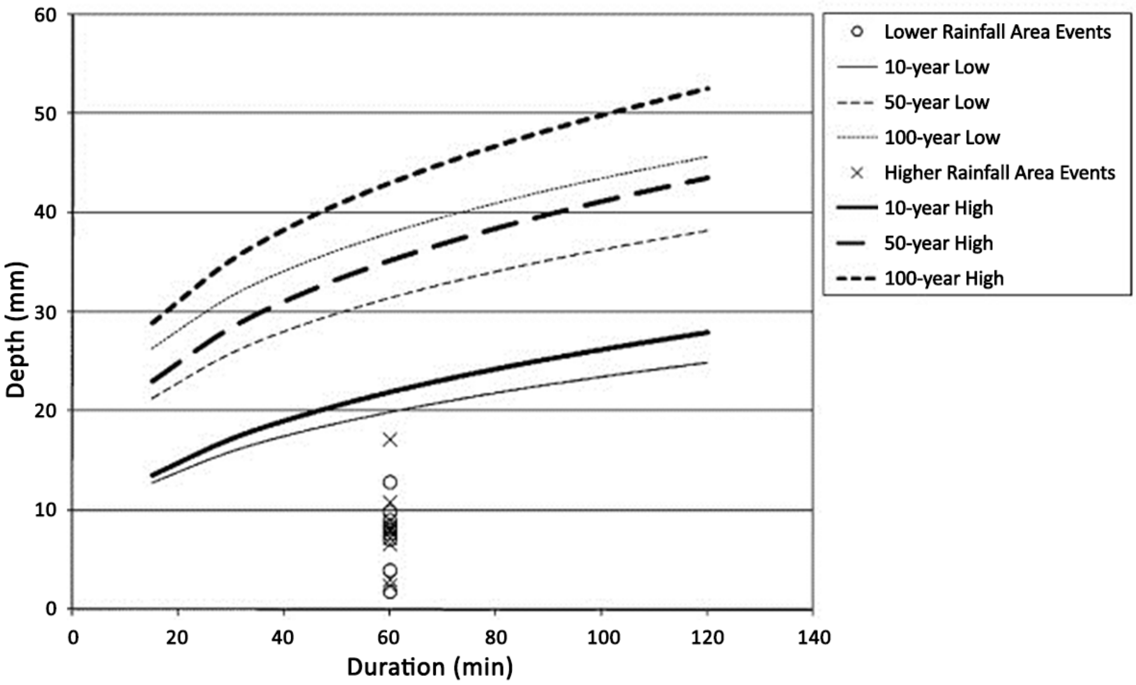


Figure 2-10. Example of DDF curves, for peak 1-h rainfall associated with surface water flood events, from Hurford *et al.* (2012).

An appropriate rainfall profile allows to distribute the design rain within the design duration. In urban catchments, 50% summer and winter profiles can be adopted (Figure 2-11).

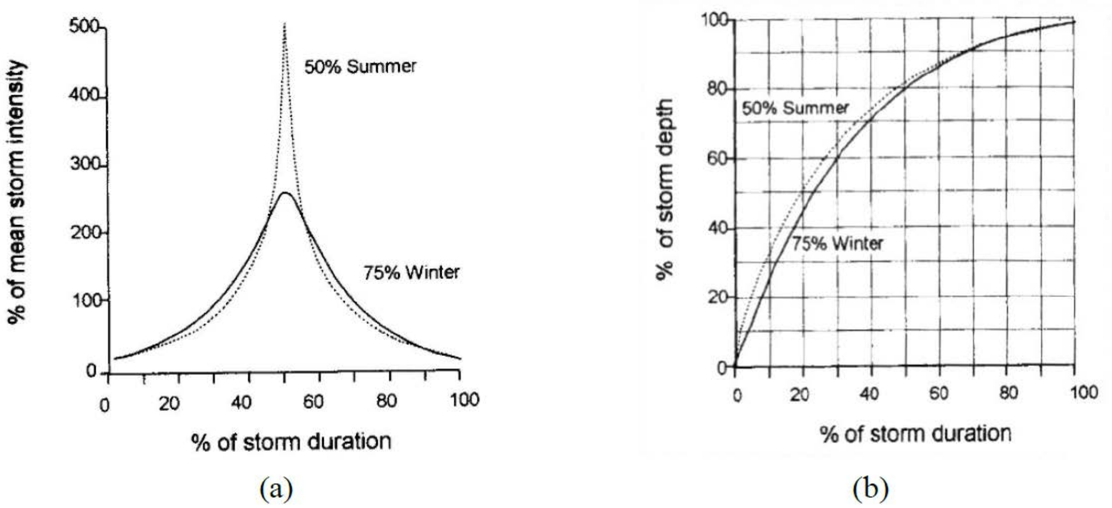


Figure 2-11. Design summer and rainfall profiles from Houghton-Carr (1999) in function of: (a) mean storm intensity; (b) storm depth.

Hydraulic models are modelling tools to simulate water flows. They can have different levels of accuracy and use one, two or three dimensions (Table 2-1). Specifically:

- 1D models: they give a good description of flood rerouting, but schematise a river channel into cross sections, so inundations and flood propagation can be inaccurate (Crispino *et al.*, 2015).
- 2D models: they ignore the vertical variation of the flow, using a two-dimension representation with shallow water. Depending on the scale and resolution of the simulations, they could be computationally expensive (Crispino *et al.*, 2015).
- 3D models: full representations in three-dimensions of flow processes with accurate results; however, they are computationally demanding (Tonina and Jorde, 2013).

Table 2-1. The most used hydraulic models for flood inundation modelling.

1D MODELS	
ISIS	Halcrow and Wallingofrd, 1987
MIKE11	Danish Hydraulic Institute, 2001
HEC-RAS	USACE, 2010
2D MODELS	
TELEMAC-2D	Division for Research and Development of the French Electricity Board, 2000
MIKE21	Danish Hydraulic Institute, 2011
TUFLOW	BMT WBM, 2010
3D MODELS	
FLUENT	Fluent Incorporated Company, 2006
MIKE3	Danish Hydraulic Institute, 2011

Hydrological models are able to simulate the runoff processes, considering discharge and infiltration. They usually require less computational time than hydraulic models. Coupling hydraulic and hydrological models is a way to improve the computational efficiency of hydrodynamic models (Lian *et al.*, 2007).

Flood simulations are based on Digital Elevation Models (DEMs) of the area, which are the 3D representation of a terrain. In addition, buildings play an important role, and their footprint can be included in simulations for example by taking out the buildings cells from the model.

The outputs of a flood model are hazard maps spatially representing flood extent and depth (an example is shown in Figure 2-12). The accuracy of the map depends on the resolution of the simulation and on other factors, such as the number of terms in the governing equations or the order precision of the numerical method (Chen *et al.,* 2012).

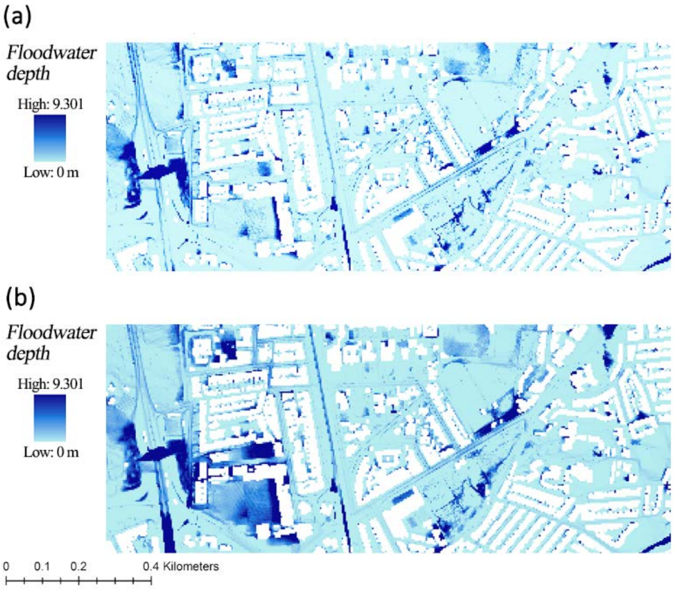


Figure 2-12. Example of output from a flood model, considering a one-hour-duration event: (a) flood map for a 1-in-10-ys event; (b) flood map for a 1-in-200-ys. White areas represent buildings.

2.3.4 EXPOSURE AND VULNERABILITY

Potential losses due to a hazard depend on the environment features. The exposure consists in the value of the exposed elements, *i.e.* objects potentially impacted by a defined flood scenario for a certain environment (Aerts *et al.*, 2013a). This information can be derived from geo information systems, Census data and other available datasets (*e.g.* insurance) covering data about: land-use, people, buildings and infrastructure. These are objective properties, independent from the hazard.

The value of the exposure is used to assess the degree of vulnerability of the urban environment (Kron, 2005). Typically, vulnerability or damage functions define the loss in terms of percentage of the asset value (that is its replacement value) expected to be lost at a defined hazard level, specific to the exposure category.

The vulnerability is a "system property", which is related to those characteristics of the exposed elements that favour adverse effects, and hazard-specific, *i.e.* related to a specific hazard event (IPCC, 2012). By instance, a building can be vulnerable to earthquake, but not to flooding.

Vulnerability differs from exposure (IPCC, 2012). Exposure is a necessary, and not sufficient, condition of risk. A building in a floodplain with sufficient measures to bear the impact is exposed, but not vulnerable. Nevertheless, an asset vulnerable to a hazard is also necessarily exposed to it. A highway bridge cannot be vulnerable to coastal flooding, if far away from the sea.

Vulnerability and exposure are dynamic entities, dependent on temporal and spatial scales, demographic, economic, social, institutional, geographic, cultural, climatic and environmental factors (IPCC, 2012). This means that changing the conditions can affect the level of vulnerability of the environment.

A better understanding of the degree of vulnerability faced by the various assets, and especially networks, is fundamental for developing protection for flooding events. It consists in assessing the potential physical damage given by certain floodwater depths.

2.3.5 DAMAGE ESTIMATION

The damage estimation consists of evaluating costs and losses caused by floods to assets (*e.g.* buildings, infrastructure, environment), under different load conditions of hazard. Worldwide Damage Functions (DFs) are recognised as the standard method for urban flood assessment, and a wide range of research is present in the literature (Smith, 1994; Herath, 2003; Scawthorn *et al.*, 2006b; Merz *et al.*, 2010; Jongman *et al.*, 2012; Penning-Rowsell *et al.*, 2013). DFs relates the intensity measure of the hazard to the relative damage experienced by the element at risk, representing the susceptibility of the object to the hazardous event.

A wide bulk of research is dedicated to the standard approach in relation to buildings, presenting the monetary damage dependent on the use and typology, so that similar buildings (for age, materials, etc.) have the same DF. The most applied functions are depth-damage functions (Tariq *et al.*, 2014), which link water depth (stage height) to direct damage (Middelman-Fernandes, 2010).

DFs can be also applied to the direct losses of commercial and industrial buildings (Su *et al.*, 2009), or crops and infrastructure (Dutta *et al.*, 2003), and other elements of the natural and built environment (Figure 2-13).

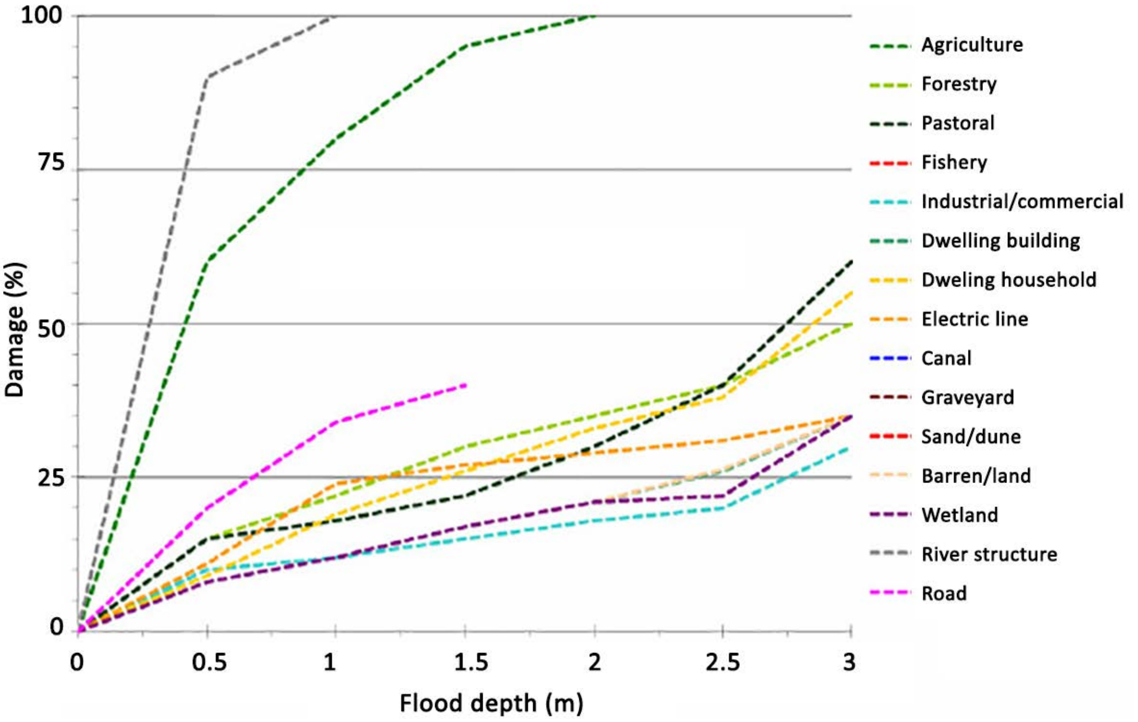


Figure 2-13. Flood damage functions used for a range of elements (Tariq *et al.*, 2014).

Other important parameters could be included (socio-economic variable, emergency preparedness, etc.) as well as other type of damages. Monetary losses represent just one typology of damage. When estimating losses, a distinction should be made between the different nature of losses.

A common classification of types of flood damage (Parker *et al.*, 1987; Smith and Ward, 1998; Chen *et al.*, 2016) includes (Table 2-2):

- direct costs : due to the physical contact with flood water;
- indirect cost: not due to the physical contact with flood water;
- tangible damage: evaluable in monetary terms;
- intangible damage: not evaluable in monetary terms.

Table 2-2. Categories of damages due to flooding, from Aerts *et al.* (2013a).

	Tangible	Intangible
Direct	• buildings (physical damage) • contents • infrastructure (physical damage) • crops and agriculture production	• loss of life • health • loss of ecological goods • loss of historical heritage
Indirect	• loss of industrial production • business interruption • traffic disruption • emergency costs	• post-flood recovery • migration • psychological damages • increased vulnerability of survivors

Including different types of flood losses adds extra-complexity to flood risk assessment. Indeed, estimations are usually restricted to monetary losses (mainly of buildings). However, this limited approach could misrepresent the reality of the impact of an event, which should include all the adverse consequences concerning the flood extent. Hence, there is a need to better address damages, including interruption to flows and linkages between systems (Begum *et al.*, 2007; Chen *et al.*, 2016).

Regarding infrastructure, lifelines suffers from both direct (*e.g.* cost of repair) and indirect damage (*e.g.* service disruptions, delay cost). Within this sector, it is possible to define multiple categories of assets: water supply, gas supply, sewerage and drainage, power supply, telecommunication and IT, and transportation. In order to assess the indirect damage, the literature indicates just a few models, derived from earthquake engineering (Dutta *et al.*, 2003; Scawthorn *et al.*, 2006a).

2.3.6 CONSEQUENCE MODEL

After the stages of modelling the hazard and computing the level of damage on the basis of the exposure, the last step includes the modelling of the consequences. This analysis consists in the assessment of losses, related to the type of damage of interest (Figure 2-6).

A consequence-based approach focuses on the potential negative effects from hazards, as well as the potential benefits from potential mitigation actions. The analysis of damage consequences includes the risk estimation of the costs of the asset of interest for the likelihood of a given hazard, and can follow the classification into tangible and intangible damage. The greater the consequences, the lower the frequency can be accepted for an event (Coppola, 2010).

Regarding the transport sector, flood risk management strategies aim to reduce the consequence on traffic flows when roads are flooded (Coppola, 2010). Transportation lifelines suffer from direct and indirect damage, thus costs due to traffic or business disruptions are classified as indirect tangible damage (see Section 2.3.5). In the literature, a limited number of studies includes risk modelling from indirect damages like interruption to flow and linkages (Chen *et al.*, 2016).

Together with the modelled effects of flooding, data on the consequences from past floods is of great importance. Past records allow comparison with real situations, leading to better estimates of future risk. Modern technology and devices allow to produce large datasets of data ("Big Data"), such as rainfall rate or flood depths (for the hazard), vehicle flows or speed (for the exposure). They are fundamental for the calibration and validation of models and damage functions, as well as for monitoring and analysis.

The following section will illustrate strategies and techniques of flood management, focusing on the assessment of the cost and benefits related to adaptation in urban environments.

2.4 OPTIONS FOR FLOOD MANAGEMENT

Once the impact have been quantified, the next stage is to consider how this can be lessened by ad-hoc strategies on the territory. In order to manage the risk of flooding, flood adaptation measures could be identified in the urban context. Such measures can be traditional interventions of structural engineering (like dams), or alternative approaches like Sustainable Drainage Systems (SuDS) or Blue Green Infrastructure (BGI). At the urban scale, the latter would involve a series of co-benefits in addition to stormwater management, like pollution reduction. Extensive literature has been focused on multi-functionality and co-benefits of BGI, however little consistency can be found regarding the assessment and quantification of the actual effects (Tzoulas *et al.*, 2007; Farrugia *et al.*, 2013; Demuzere *et al.*, 2014; Wright *et al.*, 2014). My research contributes to understand the effectiveness of a portfolio of adaptation options, through a methodology for measuring the improvements brought by adaptation.

2.4.1 CLIMATE CHANGE AND ADAPTATION

The Intergovernmental Panel on Climate Change (IPCC) is the international body for assessing the scientific basis of climate change, impacts, future risks, and effectiveness of adaptation and mitigation options. IPCC (2014) defines adaptation as “adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderate harm or exploit beneficial opportunities” (Doll *et al.,* 2014b). Adaptation should carefully consider the cross-cutting nature of risks and adaptation strategies, in order to be efficient in terms of their costs and benefits for current and future scenarios (DEFRA, 2016).

In the UK, the Climate Change Act (2008) established the Committee on Climate Change (CCC) as an independent, statutory body to advise the Government about tackling climate change. Climate change is considered the major national threat of current times, more dangerous than terrorism (ICE, 2009). Within the CCC, experts from climate change, science and economic sectors form the Adaptation Sub-Committee (ASC), to set the direction for adaptation.

Climate is changing and it is bringing increased frequency and intensity of adverse weather events, hence aggravated infrastructure damages (Stewart and Deng, 2014). The conclusion of the 5th assessment report of the Intergovernmental Panel for Climate Change (IPCC, 2014) stated that climate change is “unequivocal”. A changing climate means an increase in CO_2, temperature, humidity; less certain is the impact of these changes on weather-related phenomena such as rainfalls, winds, and sea-level rise. In detail, climate change can involve (Doll *et al.*, 2014a; Doll *et al.*, 2014b):

- changes in temperatures (average and extreme values);
- rising sea levels and warmer water;
- snow, ice cover, permafrost thawing;
- more frequent droughts and wildfires;
- changing weather pattern (storms, rainfall, heat waves, …);
- increase in annual rainfall, flooding and landslides;
- increase in intensity and frequency of climate extremes.

Such changes are likely to lead to environmental, socio-economic and human impacts, exacerbating existing vulnerabilities and risks (*e.g*. riverine or coastal flooding). However, as weather impacts will appear gradually, long-term interventions can be put in place by investing in mitigation and adaptation measures for infrastructures (Birkmann and Mechler, 2015).

The Climate Change Act included the adaptation reporting power that concerns the invitation of certain organisations (*e.g.* water companies, electricity distributors) to produce reports about the effects of climate change on themselves for current and future scenarios, alongside proposals of adaptation options. The transport sector was identified as a crucial one (DEFRA, 2015). Nevertheless, such reports were characterised by simplicity of guidance and assessed what was being done only, without justifying or identifying investments; for more expensive investments, more sophisticated approaches are needed.

2.4.2 ADAPTATION BEST-PRACTICE

In a context of highly vulnerable urban systems to hazards, adapting and reducing the harm is recognised as a primary need of the modern society (Aerts *et al.*, 2013a). Adaptation is a very complex issue, not yet completely defined and developed. It is still a “matter of learning by doing” (Aerts *et al.*, 2013a), which should involve all available options due to the uncertainties related to future climatic and socio-economic conditions. Given that, it is not possible to exactly predict the future and the strategies needed, no- or low-regret and flexible options should be considered. These options could yield benefits even in absence of impact and enable amendments.

Decision-makers can plan the process of adaptation to an adverse climate through different types of strategies. The source-pathway-receptor-consequence (SPRC) model (DETR, 2000; Kandilioti and Makropoulos, 2012; Ford *et al.*, 2016) can be adopted to analyse the relationships between the hazard trigger (such as rain), the pathway by which it is transmitted (such as over the floodplain) and their consequences on the built environment (households) (Figure 2-14). Interventions have historically been focused on the receptor (ICE, 2001), however implementing strategies at the pathway level (floodplain or flood defences) is a promising direction of research.

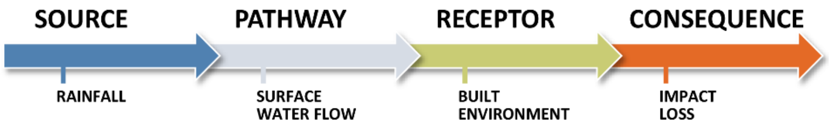


Figure 2-14. The SPRC (Source Pathway Receptor Consequence) scheme, modified from Kandilioti and Makropoulos (2012).

According to the different focus and nature, these techniques can be divided into grey (or hard) and green (or soft) engineering options. These types of adaptation intervene in the SPRC methodology at different points.

Grey adaptation options intervene at the reception of the surface water flow on critical infrastructure (*e.g.* transport network links), reducing the vulnerability of those links to a given hazard level. Those are structural measures of engineering, such as dams or floodwalls. They tend to be more expensive and have a significant localised impact on the area of interventions.

Blue-green infrastructures intervene between the rainfall and the transmission of rainwater along surface pathways, thus reducing the experienced hazard severity. Green engineering solutions are more ecologically sensitive and consist in alternative approaches of flood alleviation. These strategies aim to reduce the water runoff before this reaches the built environment. Alternative flood management techniques (for example green spaces and roofs, roof or underground storage, or permeable surfaces, see Figure 2-15) can play a part in reducing the impact of floods, replacing traditional "hard" measures, facing a "new era" of flood risk (Kilsby, 2016). The report on the UK floods of 2007 (Pitt, 2008) highlights a number of examples of such innovative solutions, including garden without impervious surfaces, small-scale buildings on floodplains, systems to allow water from roofs and streets to seep and be filtered into the ground, or permeable car parks.

Figure 2-15. Examples of BGIs that can be applied in urban environments: (a) green roofs (source: https://goo.gl/994SCk); (b) retention basins (source: https://goo.gl/FVaGYW); (c) permeable pavement (source: https://goo.gl/azp3m5).

2.4.3 ADAPTATION BENEFITS ASSESSMENT

The implementation of adaptation measures involves policy-making and financing. At the stage of planning, a portfolio of various measures should be taken into account, alongside a range of decision time horizons (short-, medium-, and long- term). By estimating the benefits from adaptation, interventions related to infrastructure and urban planning could be seen as opportunities and innovations by investors and planners (Dawson *et al.*, 2015).

The assessment of the benefits is currently a topic of research, aiming at "appraisal-led" scheme options (Penning-Rowsell *et al.*, 2013). The Flood and Coastal Erosion Risk Management appraisal guidance (FCERM-AG) is the DEFRA's guidance on appraising the risk of flooding or erosion, and identifies solutions of best practice implementation that could provide benefits at both local and national level (DEFRA, 2010). The methodology consists of calculating the losses cost in the scenarios without adaptation and compare them to the losses in the scenarios with adaptation. The difference of the losses plus the cost of the intervention itself gives a measure of the effectiveness of the strategy (Figure 2-16).

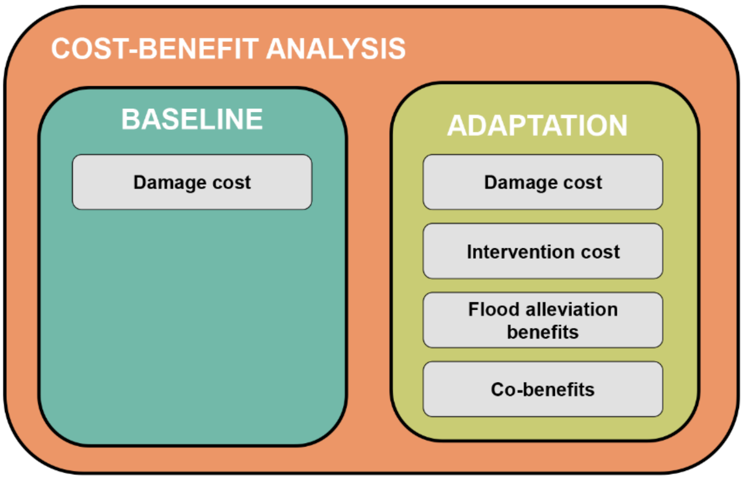


Figure 2-16. The scheme for appraising cost-benefits in relation to adaptation.

Losses can be quantified using direct damages (*e.g.* to buildings) or indirect damages (*e.g.* traffic flows); intervention costs can be easily calculated from tables providing indicative costs for SUDS and other drainage infrastructure (Keating *et al.*, 2015). However, quantifying co-benefits due to non-structural measure (*e.g.* urban amenity, CO_2 reduction) is less straightforward as co-benefits cannot easily be quantified in monetary terms. Nevertheless, comparing losses, costs and benefits can give a qualitative and worthwhile measure of the effectiveness and potential of a strategy.

Multiple methods can be applied to assess costs and benefits, in order to appreciate the effectiveness of an intervention (Gill *et al.*, 2007; Aerts *et al.*, 2013b; Hinkel *et al.*, 2014; Horton *et al.*, 2016). The most common cost-benefits analyses (CBA) are listed below (Watkiss *et al*., 2015):

- benefit-cost ratio (BCR): since the assessment is given by the ratio between benefits and cost, all cost and benefits have to be quantified in monetary terms;
- cost-effectiveness analysis (CEA): it compares the relative cost to benefit, typically adopted where a single parameter is considered;
- multi-criteria analysis (MCA): “umbrella term” that includes both quantitative and non-quantitative assessment analysis, aiming to integrate monetised and non-monetised results by assigning weights and indicators.

Developing cost-benefit estimations is functional for understanding the potentiality for the different options alongside a particular scenario. Adaptation interventions have a cost and the point is to understand if the benefit from them justifies the implementation, and amongst them which ones are the most attractive in relation to specific socio-economic and environmental conditions (Dalziell and Nicholson, 2001).

All costs and benefits should be converted into present values in order to be compared. The HM Treasury’s Green Book (HM Treasury, 2013) explicated the discounting technique to calculate the Net Present Value (NPV) of an option, to evaluate the economic efficiency of a range of interventions. Risk and uncertainty can be implemented in the procedure, by considering the likelihood of an event and calculate the expected NPVs for different scenarios. Additionally, the Return on the Investment (ROI) measures the investment gains compared to the investment cost, evaluating the efficiency (profits) of an investment. The repayment or payback time gives the number of years that are needed to recuperate from the initial expenditure; this contributes to understand the profitability of an investment and the timeframe of the economic risk (Farris *et al.*, 2010).

After having determined costs for events of average probability (*e.g.* 1-in-100-years) and identified particular vulnerable areas, the interventions should be driven by a prioritisation principle, which assesses the economic (and not only) relevance of specific interventions. The selection of the best options can follow different criteria, for example favouring the option that maximises the benefits or the one that offers the maximum return. Practically, non-quantifiable benefits and costs will also influence the decision; however, valuing non-market factors is a difficult task.

Estimating methods for adaptation is still a developing topic, and new information will be transformed in pioneering tools soon. This study examined potential adaptation measures that can be employed to improve the resilience of the urban system.

2.5 APPRAISAL FOR TRANSPORT

Road networks are the most vulnerable and affected transport mode in Europe covering almost the 80% of total costs, followed by air (16%) and rail transport (3%) (Doll *et al.*, 2014b; Molarius *et al.*, 2014). The transport system is mostly affected by winter climate (43%) and floods (39%) (Doll *et al.,* 2014a). The latest ONS projections suggested that the total UK population could increase of 6.3% by 2020, and up to 21% by 2050 (ONS, 2012). The number of cars on British roads has increased from 2 million in 1950 to 31 million in 2010, and nowadays congestion costs the UK economy £17.5 billion annually (BCC, 2007).

Ensuring the persistence of the performance even during adverse weather events is pivotal for the smooth functioning of a city, and for the management of the emergency (*e.g*. evacuation plans, emergency service, communication, etc.). In order to protect infrastructure from flooding, various measures can be put in place. However, any policy or scheme needs to point out what is the best way to achieve the objective, which resources are needed and which is the level of confidence in adopting that specific measure (HM Treasury, 2013).

Journey time reliability is considered the key output measure to assess the performance of a transport network (Smith and Blewitt, 2010). Parameters relative to traffic flows indeed are especially important with regards to monitoring the performance of a road network. In fact, average speed and average delay statistics are adopted by the

Department for Transport (DfT) to measure the reliability for the Strategic Road Network (SRN) (DfT, 2016b). In particular, the average delay is assumed as a proxy for congestion.

Transport modelling can support improved analysis for better decision-making in the field of urban planning (Ortúzar and Willumsen, 2011). A transport appraisal process (Figure 2-17) provides information to evaluate alternative solutions, supporting the development of a business case, through a transport model that includes option generation, development and evaluation of intervention impacts (DfT, 2014c).

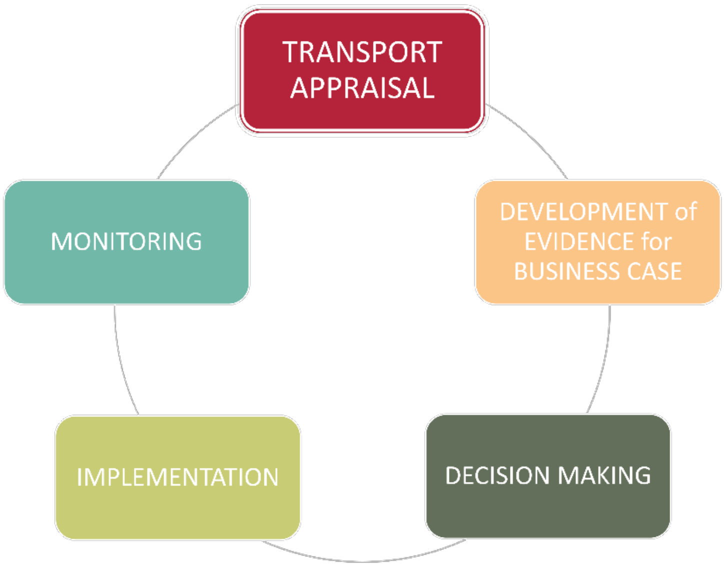


Figure 2-17. Overview of transport appraisal procedure (DfT, 2014c).

2.5.1 TRANSPORT METHODS

Transport models allow the mathematical modelling, or simulation, of transportation systems to inform the design process, looking at present and future conditions (Smith and Blewitt, 2010). A transport model includes the transport network, made by the stretches of roads (links, and their nodes), users, and costs due to the travelling.

Penning-Rowsell *et al.* (2013) identified four approaches to appraise road traffic disruptions.

(1) The delayed-hour method (Chatterton *et al.,* 2010)

It consists in a simple assessment of disruption cost based on the average cost of Highways Agency data. An estimate of £21.35 per hour is drawn from the average flood and the average velocity on the SRN. This method should be used on Highways Agency roads only and, in general, a more refined model is recommended when possible.

(2) The diversion-value method (Chatterton *et al.,* 2010)

It considers the diversion of vehicles to road closed due to the disruption; however, vehicle speed is not affected. The equation applied in this method is Equation 2-4:

$$C = veh * C_{veh} * f \qquad \textbf{Equation 2-4}$$

where C is the estimated cost due to a flood (£) , *veh* is the number of vehicles delayed, C_{veh} is the additional cost per vehicle (£/hr) and f is the flood duration (hr).

(3) The speed-time method (Penning-Rowsell *et al.*, 2005)

This method links road closures with annual probabilities and duration of floods, and accounts for speeds reduction. However, a very simplistic principle is applied to decide whether a road is open or closed: "when the middle of the lane is inundated and certainly when the crown of that road is flooded".

A more complex equation (Equation 2-5) is proposed:

$$C = veh * L * C_L * f \qquad \textbf{Equation 2-5}$$

where C is the estimated cost of the road disruption (£), *veh* is the number of vehicles (for different vehicles type), and L is the diversion length (km), C_L is the cost of travel per km and for each vehicle type, and f *is* the flood duration (hr).

(4) The origin-destination matrix method (DfT, 2014b)

Assessing disruption costs through an origin-destination matrix is the most accurate of the approaches. In relation to users' journeys, it is based on a table of origins and destinations, consisting of a matrix with the number of trips going from each origin to each destination (Timms, 2001). Within an origin-destination (OD) matrix, a general traffic assignment model could be developed. This is a sophisticate technique and an appropriate expertise is needed in order to handle the complexity of the model.

According to the level of detail, the geographic scale and the analysis scope, three basic types of models can be found (Hardy and Wunderlich, 2007).

They are:

1. macro-scale models: transportation elements characteristics are aggregated, representing a wide area, like a metropolitan region. They do not represent vehicles individually, but the overall system. An example is OREMS (cta.ornl.gov);
2. meso-scale models: modelling occurs by simulating groups of vehicles, considered homogeneous. They offer a reasonable and practical simplification (*e.g.* no individual lanes), allowing to elaborate large networks with high computational efficiency. An example is SATURN (Hall *et al.*, 1980) or TRANSIMS (www.transims-opensource.net);
3. micro-scale models: vehicles movement is simulated individually, and there are features of traffic flow theories such as car-following or lane sections. Other parameters relative to the driving culture of a given environment can be implemented too. They require a relevant amount of input data and computing power. They perform well at the scale of a junction or road segment, producing also animated visualisation. Actual models are VISSIM (www.ptvamerica.com) and AIMSUN (http://ww.aimsun.com).

Given the complexity of contemporary urban environments, the separation among the three models can be quite indistinct; an effective analysis should integrate a combination of elements from all the three approaches (Barcelo *et al.*, 2007).

2.5.2 TRANSPORT MODELLING

Research about traffic management under hazardous events began in the 1930s with the studies of Greenshields (1935). His fundamental diagram (Figure 2-18a) defined the relationship between travelling speed and vehicle density along roads. Since then, various authors reconsidered the results (Greenberg, 1959; Underwood, 1961; Drew, 1965; Drake *et al.*, 1967; Quek *et al.*, 2009; Thankappan *et al.*, 2010), developing the fundamental traffic diagram (Figure 2-18b), commonly used in traffic management (Gordon and Tighe, 2005).

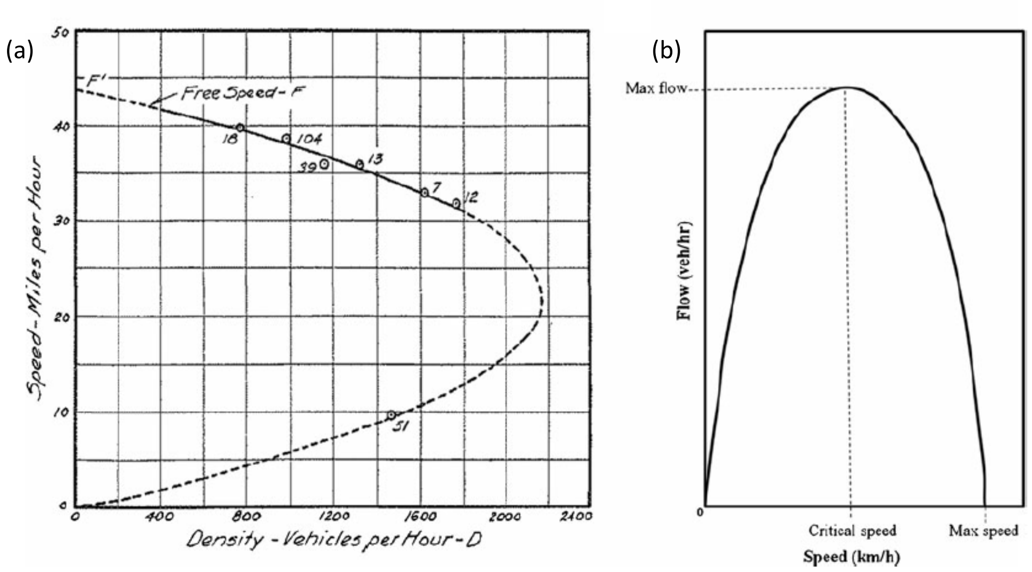


Figure 2-18. First (a) and current (b) fundamental diagram for traffic management, from Hooper *et al.* (2013).

The fundamental traffic diagram is practical to characterise the travelling speed as a function of density and flow in urban environments in normal conditions, such as good weather. Nevertheless, existing studies rarely model vehicles speed within the outcome of climatic effects, and those that do that are quite limited (see Chapter 4).

Within a transport model, vehicles and people can be assigned to the road network with the trip-assignment approach (Ortúzar and Willumsen, 2011). The level of service can be measured by the cost of travel, inclusive of the travelling time. Costs are indeed a function of a number of attributes, *i.e.* distance, free-flow speed, capacity, frequency and a flow-generalised cost relationship. If the level of service drops below a certain thresholds, then a reduction in demand or a switch in the journey is expected. In private transport, equilibrium is sought by travellers by finding the least cost path between an origin O and a destination D.

Trip-assignment modelling of private transport allows estimates of commuting journeys along each segment of the road network. This is a common feature in many proprietary micro- and macro-scale transport models, but it is often an extremely computationally- and data-intensive part of the transport modelling process (Hamdouch *et al.*, 2004). Whilst highly sophisticated modelling approaches have been developed, a simple approach is favourable when a number of future scenarios needs to be tested, still delivering results at an acceptable level of accuracy (Ford *et al.,* 2015).

2.5.3 MODELLING TECHNIQUES IN THE UK

Regarding applied transport studies in the UK, the Department's Transport Analysis Guidance (WebTAG) discussed the role of transport modelling, in order to create transport models for the appraisal of alternative solutions (DfT, 2014c).

In general, the cost of journey can be expressed as generalised cost, considering time and distance travelled along the network (Grey, 1978; Bruzelius, 1981). For the UK appraisal transport models, any travel can be economically quantified in a unified value C as a "sum of both the time and money cost" (DfT, 2014b), as shown by Equation 2-6:

$$C = aD + bT \quad [£]$$

Equation 2-6

where D is the distance travelled (km), T is the time taken by the journey (hr), a and b are the distance coefficient and time coefficient respectively. This approach can be applied to private vehicles, cycling or public transport (Ford *et al.*, 2015).

The UK Department for Transport's COst Benefits Analysis (COBA) program analysed the costs and benefits of providing road schemes, in terms of reducing time and vehicle operating costs (VOCs) of road users (DfT, 2004b). The COBA model has a number of tables outlining speed-flow curves for UK roads (in particular, "Part 5: Speed on Links"). Atkins (2014a, 2014b) reviewed and updated the proposed speed/flow relationships, to improve their use into traffic models. These speed-flow curves take the form of functions relating the flow of vehicles to the speed of travel along a road link through key parameters (*i.e*. the number of vehicles per hour at which speed begins to decrease, and subsequently falls to a minimum). Thus, journey times through the network increase as congestion increases, and this is particularly important during disruptions when many travellers try to use a limited number of alternative routes. The characteristics of the road (*e.g.* rural/suburban/urban, single and dual carriageway, motorway/A/B/C, number of lanes) determine the type of speed-flow relationship (Table 2-3).

Table 2-3. COBA road classes, description and speed.

Road Class	Description	Speed
1	Rural single carriageway	na
2	Rural all-purpose dual 2-lane carriageway	na
3	Rural all-purpose dual 3 or more lane carriageway	na
4	Motorway, dual 2-lanes	70 km/h
5	Motorway, dual 3-lanes	70 km/h
6	Motorway, dual 4 or more lanes	70 km/h
7	Urban, non-central	48 km/h
8	Urban, central	48 km/h
9	Small town	48 km/h
10	Suburban single carriageway	64 km/h
11	Suburban dual carriageway	64 km/h

Roads are divided into four types, and typical speed-flow curves are given for each one: rural, suburban, urban and small town or village (Figure 2-19).

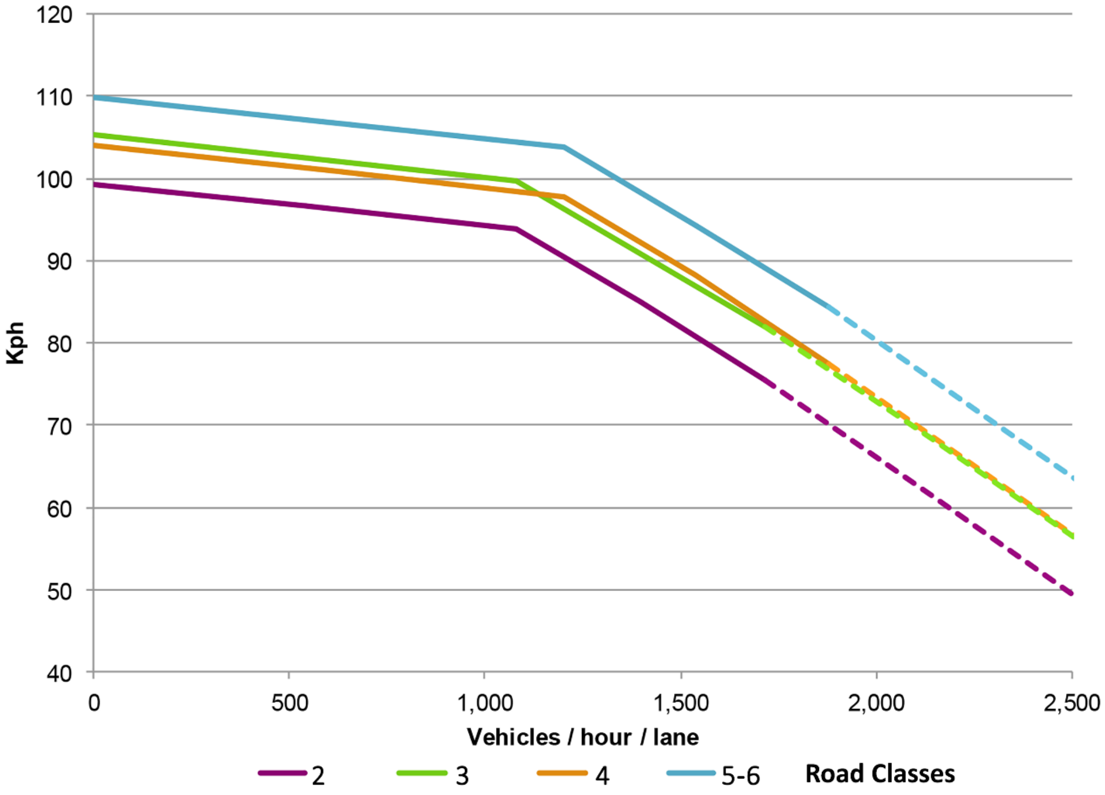


Figure 2-19. Example of COBA Speed/Flow Relationships for Road Classes 2-6 (from Atkins, 2014b).

Preserving normal conditions of travelling time and traffic flows is the major purpose of a road improvement. COBA expresses time savings in monetary terms, in order to have a common metric (£) that allows the comparison with the costs of intervention and the VOCs. The difference between the costs incurred by the system using the Do-Nothing road network and the ones incurred using the Do-Something network records the benefits resulting from a road improvement. The model referred to the WebTAG Guidance for a complete economic assessment of the transport appraisal process and the development of investment decisions.

2.6 ISSUES IDENTIFIED AND PROGRESS NEEDED

The analysis undertaken in Chapter 2 showed up the limits as well as the areas of improvement that need to be addressed. Surface flooding is a major threat in urban environments and no satisfying methods can be currently applied to overcome the issue. Transport networks are fundamental for the functioning of a city and a key element in emergency management. Indeed, ensuring resilience to such networks would provide robustness (*i.e.* reliability and resistance) to the whole system "city". An increasing body of evidence recognises that probabilistic methods are necessary to develop an appropriate estimation of risk; however, they are mainly applied to buildings and direct damages. New models and new tools are necessary in order to tackle the impact of flooding on urban areas in a more complete way, especially in light of climate change and demographic increase.

Through the literature review presented, some gaps have been identified in the topic of flood risk management (FRM).

1) When considering flood risk, the hazard assessment stage is usually emphasised, and damage assessment often considered as an appendix of risk analysis.
2) Surface water flooding is rarely investigated; in fact, for example there is no warning service for surface water flooding.
3) In most cases, existing research in flood risk assessment investigates uncertainty only from the hydrological point of view. Moreover, model validation is rarely performed in damage modelling, and model transferability is seldom questioned.

Specifically for the transport sector, gaps in the current methods and tools to improve transport resilience to flooding have been identified. In particular:

1) Existing approaches to assessing the impact of flooding on transport disruption do not capture the complexity of interactions between the flood hazard and transport system. Simple approaches are currently adopted, due to lack of data and knowledge, ignoring the relationship between the performance of flooded roads and the flood depth.
2) Risk analyses usually do not consider the complete range of damage types, but are just limited to the economical aspect of direct losses. Very few studies include risk from indirect damages regarding infrastructure, like interruption to traffic flows and road linkages; moreover, scarce data and no well-established models are provided by them.
3) Flood risk is a dynamic phenomenon, as well as flood impact. Indeed, it should be investigated as such. However, the literature is currently limited to the investigation in dynamic terms of transport disruptions due to rainfall or other weather-related events, but not due to flooding (*e.g*. for weather impacts/road accidents).

In order to address these gaps, an integrated and multi-disciplinary approach is presented in Chapter 3, involving all stages of modelling and looking at cities in a system-perspective. This is focused on the indirect damage due to floods, considering flooding as a dynamic event with a specific scale and time frame. An innovative function that related flood depths and vehicle speeds is integrated in the method, as explained in Chapter 4. The model provides risk-based information to assist policy-makers and practitioners in understanding the cost/benefit payoff of adaptation measures, leading to a better decision-making. The model is applied and validated using a case study, illustrated in Chapter 5.

CHAPTER 3: A FRAMEWORK FOR TRANSPORT FLOOD ANALYSIS

3.1 INTRODUCTION

Chapter 2 presented an overview of the state-of-the-art surrounding flood risk management, where current approaches and best practice were reviewed, highlighting limitations and potential areas of development. Hranac *et al.* (2006) showed that adverse weather events can cause significant disruption to the transportation sector and these are significant in terms of both efficiency and safety. They also argued that existing research is limited to silo-based approaches that consider either weather impacts or traffic analysis in isolation and that common risk approaches rarely include surface flooding or the indirect damages resulting from it. Furthermore, observational studies have demonstrated that relationships between hazard magnitude and the performance of the transport system are not linear and so a range of events must be considered to be able to map the total risk. Responding to all these aspects this chapter develops a model that can perform city scale dynamic simulations of pluvial flood risk for a range of climatic events.

In order to fill such significant gaps, this Chapter 3 illustrates an original integrated framework to couple simulations of flooding and transport, and calculate the impacts of disruptions. It addresses objective no. 2 of this thesis. A function, constructed from a range of observational and experimental data sources, is used to relate flood depth to vehicle speed, which is more realistic than the typical approach of categorising a road as either ‘blocked’ or ‘free flowing’ (Chapter 4). A criticality index, based on the hazard and the network, is developed as an effective metric to prioritise intervention options on the road network. The framework allows the users to assess benefits and costs of adaptation options to manage flood risk, improving the existing crude approaches of calculations.

3.2 CAT MODELLING OVERVIEW

The proposed modelling framework needs to be able to assess the impact of flood-related disruptions on the urban transport network and follows the CAT modelling approach outline in the likes of the literature (Apel *et al.*, 2004; Grossi and Kunreuther, 2005; Kron, 2005; Dawson *et al.*, 2008). This framework is composed of a hazard model, asset database and vulnerability relationships to translate hazard intensities into asset impacts (Figure 3-1). The approach adopted in this work has significant extensions, which include transport, traffic delay vs hazard intensity, and adaptation assessment.

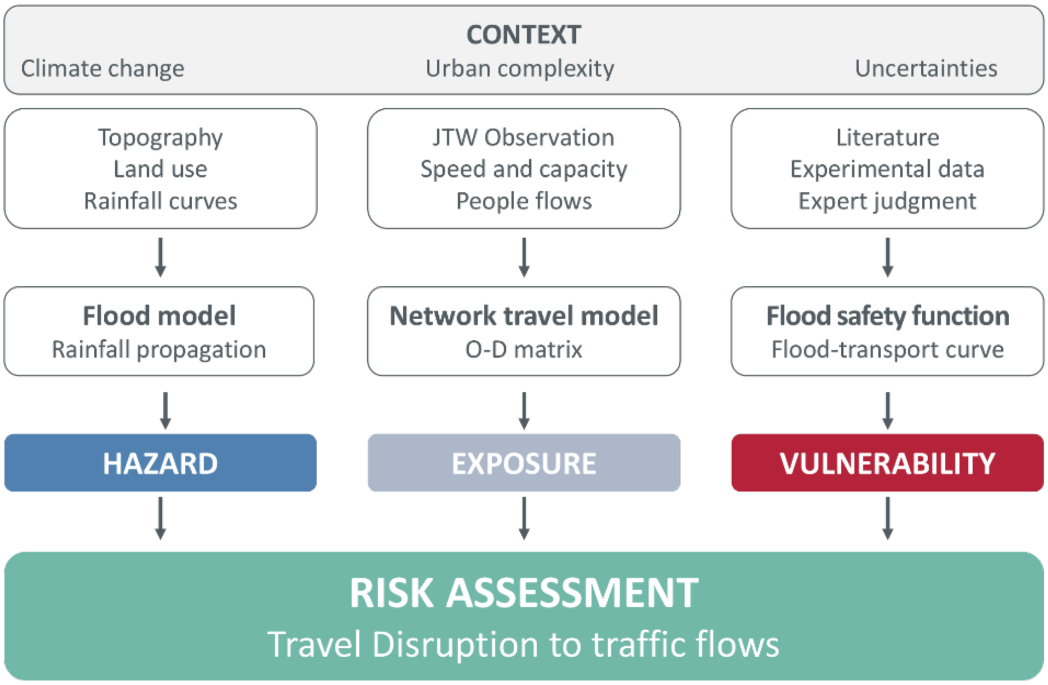


Figure 3-1. Overview of the modelling framework to assess the impact of adverse events on transport disruptions from surface water flooding.

Hazard information is derived from climate and flooding simulations, and combined with analysis of the exposure of the transport network. The consideration of the vulnerability of moving vehicles to flood disruption is an important stage of the framework, and is fully developed in Chapter 4.

The computational framework of the model compromises between accuracy and computational resources. It describes (Figure 3-2): (a) the process that computes the baseline (Section 3.4.3); (b) the process that computes the disruptions due to flood impact (Section 3.6.1); (c) the implementation of adaptation options (Section 3.7.1).

The model's output includes the impact assessment related to transport network, in terms of People Hour Delay (PHD), *i.e.* the total hours of delays due to disruption multiplied by the number of users impacted, and the potential benefits from implementing options of urban adaptation. This can be useful for: (1) supporting decision-making about investments; (2) project appraisal; (3) emergency management; (4) providing information and raising awareness in the society (FLOODsite, 2007).

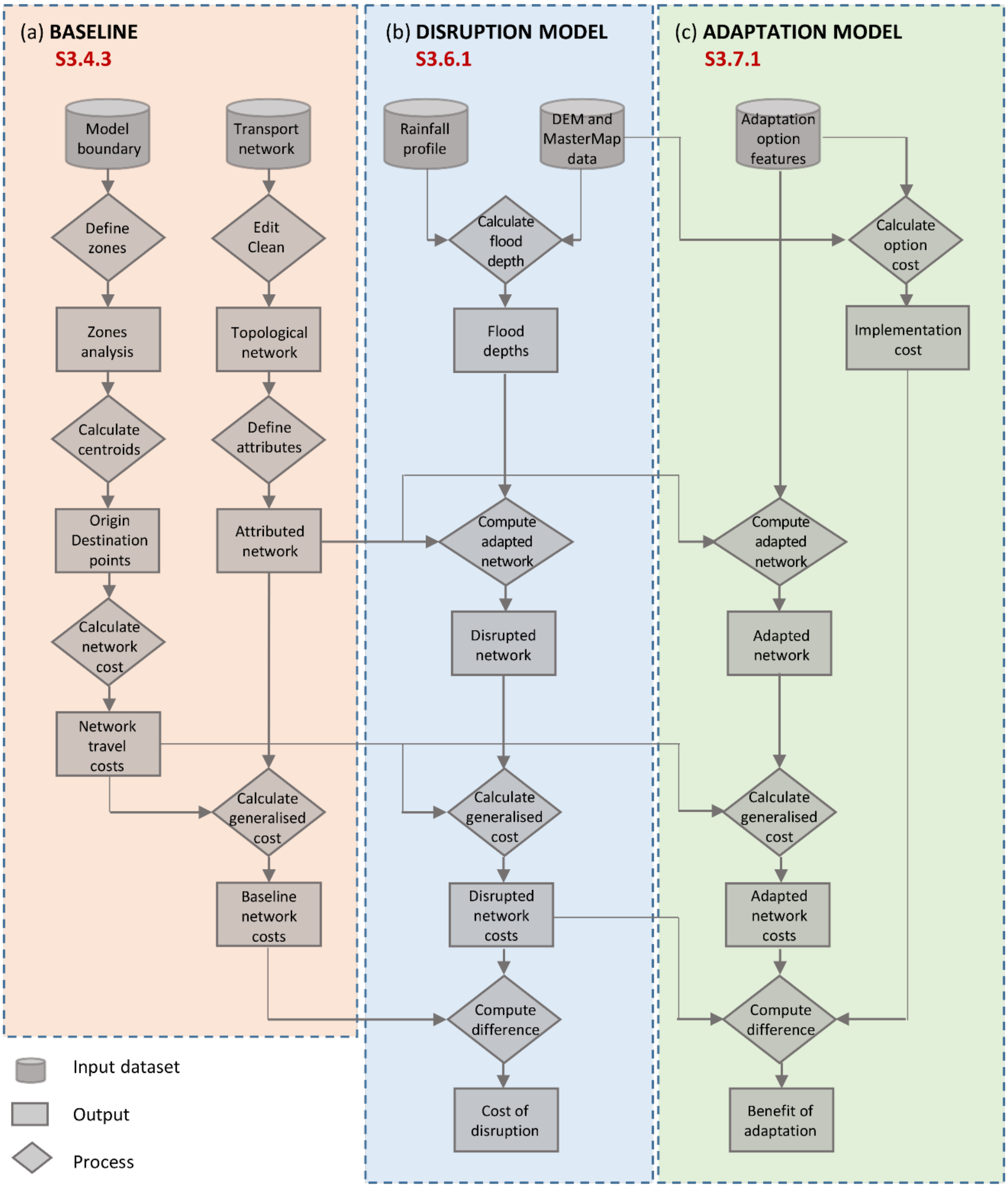


Figure 3-2. The computational framework that underpins the model: (a) the process that computes the baseline (Section 3.4.3); (b) the process that computes the disruptions due to flood impact (Section 3.6.1); (c) the implementation of adaptation options (Section 3.7.1), which can include both modification at DEM/MasterMap level (*e.g.* increasing the soil permeability in certain areas) and network improvements (*e.g.* adding redundancy).

This chapter describes the individual models used in the integrated model, namely the baseline model, the disrupted model and the adaption model; these are based on hazard and transport modelling.

Although CAT models are usually applied to compute direct damages, the methodological framework will be compatible to assess indirect damages due to traffic disruption. The compatibility is ensured by the parameter (the Value of Time) that allows to associate to indirect damages (delays) a monetary loss (DfT, 2014b).

3.3 HAZARD MODELLING

Surface water flooding is caused by intense rainfall above the capacity of the drainage system; the inundation due to an excess of surface runoff can be simulated through hydraulic models.

The calculation of the flood outline can be summarised through the following steps (Kjeldsen *et al.*, 2005), as explained in Figure 3-3. Specifically:

1. Acquisition of input data, such as a DEM and land use; the initial condition are chosen according to catchment characteristic (soil, urbanisation, etc.). The surface area is considered as a grid of cells.
2. Definition of return periods and rainfall curves for a given scenario, using synthetic 'design storm' events. These are generated following the standard UK procedure from the Flood Estimation Handbook (FEH) by Robson and Duncan (1999) and the Revitalised Flood Hydrograph (ReFH) model by Kjeldsen (2007).
3. Propagation of the rainfall time-series for the given scenarios over the surface using a set of equations, according to the type of model (one-, two- or three-dimensions). Various software could accomplish this task (see Section 2.3.3).
4. Generation of the flood maps for each scenario considered. All cells in the grid are associated with a value of water depth and flow velocity, representing the flood extent and magnitude of the event.

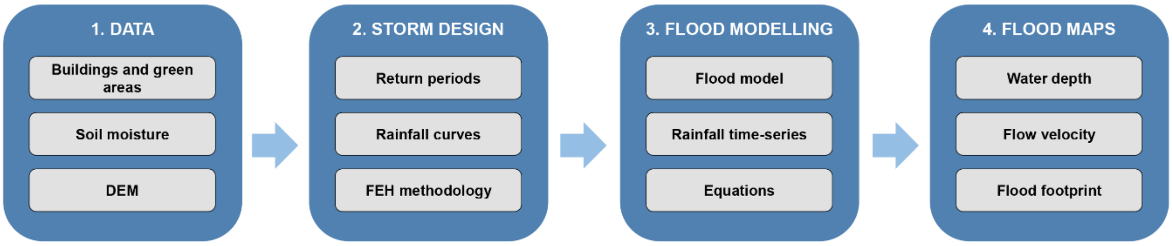


Figure 3-3. Methodological steps of the flood modelling procedure.

Assuming an interest in large-scale areas and at the same time the necessity for a good resolution, a two-dimensional hydrodynamic model represents the ideal flood model to

simulate pluvial inundation in acceptable computational times (1-2 days). In fact, a 2D model reasonably balances the accuracy of the output and the computational costs; a 1D model would not consider important details in modelling (*e.g*. multiple direction of the flows), whereas the complexity of 3D model is unnecessary for computing flows of shallow water in urban areas. Moreover, the 2D model CityCAT is well-validated within Newcastle data, and available with appropriate resolution (*i.e*. 4m).
The input data are a rainfall profile, a Digital Terrain Model (DEM) of the area, and MasterMap data of land use and built environment (*e.g.* buildings).

A 2D flood model can provide a flood outline with depth and velocity of surface water associated with rainfall events of specified severity (duration, intensity), accounting for the topography of the floodplain and characteristics of the built environment (Glenis *et al.*, 2013). In fact, modelling surface water flows takes into account building locations and their footprint, ground permeability, and topography. Water depth and velocity are calculated dynamically throughout the simulation period and reported at each time-step as a raster grid, functional for further analysis. The sub-surface drainage can be simulated as a dynamic network, although this implies an additional relevant computational burden.

3.3.1 CATCHMENT AREA ANALYSIS

A catchment area is the fundamental hydrological unit that allows the definition of the analysis boundary of the area of interest (an example is offered by Figure 3-4); the outlet (or pour point) is the lowest point along the boundary of a catchment, at which water flows out.

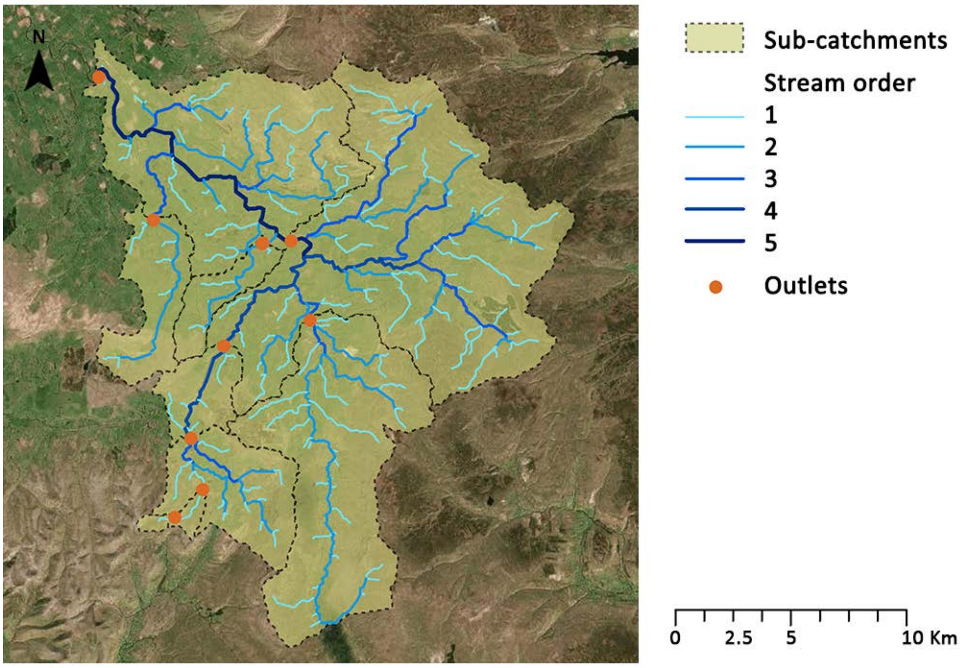


Figure 3-4. Example of hydrological analysis for the Eden River catchment (Cumbria, UK).

When a specific area of study is considered, the boundary domain should be delineated on the basis of the hydrological characteristics given by the catchment identification. Such boundary could differ from the geographical or administrative one. ESRI's ArcGIS Hydrology Tool can help to run the hydrological analysis, enabling to extract from topography (*e.g.* DEM) a range of hydrologic information such as flow directions, flow accumulation and the link hierarchy of the stream network.

The calculation of the upstream sub-catchments is based on the flow direction, the flow accumulation and outlets, all derived from the original DEM. The flow direction indicates the direction of the steepest descent from a grid cell, taking into account the eight adjacent cells into which water would flow (D8 flow algorithm - see Jenson and Domingue, 1988). The flow accumulation contains the accumulated number of cells upstream of each cell in the input grid. All the cells with more than a certain number of feeders (cells flowing into themselves) constitutes the stream network, whose hierarchy is obtained via the Strahler method (Strahler, 1952).

The resolution of the grid cell size determines the accuracy of the sub-catchments delineation: higher resolution grids (smaller cell size) permit a more accurate representation of the topography. Land use can affect the physical mechanism generating runoff flooding, however ArcGIS Hydro takes into account topography only.

This complex issue is addressed by the flood model, both at the spatial and temporal level.

3.4 NETWORK AND TRANSPORT MODELLING

Transport modelling enables the estimation of travel times across a network, which are essential for calculating indirect losses. Based on Chapter 2, this work has adopted an origin-destination matrix method (Section 2.5.1). This type of model requires origin-destination information and mechanism for calculating both travel times and how trips proportion themselves on various paths. Specifically, in this study network analysis is used to determine travel time and distance between an origin (O) and a destination (D), organising data in a OD matrix.

This analysis is functional for characterised flows and movements of people, understanding interactions and the cost of travel. People are not individually mapped within each zone (ward), thus the total population is considered. The 2011 census statistics produced by the Office for National Statistics (ONS) for Middle-level Super Output Areas (MSOA, Table 3-1) offer the population for each ward (ONS, 2011a), and population-weighted centroids; an example for London area is given in Figure 3-5. At the time of this research, information about Journey-To-Work travels (JTW tables) were only available at MSOA level for the 2011 Census.

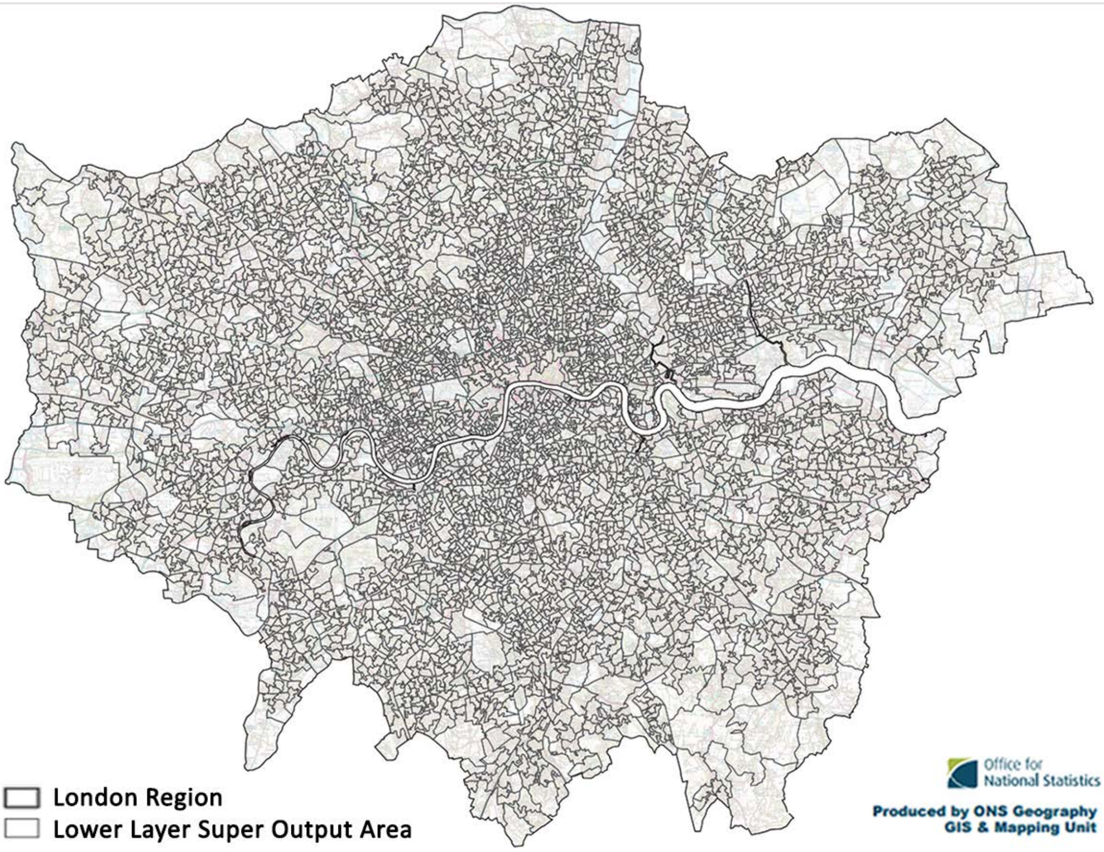


Figure 3-5. Example of MSOA, for the London region at December 2011, free downloadable from the Census Maps section of http://geoportal.statistics.gov.uk.

All the information are geo-referenced and organised in the attribute Table 3-1.

Table 3-1. The Census information for the MSOA.

Parameter	**Description**
ID Code	Identification code
Area Name	Geographical reference name of the area
Area (m^2)	Area dimension
N. people	Number of people living in the area
Centroids coordinates	Latitude and Longitude of the people-weighted centroid point

Census data also provides information about commuting patterns of UK workers, giving the wards of origin and destination of the JtW routes (ONS, 2011b) for the region of interest (Table 3-2). A matrix of peak traffic flows between origins and destinations for each transport model is constructed from these census and travel survey data.

Table 3-2. The JtW (Journey to Work) information for each origin-destination pair.

Parameter	**Description**
Origin	Ward of origin (ID code)
Destination	Ward of destination (ID code)
Total people	Total number of commuters for the OD route
Car	Total number of people commuting by car
Bicycle	Total number of people commuting by bicycle
Bus	Total number of people commuting by bus
Train	Total number of people commuting by train
Other	Total number of people commuting by other mean

The road network is represented as a sequence of nodes and links, where the links are the stretches of road and the nodes are the junctions. The input data are obtained from public available sources such as the Ordnance Survey Integrated Transport Network (ITN) (Ordnance Survey, 2008), a nationally-available UK dataset specifically designed for network analysis (and thus supplied in a topologically-correct form). From the UK COBA model, free flow speeds on the links are defined using classes (DfT, 2004a; see Table 2-3), although speed-flow curves were not considered enough sophisticated to be adopted. Free flow speeds were integrated into the attributes of the Ordnance Survey MasterMap data, *i.e.* road links and nodes.

The model of this study is GIS-based and designed to use the above public available data, aiming to be flexible and transferable. It consists in a macro-scale traffic model to simulate flows on the urban transport network under various hazard scenarios. Transport journeys between origin and destination locations (*e.g.* places of residence and employment) are estimated using a trip-assignment routine, which simulates commuting journeys along each segment of the road network (Ortúzar and Willumsen, 2011). Travel time is computed as a function of a number of attributes, *i.e.* distance, free flow speed and capacity for private transport road users. Equilibrium is sought by travellers selecting routes that find the least cost path between an origin O and a destination D, using generalised cost of travel to assess the shortest route between the two points. The model is based on the Dijkstra's algorithm, used in an iterative process to identify the shortest journey in terms of time for each OD pairs (Dijkstra, 1959).

The model is used to compute commuting journeys across the network for three conditions, as shown in Figure 3-6: *(i)* normal, unperturbed conditions (baseline); *(ii)* following disruption due to a flooding hazard (disruption scenarios); and *(iii)* following the implementation of adaptation strategies (adaptation scenarios).

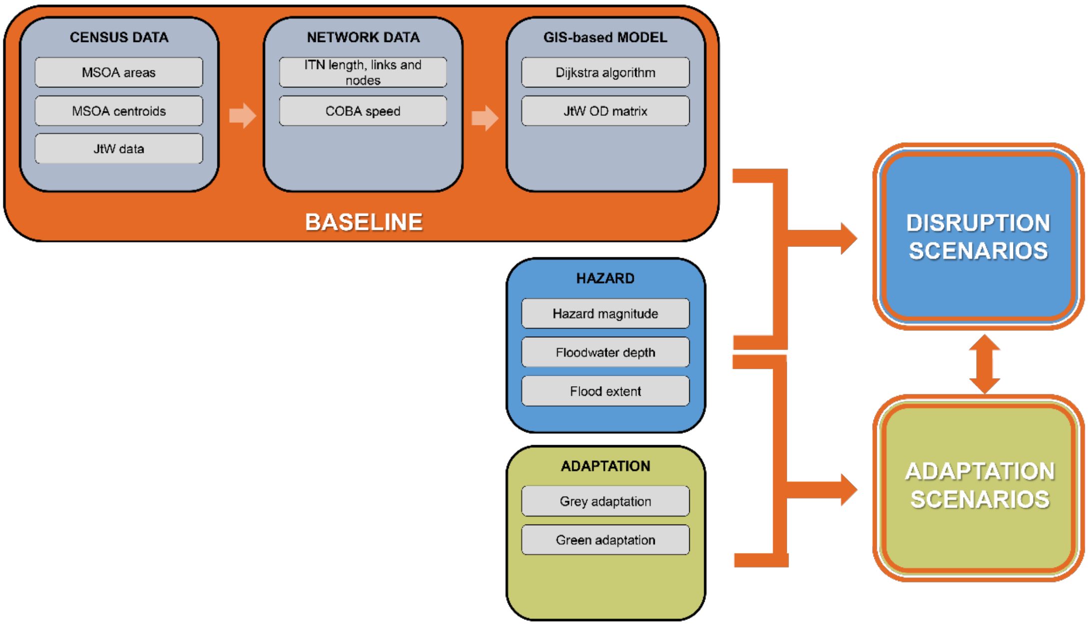


Figure 3-6. The three conditions in which the model is run: the baseline, disruption and adaptation scenarios.

This section gives more insights about the modelling process (*e.g*. boundary conditions, assumption), whereas Section 3.5 introduces the vulnerability assessment via a flood-transport function. Section 3.6 explains how the model assesses flood impacts on the network, while Section 3.7 describes how to implement adaptation strategies in order to enhance its robustness. Impact costs and benefit savings can be assessed in monetary terms; and the methodology for this is explained in Section 3.8.

3.4.1 TRANSPORT AREA BOUNDARY

Similarly to the definition of the catchment area for the hazard analysis (Section 3.3.1), a transport boundary should be set for a transport study. Given the focus on commuters' journey, the boundary can be defined using an analysis of job location in the region. The analysis reflects two research questions: (*i*) "Which wards of the city are responsible for the major number of job location in the wider area?"; and *(ii*) "Where do such commuters come from?". The answer to the first question involves the definition of an "Urban Core", constituted by the districts of the city offering more jobs in the region.

The second question concerns the identification of a "transport catchment area" which is composed by the wards whose inhabitants are working in the Urban Core (Figure 3-7).

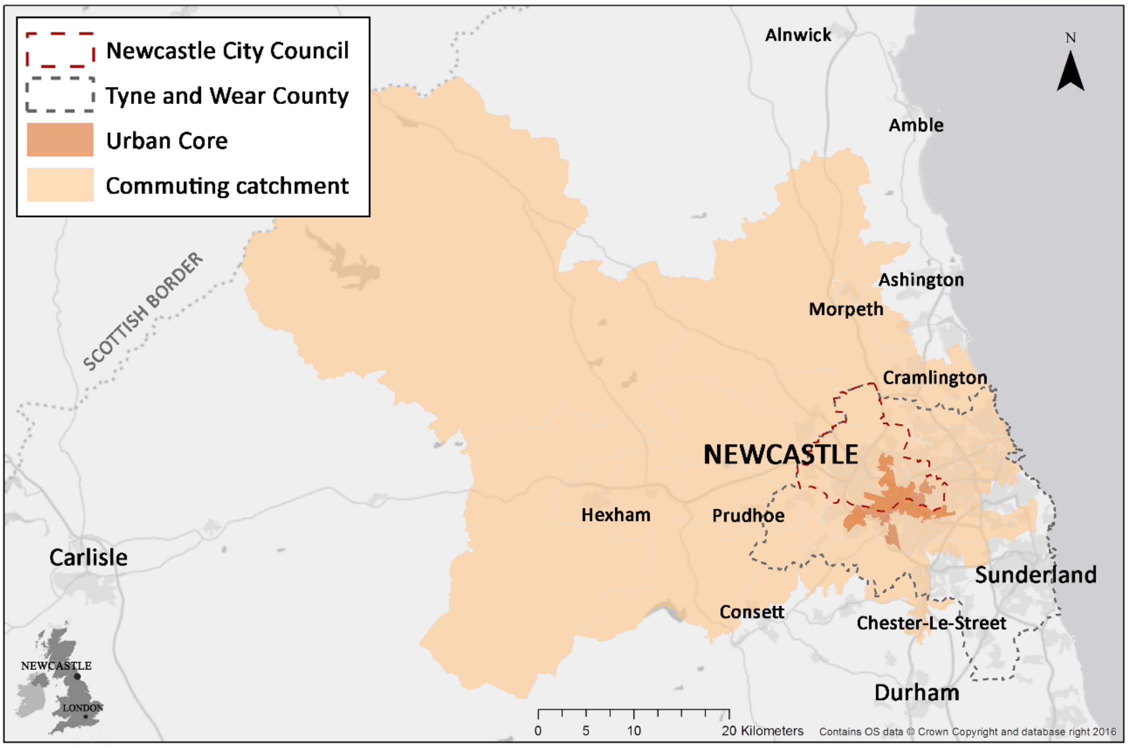


Figure 3-7. The analysis to delineate the transport model boundary, using an analysis of job locations (Newcastle). The Urban Core collects the wards that offer the 90% of the job in the administrative region; the catchment area collects the wards whose 5% of residents or more commute towards the Urban Core.

This transport analysis can give the basis for the definition of the boundary of the transport model, although for simplicity the administrative boundary could be used as "transport catchment area". The network needs to be consequently limited to this boundary, introducing some limitation regarding possible routes outside such administrative edges. The interest of decision-makers and data availability could drive the choices in this context.

3.4.2 MODELLING ASSUMPTIONS

The model is at urban scale (Newcastle City Council area: 114 m^2, 292,800 inhabitants), indeed it represents a number of transport processes at reduced complexity to enable realistic analyses at reasonable computational cost (implications of these assumptions are revisited in Section 3.10). Considering that *(i)* Census data provides JtW journeys; *(ii)* commuting trips by car currently represent the highest percentage of all the commuting trips (FHWA, 2007; Dft, 2016c), the model focuses on simulating commuting trips undertaken by private vehicles.

Firstly, spatial geography is simplified in terms of wards and centroids, as explained in Section 3.4. Secondly, it provides a low complexity representation of driver behaviour, for example it does not consider vehicle-to-vehicle interactions at road junctions, and assumes that travellers have complete knowledge of the network and associated journey disruptions. This provides a computational advantage, whilst still capturing the macro-scale transport interactions that this work is seeking to understand. Although the algorithm does not account for congestion and traffic signals, very minor residential roads are removed from the analysis to reflect the real lack of perfect knowledge that many road users have (compensating the assumption of having it). This was also observed during most of the flood events; the major roads were impacted to such an extent that minor roads were quickly overwhelmed by the volume of traffic and did not offer alternative route choices. In addition, social aspects, like personal perception of the risk and the driving ability of people, are not included in this study.

There is no stochastic variation in the speeds of the vehicles along each link, all traffic on a road link travels at either the maximum free-flow speed, or a reduced speed accounting for congestion. Moreover, large uncertainty stays within the variability of damage between network links subjected to the same hazard, *e.g.* the same flood event can impact very differently to roads of the same classes due to non-foreseen influences of secondary factors (*e.g*. warnings, maintenance, etc.). However, such aspects are beyond the scope of this work.

Only commuting journeys are simulated since disruption during the morning or evening peak has the potential for the greatest economic impact (Hallegatte and Przyluski, 2010). Network disruptions are limited to the ones caused by flooding, thus non-flood disruptions (*e.g*. roadworks, incidents) and other circumstances (such as the loss of visibility due to the bad weather) are ignored. This is due to the choice of looking at flooding as a hazard in isolation, neglecting the potential concurrence of other weather impacts (rainfall, fog, flooding, etc.).

3.4.3 BASELINE MODEL

The model is firstly employed to develop a shortest route analysis, for the Business-As-Usual (BAU) conditions (normal, unperturbed conditions), creating a matrix of distances and costs for the baseline.

The spatial network is built in GIS system on the basis of ITN network and Census data. The OD matrix uses two sets of locations - one for origins and one for destinations, derived from the MSOA zone centroids. Travel speed is obtained from COBA class (Table 2-3), and travel time is calculated using the geometric length of each link. All the data associated with the baseline network are illustrated by Table 3-3.

Table 3-3. The network information organised in a table, to be implemented in the GIS platform, for the baseline simulation.

Parameter	Description
ID	Identification number for each link of the network
Type	Road type and classification according to DfT (2004c)
CC	COBA class according to (DfT, 2004c)
L *(km)*	Geometric length for each link of the network
v^{BS} *(km/h)*	Maximum allowed speed on the road stretch (for the baseline BS), according to (DfT, 2004c)
t^{BS} *(h)*	travel time for the baseline BS on the link, where $t^{BS} = v^{BS} * l$

The Dijkstra algorithm (Dijkstra, 1959) is used on the GIS platform to calculate the shortest route between each OD pairs (Figure 3-8). The shortest path could be used either based on time or distance, considering the travelling speed of each network link. ESRI’s Network Analyst extension facilitated this computation.

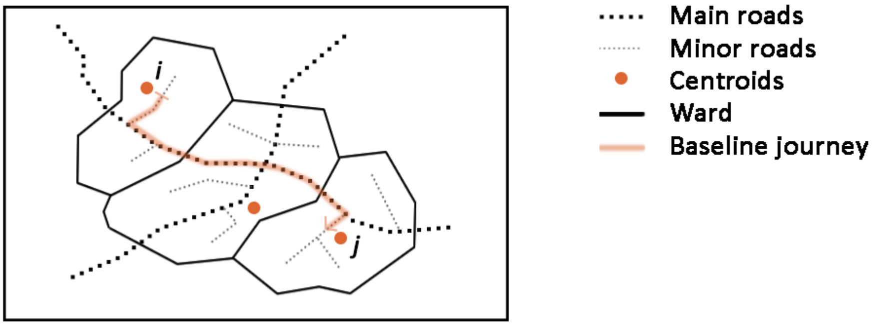


Figure 3-8. Schematic representation of a journey from an origin O_i (centroids of the ward W_i) and a destination D_i (centroids of the ward W_j).

The OD matrix stores the distance and the time along the network accrued during the journey from origin to destination, as output of the simulations. This is joined with the network data and a table of information is built (Table 3-4).

Table 3-4. The information for the OD matrix, as output of the simulation.

Parameter	Description
O	Origin ward, using the Census MSOA
D	Destination ward, using the Census MSOA
JT^{BS} *(h)*	Journey Time using the network characteristic of the baseline BS
JL^{BS} *(km)*	Journey Length using the network characteristic of the baseline BS

Although all commuting journeys across the region are simulated, distances and travel times can be analysed from a particular area (*e.g*. the ward of the city centre).

3.5 VULNERABILITY ASSESSMENT

The vulnerability stage involves translating the flood depth, output of the hazard modelling (Section 3.3), into increases in journey travel times on the transport network. Total delays can only be calculated using a transport model; however, current models do not consider how individual trips may be delayed. In CAT models, impacts on individual components are estimated using fragility curves. A damage curve is the best tool to express such relationship, and this is already in common practice in risk analysis for buildings (Kron, 2005; Begum *et al.*, 2007; De Risi *et al.*, 2013; Muis *et al.*, 2015; Scorzini and Frank, 2015). However, existing methods (*e.g*. Penning-Rowsell *et al.*, 2013) assume roads that are flooded to any depth to be entirely closed, using a binary approach. This is perhaps suitable for fluvial or coastal inundation where depths are typically large across the flood extent, but flood depths from intense rainfall can vary substantially according to local conditions. Therefore, current practice is incapable of capturing realistic delays.

The study developed a depth-disruption function (Figure 3-9) by synthesizing experimental reports, safety literature, experimental data, analysis of videos of cars driving through floodwater, and expert judgment (*e.g*. The Automobile Association). Data were from the EU, USA, Canada and other countries, and for asphalt roads and so comparable. This moves beyond the crude assumption that the road is either open or closed according to a single arbitrary depth threshold, which is consistent with observations from real flood events that drivers travel slowly through floodwater. A function seems to be the best-fit for available data (Pregnolato *et al*., 2017b)

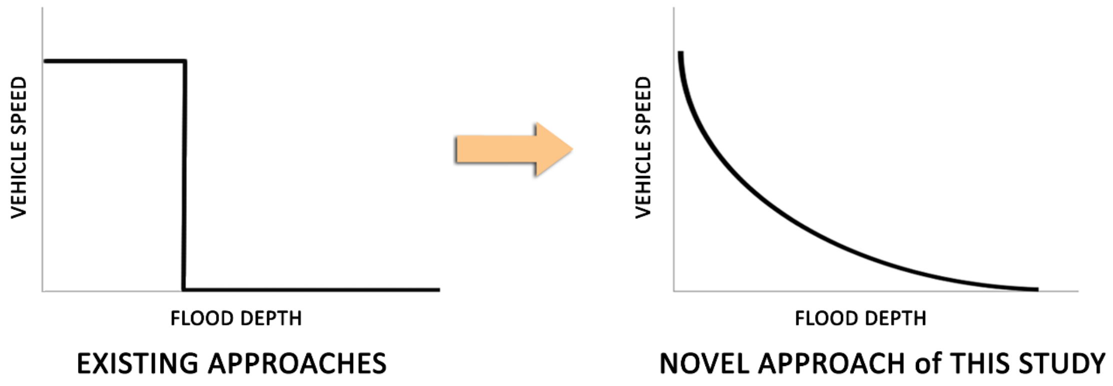


Figure 3-9. Evaluating the network performance in function of the flood depth overcomes the existing binary approaches that consider roads either open or closed according to a single arbitrary depth threshold

Considering the relevance of this stage of the study, an entire chapter is dedicated to it (Chapter 4).

3.6 IMPACT ASSESSMENT

The model in this study computes the changes in time and distance for the case of flooding disruptions by coupling a network model with the hazard assessment. This evaluation consists of calculating the disruption to network links as a result of the hazard. Timeseries of floodwater depths across the model domain are integrated with the spatial network model; for each scenario considered, the last timestep was used to define the flood map for the analysis. Flood water reduces speeds, or stops entirely, traffic flows along flooded network links according to the depth of inundation.

The curve, which will be presented in detail within Chapter 4, relates water depth to safe driving car speed (between 0 and a critical flood depth where the road is impassable). Thus, the network properties of a link (*e.g.* travel speed) are modified according to this relationship, and traffic parameters recalculated for this perturbed state. Subsequently, journey travel time will increase in comparison with the baseline scenario and the city-wide disruption is assessed by considering all user delays across the network.

3.6.1 DISRUPTION MODEL

After generating the baseline settings (Section 3.4.3), the transport model can be perturbed by a series of hazardous scenarios, for different return periods. By overlaying the water depth from flood simulations onto the road network, the depth of water on each link can be measured. Subsequently, these water depths are integrated with the vulnerability curve enabling the calculation of the speed reduction, according to the depth of floodwater, and of delayed journey travel times (Figure 3-10).

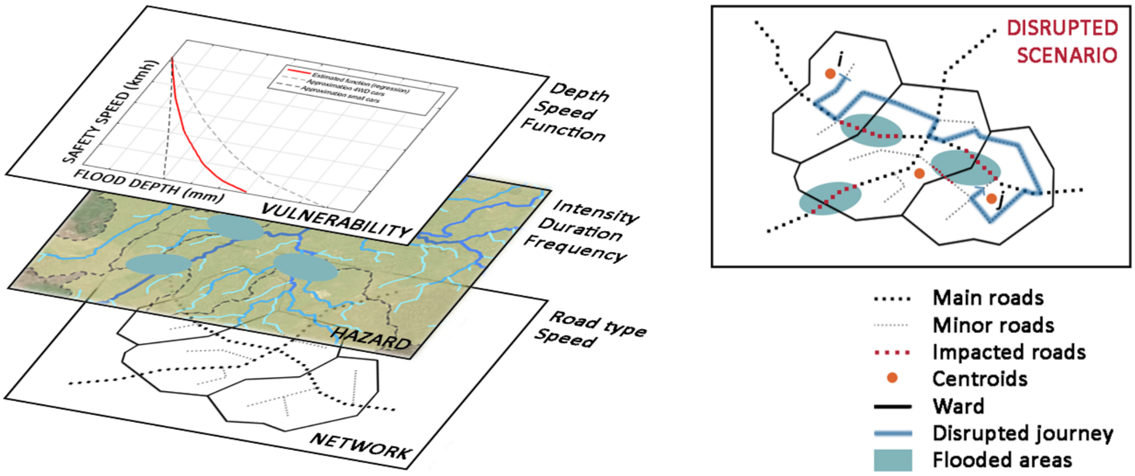


Figure 3-10. How the baseline model is disrupted through a range of hazard scenarios. The flood footprint (output of the flood model) is spatially overlaid with the network; a function (Chapter 4) relates flood depth on links with the speed considered safe to drive along them.

The attribute table associated with the network is then modified as below, by adding the hazard information and the metrics related to disruptions (Table 3-5).

Table 3-5. The network information organised in a table, for the disruption scenario.

Parameter	Description
z^s *(mm)*	Flood depth associated to a certain hazard scenario S on the road stretch
v^S *(km/h)*	Disrupted speed on the road stretch (for the scenario S). If z^s is greater than 0, v^S is expected to be less than v^{BS}.
t^s *(h)*	Travel time for the scenario S on the link, where $t^S = v^S * l$

The flood depth *z* is obtained by spatially overlaying the output of the flood model and onto the network links. The ArcGIS geoprocessing tool "Add Surface Information" facilitates this process. Note that the depth considered is the maximum flood depth that "touches" the road stretch (conservative hypothesis).

The disrupted speed v^S (for the scenario S) is calculated by applying the transport curve, to translate water depth *z* to speed reduction (see Chapter 4):

$$v^S(z) = f(z) \qquad \textbf{Equation 3-1}$$

Roads are considered impassable (therefore closed) when the flood depth *z* reaches the limit of 300 mm (see Section 4.4.1), thus the velocity is null.

The model can now be used to produce simulations for a series of hazardous scenarios that are significant enough to result in a disrupted network. The resultant OD matrix will have the information organised in Table 3-6.

Table 3-6. The information for the OD matrix, as output of the simulation for the disruption model.

Parameter	Description
q *(person)*	Number of commuters for a certain OD trips (JtW routes given by ONS (2011b).
JT^s *(h)*	Journey Time using the network characteristic of the disrupted network for the scenarios S
JL^s *(km)*	Journey Length using the network characteristic of the disrupted network for the scenarios S
D^s *(h)*	Delay in time using the network characteristic of the disrupted network for the scenarios S, in comparison to the baseline
PHD^S *(h*person)*	Person Hour Delay, considering the number of users for a certain journey for the scenarios

The delay D^s for each journey is given by the difference between the baseline travel times with the disrupted ones.

$$D_{ij}^{S} = \sum_{i}\sum_{j}(JT_{i,j}^{S} - JT_{i,j}^{BS})$$ **Equation 3-2**

where $JT_{i,j}^{S}$ and $JT_{i,j}^{BS}$ are respectively the journey travel time of the disruption scenarios S and of the baseline for the journey with origin *i* and destination *j*.

If the number of users *q* are considered (using the Census Journey-to-Work data), the Person Hour Delay PHD^S for the specific scenarios *S* can be calculated for each journey *ij*:

$$PHD_{ij}^{S} = \sum_{i}\sum_{j} q_{ij} * D_{ij}^{S}$$ **Equation 3-3**

And the overall impact on the network is similarly given by the PHD_{net}, aggregating the Person Hour Delay across the network:

$$PHD_{net} = \sum_{i}\sum_{j} PHD_{ij}^{S}$$ **Equation 3-4**

Other metrics, such as the percentage of roads flooded or severity of damage to infrastructure, could be used to assess the impact, however the focus of this study is the most important and least understood impact, *i.e.* the reduction in road network performance.

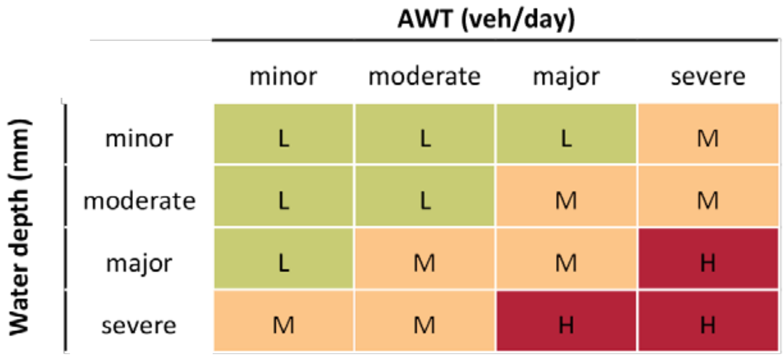
3.6.2 HOTSPOTS IDENTIFICATION

The susceptibility of the infrastructure asset depends on a series of factors: *(i)* the role of the links in the network (assessed for example by graph measures); *(ii)* the exposure to the hazard; and *(iii)* the number of users who rely on the asset during the use of the network.

Identifying the areas more likely to fail in case of hazard is fundamental for flood risk management (Jalayer *et al.*, 2014). Such hotspot identification provides strategic information regarding urban dynamics and urban planning, which can be used to select critical links and target adaptation options.

As described in Section 2.3.2 (Figure 2-8), risk matrices can be an appropriate method of showing the level of risk, calculated on the basis on Equation 2-1. This study identifies the most at-risk locations in the road network through a matrix (Larsen *et al.*, 2010; Naso *et al.*, 2016; Pregnolato *et al.*, 2016) combining the hazard, *i.e.* the depth of water on the road, and the exposure, *i.e.* the average daily traffic flow along the road (Table 3-7).

Table 3-7. Criticality assessment of road links, according to the magnitude of the hazard (flood water depth, mm) and exposure (Average Weekday Traffic, veh/day) of vehicles. Road links are subsequently categorised as: n for "negligible", L for "Low", M for "Medium" and H for "High" criticality.



		AWT (veh/day)			
		minor	moderate	major	severe
Water depth (mm)	minor	L	L	L	M
	moderate	L	L	M	M
	major	L	M	M	H
	severe	M	M	H	H

The application of the matrix is useful for identifying and ranking the criticality of road stretches in an urban network (Pregnolato *et al.,* 2016) for the entire domain. Road stretches can comprise a number of neighbouring links and nodes (for example, it would not be convenient to protect just one spur of a roundabout). The road links where both the exposure (*i.e*. traffic flow) and hazard (*i.e*. water depth) are in the highest categories are selected as most critical, and indeed included for the analysis of adaptation options.

3.7 ADAPTATION ASSESSMENT

Previous sections have illustrated how to assess the impact of flooding on the network. The next stage consists of evaluating which strategies can be put in place to lessen such impact, comparing Do-Nothing and Do-Something scenarios. Adaptation interventions can be tested by altering inputs to either the flood module or the network module (Figure 3-11).

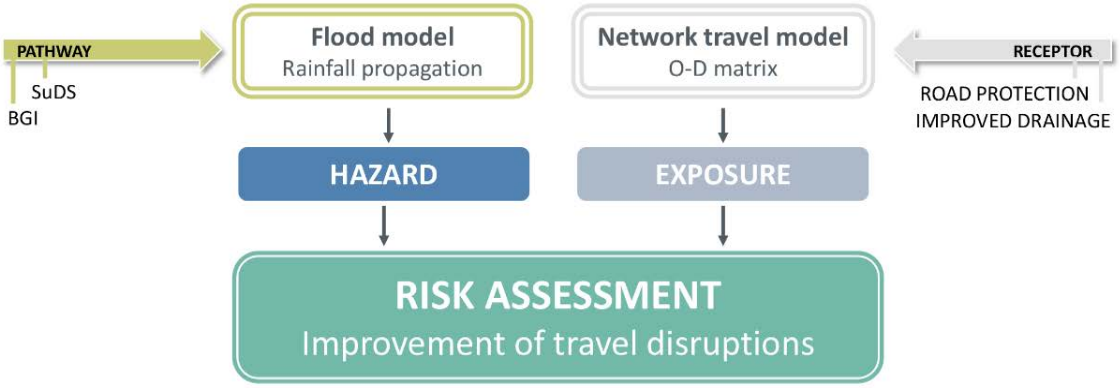


Figure 3-11. The methodological framework of Figure 3-1 modified in order to test a set of adaptation strategies.

As described in Section 2.4.2, these interventions include a combination of measures, which can be implemented at the source of flooding (*e.g.* extreme rainfall causing a build-up of surface water), along its pathway (*e.g*. an overland flow of surface run-off) or at the receptor itself (*e.g*. a section of road in the transport network).

One strategy to make infrastructures in those locations more robust is to intervene with some measures of grey (hard) engineering at the receptor level, such as improved drainage or raising the level of the link. This study refers to such strategies as “link hardening”, which means that such a link has been made completely invulnerable to flooding. There are many options available for “hardening” a link, for instance better drainage, or road elevation.

Alternative strategies include operations of green adaptation, looking to reduce the surface water flow before reaching the urban assets. Blue Green Infrastructure (BGI) or Sustainable Drainage Systems (SuDS) represent an increasingly important option for increasing urban resilience to flooding. They seek to use natural processes to reduce initial run-off through source interventions, such as blue or green surfaces (*e.g.* parks, ponds, roofs) and to increase the retention and infiltration of water (Ellis and Viavattene, 2014). Green roofs, ponds, permeable pavements and swales are options that can be all tested within the model.

3.7.1 IMPLEMENTING ADAPTATION MEASURES

When one or more adaptation strategies are applied to the urban system, the model needs to be modified in order to reflect such interventions (Figure 3-12). Interventions are localized in the weakest part of the network, *i.e.* the identified hotspots (see Section 3.6.2).

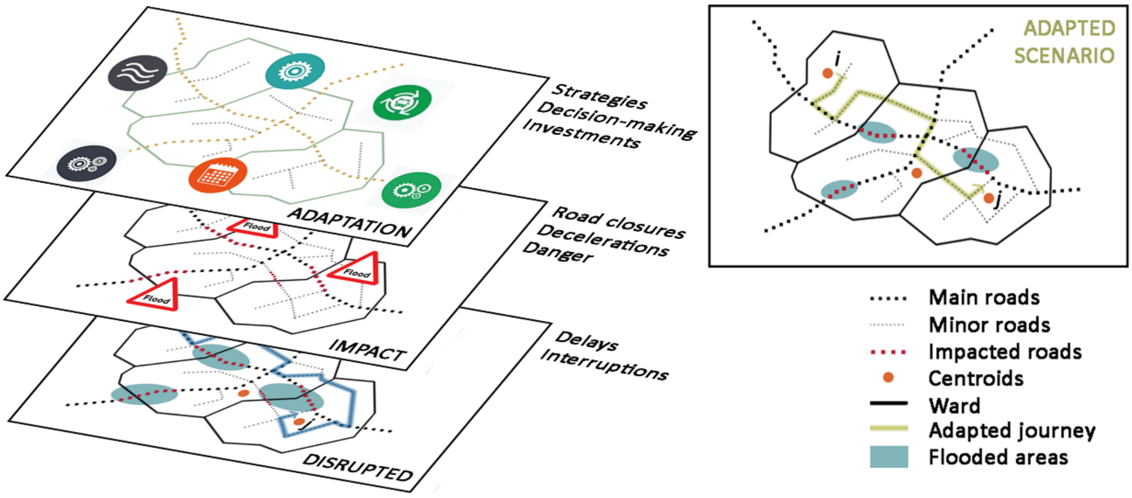


Figure 3-12. How intervention strategies of adaptation are integrated into the model, in order to improve network resilience to flooding.

In the case of link hardening, network characteristics and metrics can be locally modified for the selected links so that they result less or not impacted by floodwater (*e.g.* by reducing the floodwater depth z), simulating for example the installation of stormcrates along the road.

Green adaptation can be represented in the model by the modification of coefficients of infiltration (permeable pavements) and storage (green roofs) in the flood model (Demuzere *et al.*, 2014; Lawson, 2014). Variations in the DEM allow the user to test solutions as swales or retention basins (ponds) (Hoang and Fenner, 2014).

After the implementation of an adaptation strategy, traffic flows are recalculated and disruptions assessed in terms of journey time and reduced delays, following the methodology adopted for the disrupted conditions (see Section 3.6.1).

Recalling Table 3-5, the attribute table associated to the adapted network includes the hazard information and the metrics related to the adaptation scenarios AS (Table 3-8).

Table 3-8. The network information organised in a table, for the adaptation scenario.

Parameter	Description
z^{AS} (mm)	Flood depth associated to a certain adaption scenario AS on the road stretch
v^{AS} (km/h)	Disrupted speed on the road stretch (for the scenario with adaptation AS).
t^{AS} (h)	Travel time for the scenario with adaptation AS on the link, where $t^{AS} = v^{AS} * l$

Where the adaptation strategy is effective, z^{AS} results less than than z^{s}, and more than or equal to z^{BS}. Consequently, in such areas v^{AS} is expected to be higher than v^{s}, and less than or equal to v^{BS} . This means that the delays in the network will decrease, and the level of betterment of the performance will give the degree of effectiveness of the intervention.

The simulations are run for a portfolio of adaptation options, using the adapted conditions of the chosen intervention. The resultant OD matrix will have the information shown by Table 3-9.

Table 3-9. The information for the OD matrix, as output of the simulation for the adaption model.

Parameter	Description
JT^{AS} (h)	Journey Time using the network characteristic of the adapted network for the adaptation scenario AS
JL^{AS} (km)	Journey Length using the network characteristic of the adapted network for the adaptation scenario AS
D^{AS} (h)	Delay in time using the network characteristic of the adapted network for the adaptation scenario AS, in comparison D^{s}
PHD^{AS} (h*person)	Person Hour Delay, considering the number of users for a certain journey for the adaptation scenario AS

It should be noted that the delays are calculated with respect to the disruption scenarios, rather than the baseline. This calculation will give an immediate estimation of the benefit of the intervention, *i.e*. reduction of the delay time and network-level disruption from flooding.

3.8 CONSEQUENCE ESTIMATION AND BENEFITS APPRAISAL

The cost of disruption due to flooding has been estimated at around £100k per hour for each main road affected (Hooper *et al.*, 2014). In response to a number of flood events over the last decade which caused significant damages and disruption to transport infrastructure, the UK government has committed more than £70 billion for improving transport infrastructure through a number of transport projects (Walker, 2016). Moreover, "The Brown Review" of transport resilience (DfT, 2014a) recommended that transport authorities should develop approaches to assess and consider the full-cost of disruption within network investment decisions.
This section illustrates how the study assesses the indirect cost of disruption related to transport networks, and the benefit of adaptation measures, based on the framework presented in Section 3.7.

Flooding causes a range of disruptions to roads that could be economic (*e.g*. business interruption) or represented by other metric (*e.g*. additional CO_2 dispersed in the atmosphere). In this research, the journey time is considered the key output measure to assess the performance of a transport network, following main existing approaches (Smith and Blewitt, 2010; Ford *et al.*, 2015; DfT, 2016b) (see Section 2.5).

Therefore, the economic cost of the flooding impact consists of estimating the delays in the travelling time of commuters, converted into monetary terms using an average Value of Time, VoT (Ortúzar and Willumsen, 2011; DfT, 2014c; Ford *et al.*, 2015). The cost per person delayed C_p is calculated by:

$$C_p \ = \ D_p * VoT \qquad \textbf{Equation 3-5}$$

where D_p is the delay in the journey time (hr) and *VoT* is the average value of time for commuters (£/hr). If adaptation strategies lessen the delays, reduced costs are evaluated and the amount of such a reduction demonstration the city-scale improvement brought by the intervention.

3.8.1 ESTIMATING THE COST OF DISRUPTIONS

The Transport Analysis Guidance (TAG) provides latest values and relationships for use in economic appraisal (DfT, 2014b). The value of commuting time is properly defined as "Non-Working Travel Time", which differs from "Working Time" (four times higher) for business trips or journeys made in the course of work, as commuting trips usually use the commuter's own time. Commuting time includes "all non-work journeys purposes, including travel to and from work" (DfT, 2014b). The VoT used in the model is the 2010 market price for "Commuting time" per person as £6.81 per hour, without distinction in relation to the type of job. All (currency) values change over time due to the GDP increase and inflation, improvement in vehicles efficiency and fuel cost changes over the years.

Using the Census journey-to-work (JtW) data, the individual delay for journeys between each pair of locations (*ij*) can be multiplied by the observed number of commuting trips, q_{ij}, to give a combined the overall impact, $I_{net_{i,j}}$ for those journeys.

The overall impact of the flood event for the scenario S, I_{net}, considers all the delays across the network:

$$I_{net_{i,j}} = \sum_i \sum_j q_{ij} * C_{p_{ij}} = \sum_i \sum_j PHD_{i,j} * VoT$$

Equation 3-6

Equation 3-6 captures the wider effects of the delay to transport links, weighting the delay to journeys by the number of people currently using those portions of the transport network.

3.8.2 ESTIMATING THE BENEFITS FROM LESSENING THE IMPACT

C_p from Equation 3-5 can be computed for both the disruption and adaptation scenarios. The difference between the values gives a quick estimation of the benefit due to the selected interventions. Considering the route from origin *i* to destination *j*, the benefit B_{ij}^{AS} for an adaptation scenarios AS with respect to the disruption scenario S is:

$$B_{ij}^{AS} = \sum_i \sum_j (I_{net_{i,j}}^{S} - I_{net_{i,j}}^{AS})$$

Equation 3-7

where q_{ij} is the number of users along the route *ij*.

B_{ij}^{AS} represents the advantage brought from the implementation of a specific flood alleviation intervention, whose initial cost should be deducted from the overall benefit. The revenues of climate adaptation actions are usually realised over multiple years. The Net Present Value (NPV) of the benefits in terms of risk reduction is one criterion for deciding which action is more cost-effective (Berk *et al.*, 2015).

NPV computes the long-term costs and benefits, discounted to present day rates to account for inflation. The NPV of the benefits in terms of risk reduction, NPV_r, is calculated by summing over the total disruption cost for an event, I_{net} (x), and likelihood, $\rho(x)$, of a range of flood events:

$$NPV_r = \sum_{i=1}^{N} \frac{\int \rho(x_i) I_{net}(x_i)\, dx}{(1+r)^i}$$ **Equation 3-8**

The HM Treasury (2013) offers a life-span, *N*, of 50 years for infrastructure and a discount rate, *r*, of 3% as guidelines.

3.9 EXAMPLE OF MODEL APPLICATION

To help to understand the process undertaken in the case study (Chapter 5), disruption to a single journey between an origin and a destination point is presented by way of an example illustrated in Figure 3-13.

The route taken under baseline (BS) conditions for a nearly-circular journey between five stops along the network is plotted in Figure 3-13a. When flooded by 1-in-10-year event with no adaptation (NA), the route must be modified to avoid roads that are deeply flooded, to find the fastest alternative route (Figure 3-13b).

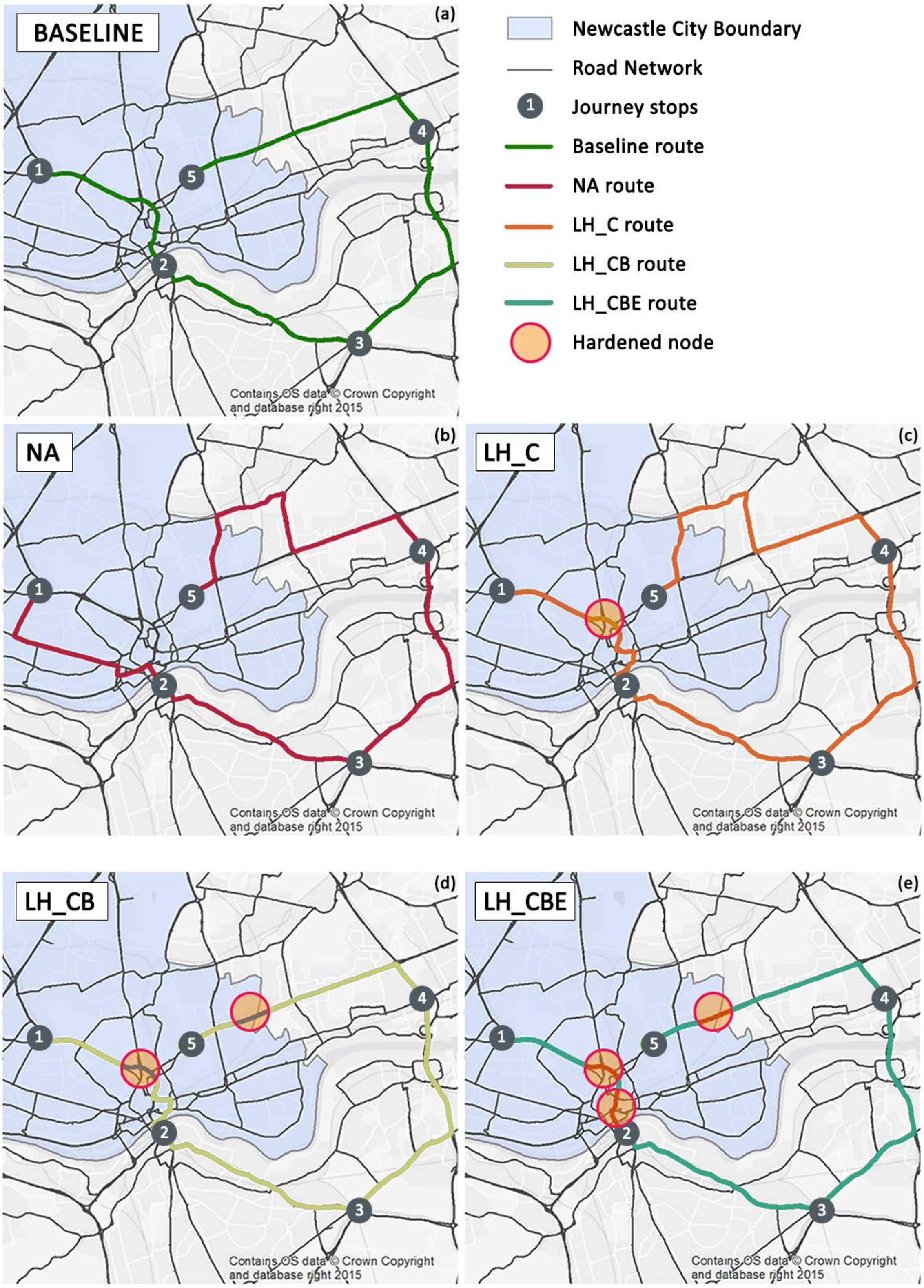


Figure 3-13. A journey from point 1 to point 5, via points 2, 3 and 4. The route is calculated for the (a) baseline (*i.e.* no flooding) conditions, (b) flooding with no adaptation, (c), (d) and (e) for a range of adaptation scenarios that correspond to the locations shown in Figure 5.8.

The successive introduction of each ‘hardened’ stretch of road (stretches B, C, and E introduced previously) are shown in Figure 3-13c, Figure 3-13d, and Figure 3-13e. With all three stretches of road hardened the route corresponds to the baseline, although the travel time is increased due to shallow flooding on some unprotected stretches of the route, as shown in Table 3-10. For this single journey the disruption caused by floodwater adds around 15 minutes to the journey time without adaptation.

Table 3-10. Additional journey time and distance after re-routing caused by flooding for a 1-in-10-year event for the journey shown in Figure 7. Legend: BS is Baseline, NA is No Adaptation, LH is Link Hardening for the locations considered in Figure 3-13.

Scenario	Disruption	
Strategy	Time [min]	Journey length [km]
BS	24	27
NA	39 (+62.5%)	32 (+18.5%)
LH_C	35 (+45.8%)	30 (+11.1%)
LH_CB	30 (+25.0%)	27 (0.0%)
LH_CBE	29 (+20.1%)	27 (0.0%)

In Chapter 5, the impact of a range of rainfall events were assessed on the road network for the whole urban system. Within the rational of this example, journeys under disrupted and adapted conditions were calculated for every pair of origins and destinations across the network, and results were aggregated across the domain. These results were shown in Table 5-8 and Table 5-11.

3.10 DISCUSSION ON THE MODELLING FRAMEWORK

The methodology has been developed with standard tools and practitioner appraisal methods in mind. For example, any flood or transport model could be used. The transport model of this research tries to balance the large scale and complexity of the analysis, and the needs of a simple tool. For this reason, it has been chosen to assume some hypothesis to reduce the complexity of the study (see Section 3.4.2). Nevertheless, the methodology could be adapted to explore other hazard impacts (*e.g*. heat waves), different types of infrastructure networks (as railway), evacuation routes and potentially cascading failures between infrastructure systems. Its versatility also accommodates more adaptation strategies than the tested ones, such as: *(i)* infrastructure away from flood-prone areas (*i.e.* diverting roads); *(ii)* building redundancy into the network (*i.e.* providing new alternative routes); *(iii)* increasing mode share for more resilient transport modes (*i.e.* encouraging shift from private car-based transport to public transport, walking, and cycling).

Similarly, the calculation of the generalised cost of travel is in line with the UK government guidance ensuring that the results are of direct value to the policy appraisal process (DfT, 2004a; EA, 2010; HM Treasury, 2013; DfT, 2014c). However, this stage of the calculation is readily adapted to suit other national approaches (*e.g*. FHWA, 2001). It is noted that VoT computation considers petrol and diesel cars, whereas inclusion of electric cars is a developing area, as the knowledge about energy consumption is currently limited. Nevertheless, the TAG Unit underlined that electric cars should be considered in transport appraisal using data from 2011 onwards (not yet available).

Whilst the VoT measure is defined for use in normal road conditions, it can be considered a low-bound to the level of economic cost, as the VoT is likely to be higher during disruptive events (Jenelius *et al.,* 2011; Mattsson and Jenelius, 2015). This appraisal could be enhanced by quantifying other impacts, such as the increase in air pollution due to vehicle emissions and a higher total CO_2 for the journey (Mao *et al.*, 2012), or social impacts in terms of driver health and wellbeing (Abu-Lebdeh, 2015). Also in the appraisal of adaptation benefits, indirect benefits (such as the improvement of the quality of life) are not captured in economic terms. Moreover, vehicles operating costs related to fuel and non-fuel consumptions (*e.g.* tear and wear, oil, tyres, maintenance) can be added as cost to the loss of time. Certainly, more refined calculations would imply extra complexities in the modelling. The implementation of traffic records from Big Data could provide additional insights in the near future.

The developed method aims to improve existing techniques regarding the analysis of disruption to urban transport networks from pluvial flooding. Chapter 2 underlined that new models and new tools are necessary in order to tackle the impact of flooding on urban areas in a more complete way. The proposed framework brings consistent improvement to current methods, however it is not meant to fully address all the identified gaps of Section 2.6 (Table 3-11).

Table 3-11. Summary of what the proposed methodological framework can or cannot achieve.

Addressed gaps	Not fully addressed gaps
Integration between hazard and damage assessment	Dynamics of flooding and traffic
Integration between flooding and transport modelling	Real-time interaction
Focus on surface water flooding	Probabilistic hazard modelling only
Focus on road transport network	Partial validation of the model
Focus on indirect losses	
Integration with adaptation economics	

In particular, the impact of flooding on transport is not investigated in real-time, indeed the results do not include dynamic interactions. Nevertheless, the hazard analysis provides time-series of flood depth and velocity, functional for a dynamic analysis of the hazard. The hazard modelling uses probabilistic techniques, however it cannot be considered a fully probabilistic model. Model validation is performed, but with some limitation due to the lack of data and the complex nature of the investigation.

The method presented enables the quantification of the indirect impacts of flooding on transport delays representing an effective strategy for prioritising investment to maximise returns. Since hard engineering measures are expensive and effective only in protecting a particular infrastructure asset, alternative options should be considered alongside these engineering interventions as part of a more sustainable approach to flood risk management. Green infrastructure and other strategies to replicate natural flow processes bring additional co-benefits. Given the longevity of transport infrastructure, the additional headroom this provides for existing transport drainage systems will yield greater flexibility in developing long-term adaption solutions for climate change.

3.11 SUMMARY

Chapter 2 analysed the current methods of FRA, identifying the more relevant gaps regarding the assessment of pluvial flood risk to transport network. Surface flooding is a major threat in urban environments and transport networks are fundamental for keeping a city running. An increasing body of evidence recognises that probabilistic methods are necessary to develop an appropriate estimation of risk; however, they are mainly applied to buildings and direct damages. Additional limitations are set by the separation between the hazard and the impact analysis, typical of current silo-based approaches.

To tackle this, an integrated framework for coupling hazard assessment, flood modelling, transport network modelling and a function that relates flood depth to driving speed has been developed in Chapter 3. The most critical step of the framework was the vulnerability assessment, given that at present no studies address this in relation to the transport sector. This stage consists in associating a range of flood depth to correspondent levels of network performance, by developing an innovative function – presented in Chapter 4.

The aim is to assess the impact of a range of flooding and adaptation scenarios, and test the effectiveness of a portfolio of adaptation options on the impacts of traffic disruption from extreme flooding. The disruptions take into account indirect costs, related to the interruption of the normal circulation, in function of several factors (*e.g.* travelling distance and speed). The baseline model of BAU commuter flows can be "disrupted" by hazardous events as well as "adapted" to target different urban interventions, permitting the simulation of a set of analysis to support decision-making.

To date this has not been considered in previous flooding appraisals in such a comprehensive way. Moreover, the method provides a mechanism for city-wide screening of priority locations for flooding adaptations based upon analysis of road network and traffic properties. Furthermore, it enables the peak disruption impact to be assessed thereby, providing important information to policy makers to determine the benefits of adaptation options on the transport network. Finally, by targeting adaptation interventions at the most critical stretches of road network, in terms of traffic flows and flood depth, the framework is used to propose a cost effective prioritisation of intervention options.

The general framework has been developed for the assessment of flooding on transport network, and it has been applied to a UK city (Newcastle-upon-Tyne) in Chapter 5, for a range of hazard scenarios and adaptation options.

CHAPTER 4: IMPROVED CHARACTERISATION OF VEHICLES-SPEED IN FLOOD CONDITIONS

4.1 INTRODUCTION

Chapter 3 illustrated a methodological framework for assessing impacts and adaptation options on transport networks for the case of flooding. It explained how to perturb the baseline condition of the transport model with a range of hazard scenarios and how to test a portfolio of adaptation strategies. Criteria to identify the most vulnerable areas of a city have been advanced too.

One of the most important steps within that framework was the vulnerability assessment. This stage consists of associating a range of flood depths to corresponding levels of performance within the network. Chapter 4 develops a function that relates flood depth to vehicle speed, using various observational and experimental data sources. This function contributes an original criteria for vehicles in motion during floods, which are currently missing in literature. This chapter addresses objective no. 3 of this thesis (see Section 1.3).

4.2 MOTIVATION

Existing approaches to assessing the impact of flooding on transport disruption do not capture the complexity of interactions between the flood hazard and transport system. Typically, assumptions can include (EA, 2010; TRB, 2010; Shand *et al.*, 2011; Penning-Rowsell *et al.*, 2013; DfT, 2014a):

- traffic volumes and speeds are assumed to correspond to regional (or even national) average statistics;
- a road is assumed to be completely closed when its crown is covered by water, regardless of depth;
- a road is assumed to be not used by drivers when flooding occurs;
- traffic on open roads continues to flow smoothly, perhaps at a slightly reduced maximum speed;
- traffic volumes do not exceed the design capacity of a road;
- traffic conditions do not change over the course of the day, or seasonally;

- diversion routes, and changes (or not) to driver behaviour as a result of the flood, are often assumed without any clear rationale.

These assumptions are increasingly inappropriate in urban areas, where traffic conditions are most dynamic, topographic and manmade features mediate flow paths leading to multiple flooded locations and a range of flood depths. If a passable road is defined in terms of the crown of the road being covered by water, the range of flood depths could be huge. Assuming a lane width of 2.7-3.7 m and a potential crossfall of 1.25% - 6% (Bartlett, 2013) this gives a possible range of threshold flood depth of 34 - 222 mm. Moreover, there is substantial evidence that roads can be, and often are, used by drivers even if flooded (Jonkman and Kelman, 2005; Jonkman *et al.*, 2008).

To better understand the impacts of flooding on road traffic disruption, this study undertakes a specific and systematic review of empirical, simulation and experimental research of the impacts of extreme weather on transport disruption. Subsequently, by synthesising across these multiple sources a function has been developed, that for the first time relates flood depth to traffic speed. This provides a significant advance on existing approaches to considering the impact of flooding on transport disruption that use coarse, or averaged, assumptions about traffic flows and flood depths. Implications, uncertainties and emerging opportunities to improve this function are considered in the final sections.

4.3 REVIEW OF SIGNIFICANT LITERATURE

A number of studies over the last decade have looked at weather impacts on road networks, including several broad reviews (Koetse and Rietveld, 2009; Jaroszweski *et al.*, 2014; Faturechi and Miller-Hooks, 2015) that consider aspects of the relationship between transport sector and climate hazards. Important reviews were also advanced about mass evacuation and emergency management during floods event (Lumbroso *et al*., 2010; Dawson *et al*., 2011; Lumbroso and Davison, 2016). However, this work is distinct from those reviews with its focus on the impact of flooding on traffic flows and network performance (without considering evacuation times and post-recovery), examined in ‘functional’ terms (*i.e*. travel time, flows, accessibility). Furthermore, it is distinct to the ‘topological’ and more abstract measures used in network modelling studies (*e.g*. Albert and Barabasi, 2002; Dunn and Wilkinson, 2013).

This study draws in these sections from the papers that couple analysis of transport and weather (including snow, ice, rain, fog, wind, heat), which cover both small (*e.g.* road-vehicle interactions) and large scale (*e.g*. city-wide impacts of weather) analysis. The literature is summarised in Table 4-1 and includes: *(i)* observations and data from extreme weather events; *(ii)* modelling and simulation studies; and, *(iii)* experimental studies that provide evidence of the impacts of water on vehicle performance.

The review of those works revealed a significant body of research that relates weather and transport. However, such studies are typically focused on particular circumstances or geographies with limited consideration of transferability or generalisation. Drawing together various data from experimental, observational and modelling sources has enabled the production of a function that relates depth of flooding to speed reduction. This thesis focuses on the reduction of vehicle speed, to ensure safe trafficability, in the presence of floodwater on road links. This includes consideration of both the ‘roadworthiness’ of vehicles in flood conditions, which is affected by their design including, for example, the heights of air inlets, as well as their ‘stability’, which in this case is dominated by aquaplaning, but could also include floating, sliding and tipping (Kramer *et al*., 2016).

Table 4-1. Overview of the most recent research considered in this chapter, organised in three categories: (1) observational studies; (2) modelling studies; (3) experimental studies.

Author	Country	Hazard(s)	Brief summary
OBSERVATIONAL STUDIES			
Agarwal *et al.* (2005)	USA	Rainfall Snowfall	Study on the impact from weather to speed reductions (up to 7% for heavy rain and 15% for heavy snow), due to snowfall or rainfall, for an urban freeway in Minneapolis.
Andrey *et al.* (2003)	Canada	Rainfall Snowfall	Focus on weather-related accidents, exploring road safety in adverse conditions for snowfall and rainfall events over a four-year period (1995-1998) for six cities. Adverse weather resulted in an increase of 75% in the number of collisions, as compared to normal conditions.
Chung (2012)	Korea	Rainfall	Estimation of the total delay to road traffic caused by rainfall, combining weather information and traffic flow data from 2008. The relationship is expressed as average non-recurrent congestion (vehicles-hrs/km) vs rainfall (mm/hr). Rainfall is considered in a discrete range of five categories, from negligible to warning.
Hooper *et al.* (2014)	UK	Rainfall	Detailed analysis regarding the relationship between rainfall intensity and vehicle speed on UK roads. A clear threshold between speeds with no precipitation and the speed when it is raining can be identified, but such relationship was shown as a complex one that requires more research. A mathematical relationship between rainfall intensity and vehicle speed is not defined.
Hooper *et al.* (2013)	UK	Rainfall	Observations about the impacts from precipitation on speed and flow for a UK motorway, including road type and congestion.
Hranac *et al.* (2006)	USA	Rainfall Snowfall	Study about the impact of precipitation on macroscopic traffic in three cities (Minneapolis, Baltimore and Seattle), considering two categories for each hazard (light/heavy rain and snow). Rainfall resulted to impact flows by reducing free-flow speed up to 9%.

Ibrahim and Hall (1994)	Canada	Snowfall	Statistical interpretation of traffic and weather datasets, from permanent traffic counters and weather stations in Alberta (2005-2009). Heavy rain resulted to reduce capacity up to 15%. Only rainfall considered, not flooding.
Kyte *et al.* (2001)	USA	Ice Rainfall Snowfall Visibility Wind	Analysis about the effect environmental factors (wind speed, precipitation intensity, visibility and pavement condition) on free-flow traffic speed. Intensity is defined by a discreet range (*e.g.*: 1 = none, 2 = light, 3 = medium, 4 = heavy).
Martin *et al.* (2000)	USA	Rainfall Snowfall	Examination of signal timing in adverse weather conditions in Salt Lake City, collecting local traffic flow data over the winter 1999-2000 to determine traffic trends during peak hours. Free flow speed decreased by 10% during rainfall events.
Sabir *et al.* (2008)	Netherlands	Rainfall Snowfall Temperature Wind	Estimation of commuter costs due to adverse weather on traffic speed, through a regression model. The commuting cost due to rainfall seemed to increase up to 15%, and up to 7% for snowfall.
Smith *et al.* (2004)	USA	Rainfall	Study of the impact of rainfall on free flow speed with the intensity of rainfall as a continuous variable. Data was collected in Virginia, and the percentage of speed reduction considered as a function of the intensity.
Stern *et al.* (2002)	USA	Rainfall Visibility Wind	Assessment of travel delay impacts of weather along specific roadway segments around metropolitan Washington D.C. (1999-2001). Meteorological data, in four categories of intensity, were coupled with travel time data, resulting in travel time increase of average 14%.

Tsapakis *et al.* (2013)	UK	Rainfall Snowfall Temperature	Study of the impact of weather conditions on macroscopic urban travel times and speed in Greater London area. The impact of adverse weather on the network is investigated during different times of the day (morning, noon, evening) and for multiple parts of the area (central London, inner, outer), comparing travel times under normal and perturbed conditions. Again, only intensity of precipitation is included, not flooding effects.
Tu *et al.* (2007)	Netherlands	Ice Fog Rainfall Snowfall	Empirical investigation of the impacts of adverse weather on travel time variability on the basis of a large database of travel times alongside weather data of rain, snow, ice fog and storm in Delft. It was found that adverse weather leads to higher travel time variability. A binary hazard is considered (*e.g.* normal or hazardous).
USACE (2009)	USA	Flooding	The study advances guidance for the use of vehicle depth-damage curves in the USA. These curves are relate to physical damages to vehicles only, and are determined using post-event surveys of vehicles assessment.
MODELLING STUDIES			
Arrighi *et al.* (2015)	-	Flooding	Focus on the description of the incipient motion stationary cars during floods, using a 3D numerical model to assess the contribution of drag and lift forces.
Chang *et al.* (2010)	USA	Flooding	Integrated impact assessment methods involving hydraulic simulations and travel forecasting, with a case study in Portland (Oregon). An integrated framework of climate change on urban flooding and transport sector was advanced, including hydrologic modelling and dynamic traffic assignment. The focus is in particular on the hours delay experienced by vehicles and on road closure as main effect from flooding, with only complete closure of links considered.

Dalziell and Nicholson (2001)	New Zealand	Ice Earthquake Snowfall Volcanic eruptions	Risk and impact of natural hazards (excluding flooding) on road networks. In particular, it investigates the effect of road closures on traffic flows through a traffic assignment model based of the least-cost path.
Gallaway *et al.* (1979)	-	Wet surfaces	Experimental derivation of a regression relationship for planar road surfaces between hydroplaning parameters (such as spin down, tire inflation pressure, tread depth, water depth and mean texture depth) and vehicle speed.
Green *et al.* (2016)	UK	Flooding	Evaluation of emergency responder accessibility during floods in Leicester (UK). Accessibility was assessed for emergency provision (Ambulance, Fire & Rescue vehicles) under a BUA scenarios and for a range of flood scenarios. A hydrodynamic inundation model was inputted into a transport model (in ArcGIS) to compute the disruption caused by surface water flooding. Results showed that total in accessibility increased up to 31% (for the most extreme scenario). Within a binary approach a threshold water depth of 250 mm was set for determining the restrictions to traffic.
Ong and Fwa (2008)	-	Wet surfaces	Discussion about numerical hydroplaning simulation model and evaluation of hydroplaning risk with surface groove deterioration, in a more mechanistic manner. Aquaplaning rarely occurs below 72 km/h (55 mph).
Penning-Rowsell *et al.* (2013)	UK	Flooding	Good practices for appraising flood risk management, in particular for road disruptions (road is assumed closed when “the crown of the road is covered by water”) and losses due to longer (in time and/or space) travelling. Multiple transport modelling approaches are presented, for impact assessment on transport network.

Pyatkova *et al.* (2015)	Caribbean	Flooding	The study integrated a flood and a transport model to study the interruptions of roads due to flood propagation. Although the methodology is holistic and advanced, no rational is behind the threshold of 200 mm that determine roads as trafficable or not. Thus, the model is limited to the binary representation of inundated roads.
Sohn (2006)	USA	Flooding	Analysis about the identification of critical links of transport network affected by flooding, using purely topological measures. An accessibility score was derived in order to quantify the potential impact of flood damage on the state transportation system, on the distance and traffic volume criteria.
Suarez *et al.* (2005)	USA	Flooding	Simulation modelling of climate change on Boston Metro Area, looking at land use, demography and climate within urban transportation system. The estimation of the impact is through a model able to simulate flows under 12 different flooding scenarios, run for the contemporary year (that was 2003) and a future time (2025). However, there is a simplistic consideration of roads intersecting floods (*i.e.* road capacity equal to zero if intersecting with floods, and trips no longer generated from flooded areas).
Teo *et al.* (2013)	-	Flooding	Numerical model to assess the hydraulic behaviour and safety degree of vehicles during flood, using hydrodynamic models of parked cars.
Yin *et al.* (2016)	China	Flooding	A 2D inundation modelling is coupled to a transport model to assess the potential impact of pluvial floods on road networks in Shanghai. Transport disruption is defined as “road closure”, thus the study is limited to a binary approach determined by a critical threshold of 300 mm.
EXPERIMENTAL STUDIES			
Kramer *et al.* (2016)	-	Flooding	In order to determine the safety criteria of trafficability during flood events, flume experiments were conducted on prototype die-cast models of vehicles. Results recommended a safety threshold

			of fording depths of 0.3 m for passenger cars (VW Golf) and 0.6 m for emergency vehicles (such as auto-ambulances).
Martínez-Gomariz *et al.* (2017)	-	Flooding	The study developed a stability coefficient for vehicles exposed to flooding. Effects of both friction and buoyancy were analysed by conducting experiments with 12 different car models, using three scales. Results enabled to define a stable area in the flow depth-velocity domain for parked vehicles in flood waters.
Shand *et al.* (2011)	-	Flooding	Based on previous experimental and analytical data (*e.g.* Gallaway *et al.,* 1979), criteria for stationary vehicle stability are proposed for three vehicle classes (small, large and 4WD cars).
Shu *et al.* (2011)	-	Flooding	Formula for incipient velocity for scaled models of cars, in partially submerged conditions (Ford Focus, Volvo XC90, Ford Transit).
Onishi *et al.* (2014)	-	Flooding	Studies on initial floating condition of partially submerged cars, considering flow velocity and water depth and a range of vehicle orientations relative to the floodwater.
Teo *et al.* (2012)	-	Flooding	Study on stationary scaled die cast model vehicles (Mini Cooper, Ford Escort, Mitsubishi Pajero, BMW X5), looking at the degree of hydraulic stability for vehicles.
Toda *et al.* (2013)	-	Flooding	Study on initial floating condition of partially submerged cars (scaled sedan and minivan) by hydraulic experiments, considering flow velocity and water depth.
Xia *et al.* (2011)	-	Flooding	Formula to model the initial velocity of flooded cars, on the basis of the vehicle mass and dimensions, buoyancy and drag forces. Laboratory experiments were run for three types of scaled cars (Mini Cooper, Mitsubishi Pajero, BMW X5), considered fully-submerged.

Xia *et al.* (2014)	-	Flooding	Study on stability criterion, including multiple ground slopes and vehicle orientation angles, for partially submerged vehicles (Honda Accord and Audi Q7). A mechanics-based formula was derived and tested using empirical data obtained from two types of die-cast vehicles.
Xia *et al.* (2016)	-	Flooding	Study on hydrodynamic impacts of vehicle blockage at bridge sites using scaled physical river model and scaled vehicles (Mini Cooper, Ford Escort, Mitsubishi Pajero, BMW X5).

4.3.1 OBSERVATIONAL ANALYSIS

A number of observational studies collate and analyse information on vehicle movement and local weather conditions. Studies have taken a range of approaches to categorise weather conditions. For example, Tu *et al.* (2007) investigated travel time reliability on the basis of a large database of travel times, but weather was considered to be either “normal” or “adverse”. Much research discretises rainfall intensity into a number of bins (see Figure 4-1), reporting vehicle speeds as a function of these categories (Ibrahim and Hall, 1994; Kyte *et al.*, 2001; Smith *et al.*, 2004; Agarwal *et al.*, 2005; Hranac *et al.*, 2006; Chung, 2012).

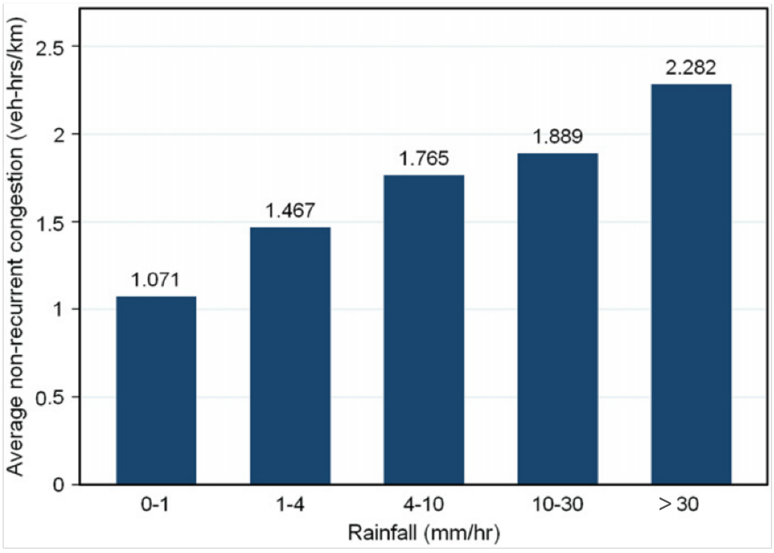


Figure 4-1. Average non-recurrent congestion per unit distance (km) as a function of the rainfall, classified into five categories (from Chung, 2012). It suggests that rainfall reduces the travelling speed, increasing the travel time.

Other studies adopted a similar approach to discretisation to study wind and visibility (Stern *et al.*, 2003) and snowfall (Tsapakis *et al.*, 2013).

Some recent studies have sought to overcome the discrete approach by looking for correlations between speed, traffic flow, and precipitation. A linear regression of traffic speed and precipitation by Hooper and Chapman (2012) showed an identifiable, but weak, relationship. This was advanced by Hooper *et al.* (2013) by considering additional factors such as road type and congestion. Nevertheless, both studies were focused on precipitation data and for one motorway corridor only. Sabir *et al.* (2008) also proposed a regression model that relates speed reduction due to adverse weather conditions (temperature, rain, snow and wind) to commuting costs, whilst Andrey *et al.* (2003)

correlate road safety and accident data against hourly observations of rainfall and snowfall. These studies recognise that correlations between weather and disruption are complex as they relate to road network capacity, drainage systems and a number of other factors. Flooding is not considered in these studies.

4.3.2 MODELLING AND SIMULATION ANALYSIS

Modelling and simulation tends to be either focused on small scale vehicle-water interactions, or transport network scale analysis. Moore and Power (2002) uses a dam break model to assess the safe distance of a road from an offstream water supply storage (or ring tank). Teo *et al.* (2013) adopts a hydrodynamic model to simulate the impact of floodplain flow on vehicles in the Muar river basin in Malaysia. Arrighi *et al.* (2015) use a detailed 3D simulation of the interactions between motion of flood water around vehicles and to systematically estimate the forces, including drag, acting on the vehicle. Although these detailed simulations provide a better understanding of hydrodynamics forces, no investigation involved study of vehicles in motion.

This scale of analysis is in contrast to the work of Dalziell and Nicholson (2001) which employs a probabilistic approach for assessing the risk of road closures due to various weather events, although not from flooding. The use of Monte Carlo simulation enabled the identification of probability distributions for the closure costs, whereas probability distributions were used for the benefit-cost ratios of mitigation. This economic analysis indicated that all the regarded options were economically attractive.

Chang *et al.* (2010) and Suarez *et al.* (2005) couple hydrological and traffic modelling to analyse vehicle delays and consider multiple scenarios and possible climate impacts. These approaches assume that flooding of a road makes it impassable (*e.g.* Figure 4-2).

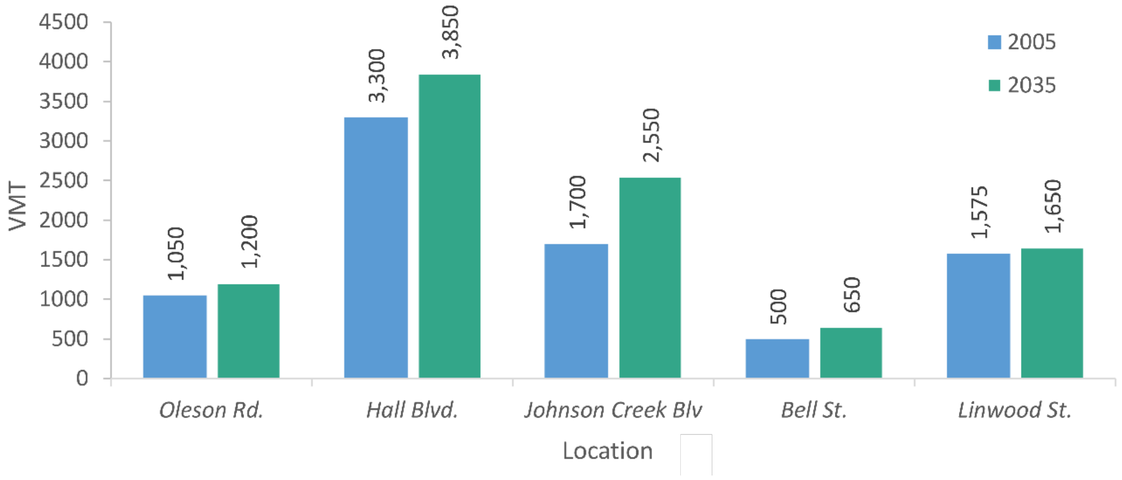


Figure 4-2. Street links prone to flooding and the average traffic volume (VMT, vehicle miles travelled) in the afternoon peak for the year of the study 2005 and future year 2035 (after Chang *et al.*, 2010).

Sohn (2006) analysed the significance of highway network links under flood damage, deriving a composite accessibility index of two factors, distance and traffic volume. Green *et al.* (2016) analysed traffic restrictions during emergency management, considering water depths higher than 250 mm as prohibitive for the circulation of emergency vehicles.

A particular type of modelling study focuses on analysing vehicle stability from theoretical principles. The critical hydroplaning (also referred to as aquaplaning) speed threshold for grooved pavement (like asphalt) has been studied with models first advanced by Horne (1968), and further developed by Stocker *et al.* (1974) and Gallaway *et al.* (1979). Hydroplaning occurs when a loss of traction prevents the vehicle in motion from responding to control, and is calculated using a multi-parameter regression function that includes spin down, tyre inflation pressure, tread depth, water depth and mean texture depth. Ong and Fwa (2008) derived a simplified version (Equation 4-1) of the hydroplaning equation, assuming smooth tyres, locked wheel condition, null surface texture effect and a typical pressure for a passenger car (206 Kpa, *i.e.* 30 PSI):

$$v_p = \frac{67.68}{t_w^{0.06}} + 18.76$$

Equation 4-1

Where v_p is the hydroplaning speed in km/h; t_w the water-film thickness in mm over a range of 1-10 mm. For a film of 10 mm the associated hydroplaning speed is 77 km/h. Dynamic hydroplaning (when a moving tyre is completely separated from the pavement by a layer of water) occurs at high speed (above 72 km/h, 45 mph) with water ponds depth of at least 2.5 mm (Kumar *et al.*, 2012). Indicative breaking distance for wet roads are provided in driving guidance, including the British Highway Code (DfT, 2016a), but these are not related to water depth.

4.3.3 EXPERIMENTAL ANALYSIS

Experimental studies usually focus on the stability of parked vehicles for a range of flood depths and have provided some of the earliest analysis (Bonham and Hattersley, 1967; Gordon and Stone, 1973) to determine the depth and velocity required for a vehicle to float or slide. However, as a result of changes in modern vehicle design, those experimental works are now of limited value (Shand *et al.*, 2011). More experimental studies by Xia *et al.* (2011), Shu *et al.* (2011) and Xia *et al.* (2014) have investigated the behaviour of parked cars in flooded streets and subjected to water forces, looking at the incipient motion velocity as a criterion of stability in flood conditions. More recent experimental work by Toda *et al.* (2013), Teo *et al.* (2012), Onishi *et al.* (2014) and Martínez-Gomariz *et al.* (2017) undertook further experimental study to explore a wider range of issues such as the threshold of vehicle instability, the effects of vehicle orientation, ground gradient, and consideration of the effects of buoyancy decrease from water inside the vehicle. Other studies have considered the interaction of vehicles with other infrastructure, such as bridges, revealing how vehicles related blockages can significantly alter flood flow paths and depths (Xia *et al.*, 2016). A comprehensive summary of experimental studies is provided in Martínez-Gomariz *et al.* (2016), but as noted by Shand *et al.* (2011) such studies are limited to parked cars moved by water flows. Although investigating vehicles in motion endangered by stagnated flooding is the focus of this study, the stability of parked vehicles represent the ultimate limit (*i.e.* floating) with respect to roadworthiness.

4.4 PROGRESSING FROM PREVIOUS STUDIES

The literature has highlighted substantial amounts of research into the impact of a wide range of natural hazards, including snow, ice, rain, fog, wind and heat, on transport disruption. These studies span events of different spatial scale and magnitude, and include results from a number of different countries. Rainfall intensity has repeatedly been shown to be a factor in transport disruption, but the correlation is not always strong. Rainfall can reduce driver visibility, and many drivers may reduce speeds as a precautionary measure. However, measuring only rainfall does not take into account where the water falls, its flow paths, and where it pools sufficiently deeply to block a road. Whereas there are many observational studies that consider rainfall, most of the evidence that looked at flooding was from experimental and modelling studies.

Data from a range of observational, experimental and modelling studies contributes to the understanding aspects of the impact of flooding on traffic disruption. Whilst some studies have sought to understand water vehicle interactions, others analysed impacts at the scale of whole networks or city-region. Collectively, the literature shows that there are many uncertainties that mediate the impact of flooding on disruption, including transport system properties such as road type and capacity, road network structure, vehicle type, and the type of the flood event (for flash floods, water levels rise rapidly, thus it does not let water to enter into the vehicle, more susceptible to be swept away) such as spatial extent, flood depth and velocity.

It is impractical to capture the breadth of variability in these factors and, in line with other flood risk assessment approaches (Merz *et al.*, 2010; Jonkman and Dawson, 2012), reflecting and analysing these uncertainties is crucial. Models in the literature, and current appraisal guidance, assume a road is either open or closed. Yet observations from flooding events have shown that flooding on a road does not necessarily preclude people from driving along it (Jonkman and Kelman, 2005; Jonkman *et al.*, 2008; Pearson and Hamilton, 2014). There is therefore a need to build a more robust relationship, improving current simulations. Whilst there are a number of studies that look into the stability of parked vehicles, these relationships do no hold for vehicles that are driving (Shand *et al.*, 2011), in the particular case of standing water.

It is infeasible to have precise knowledge of every vehicle-floodwater interaction over a transport system of any realistic scale. Development of empirical relationships to describe the performance of vulnerability or fragility curves provides a means of capturing a large number of uncertainties and enabling broad scale infrastructure risk analysis (Dawson and Hall, 2006; Merz *et al.*, 2010). In order to transition from a binary view of a flooded road being considered "open" or "closed", a curve that relates the depth of floodwater to a reduction in vehicle speed has been created by integrating data from the literature reviewed previously, and some other sources of data (*e.g.* from automatic traffic sensors). This "depth-disruption" function is presented in Figure 4-3.

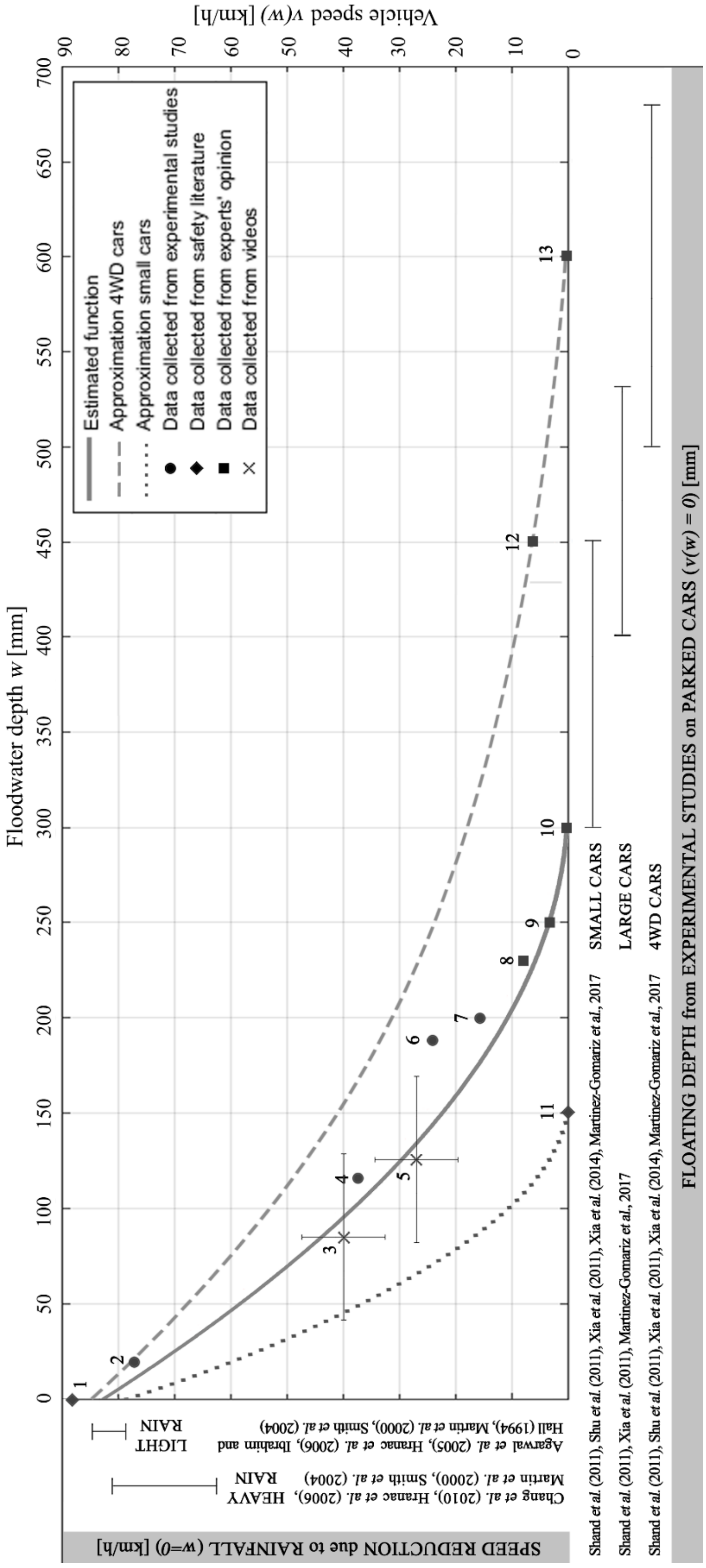


Figure 4-3. The depth-disruption function that relates flood depth on a road with vehicle speed.

The risk of disruption from flooding, R_d, can be calculated by modifying Equation 2-1 as it is shown in Equation 4-2:

$$R_d = \tau \int \rho(h). \sum_{i=1}^{N} \left(v - z_i(h). v(z_i)\right) dh$$ **Equation 4-2**

where $\rho(h)$ is the probability of rainfall h, this leads to a distribution of the maximum flood depths $z(h)$ along each journey i, v is the speed allowed by transport regulations and $v(z)$ describes the speed as a function of flood depth. The total disruption for each rainfall is calculated by summing the impact across all N journeys. The annual expected disruption is weighted according to the probability of each rainfall event, and can be converted to a cost by using an appropriate coefficient of the value of time (τ) (DfT, 2014).

4.4.1 THE DEPTH-DISRUPTION FUNCTION

The function (Figure 4-3) is derived by combining data from the experimental, observational and modelling studies reviewed (Pregnolato *et al.,* 2017b). A function was fitted, to describe the limit vehicle speed, *v*, as a function of flood depth, *z*, which has an R-squared of 0.95.

As introduced by Equation 3-1, the relationship between the speed and the water depth can be expressed by:

$$v(z) = 0.0009z^2 - 0.5529z + 86.9448$$ **Equation 4-3**

The speed *v(z)* is the maximum acceptable velocity that ensures safe control of the vehicle given the depth of water (*i.e*. not considering non-flood related safety issues). The quadratic relationship expressed by Equation 3-4 is the best-fit to the data series gathered for this study.

Not every paper reviewed contains information that can be plotted on the figure because, as noted previously, much of the research has focused on extremities of the graph such as hydroplaning or the stability of parked vehicles. Information from the scientific literature has been augmented with additional data from video analysis and guidance from driver safety groups. The complete list of sources that are plotted, explaining each point of the curve, can be found in Table 4-2.

Table 4-2. Source details of each point of the curve, including sliding floodwater depth from studies on parked cars and speed reduction due to rain from empirical studies. Definition of "heavy" and "light" rain from Hranac *et al.* (2006) and Chung (2012).

POINT No.	WATER DEPTH (mm)	VEHICLE SPEED (km/h)	SOURCE	NOTES
Estimated function				
1	0	88	1a. Morris et al. (2011) 1b. Chung et al. (2012)	In unflooded conditions (*i.e*. water depth = 0 mm), speed reduction is considered due to other circumstances (as rainfall or wet pavement).
2	10	77	2a. Gallaway et al. (1979) 2b. Ong and Fwa (2008)	Equation 4-1 has been applied.
3	87	40	Youtube (2014)	Observation of a Ford S driving through a flooded road in Bromsgrove (UK) in 2014.
4	116	37	Galatioto et al. (2014)	Data obtained in the results.
5	125	26	Youtube (2012)	Observation of an Audi A3 driving through a flooded road in Perth (UK) in 2012
6	189	24	Galatioto et al. (2014)	Data obtained in the results.
7	200	16	EVSTF (2015)	Water depth of 200 mm and vehicle speed of 10 km/h were considered as a reasonable and likely scenario for testing vehicle performance in flooding conditions.
8	230	7	8a. English (2016) 8b. Greenflag.com	Supposing a depth of water as 1/3 of the tyre, speed of max 7 km/h (4 mph) is recommended.
9	250	3	Boyce (2012)	Puddles that can reach the undertray of the car should be crossed very slowly, as at 3 km/h.
10	300	0	10a. English (2016) 10b. Gissing *et al.* (2016) 10c. Greenflag.com (2016) 10d. Kramer *et al.* (2016) 10e. Smart Driving (2016) 10f. Pyatkova *et al*. (2015) 10g. The AA (2016) 10h. Yin *et al.* (2016)	300 mm is the average depth at which a passenger vehicles starts to float, and therefore widely recognised as the ultimate thresholds for a safety drive for most of the common cars.
Bounds				
11	150	0	Pearson and Hamilton (2014)	Around 150 mm, water washes into the air intake.
12	450	8	Bavarianmw.com	Wading depth of 450 mm up to a speed of 5 mph (8 km/h).
13	600	0	Kramer *et a*l. (2016)	Maximum wading depth for special vehicles.
X-axis				
Studies on older vehicles				
–	na	0	Bonham and Hattersley (1967)	Large car (Ford Falcon)
_	na	0	Gordon and Stone (1973)	Small car (Morris Mini)
_	na	0	Keller and Mitsch (1993)	Small car (Suzuki Swift)

_	na	0		Small car (Honda Civic)
_	na	0		Small car (Ford Laser)
_	na	0		Large car (Ford LTD)
_	na	0		Large car (Toyota Corolla)
Recent studies				
_	387	0	Martínez-Gomariz *et al.* (2017)	Small car (Mini Cooper)
_	531	0		Large car (Bentley Continental GT)
_	686	0		4wd (Mercedes G55 AMG)
_	300	0	Shand *et al. (*2011)	Small car
_	400	0		Large car
_	500	0		4wd car
_	450	0	Xia *et al.* (2014)	Small car (Honda Accord)
_	670	0		4wd (Audi Q7)
_	360	0	Xia *et al.* (2011)	Small car (Mini Cooper)
_	480	0		Large car (BMW X5)
_	550	0		4wd (Mitsubishi Pajero)
_	400	0	Shu *et al.*(2011)	Small car (Ford Focus)
_	630	0		4wd (Volvo XC90)
_	580	0		van
Y-axis				
Light rain (0.25-6.4mm/h)				
_	0	81	Chang *et al.* (2010)	Speed reduction: 8.2%
_	0	79-85	Smith *et al*. (2004)	Speed reduction: 4-10%
_	0	80-83	Hranac *et al.* (2006)	Speed reduction: 6-9%
_	0	79	Martin *et al.* (2000)	Speed reduction: 10%
Heavy rain (>6.4mm/h)				
_	0	75-76	Ibrahim and Hall (1994)	Speed reduction: 14-15%
_	0	62-66	Smith (2004)	Speed reduction: 25-30%
_	0	81	Martin *et al*. (2000)	Speed reduction: 25%
_	0	76-81	Hranac (2006)	Speed reduction: 8-14%
_	0	75	Agarwal (2005)	Speed reduction: 15%

Unless otherwise stated this data relates to 2WD vehicles, however other vehicles may perform differently. For example, 4WD or off road vehicles have raised or watertight sensitive electronics and air intakes. This can allow safe driving in depths up to 450 mm, or even 900 mm. For smaller cars, some literature suggests that 150 mm depth may be sufficient to stall a car as water can wash into the air intake (Kramer *et al.,* 2016; Pearson and Hamilton, 2014). These values are used to identify “lower” and “upper” bounds to the curve to reflect the variability in fleet. Unlike the central curve, there is insufficient data to fit the upper and lower curves. Therefore, the limited points were used to stretch the curve accordingly. Given sufficient information car fleet composition, it would be possible to reflect this within an impact assessment by adopting the appropriate percentage of different vehicles. Without this information, it is only recommended to use these lower and upper curves to provide indicative estimates of uncertainty. Other uncertainties are from factors unrelated to flood depth, such as tyre pressure, road pavement, behaviour of the driver, visibility, etc. which may be considered in more detail if sufficient data is collected.

The analysis on the x-axis (floating depth from experimental studies on parked cars) draws from studies of the impact of floodwater on parked cars and the depth at which they slide, tilt or float. This shows a large range that is influenced by factors such as vehicle size and other assumptions about the relative orientation of the vehicle to the velocity of floodwater (Shand *et al.*, 2011; Shu *et al.*, 2011; Xia *et al.*, 2011; Xia *et al.*, 2014; Martínez-Gomariz *et al.*, 2016). In these studies, “small cars” include passenger cars such as the Ford Focus, Mini Cooper and Honda Accord, whilst “large cars” include the BMW M5, and “4WD vehicles” include the Pajero, Volvo XC90 and Audi Q7 (Table 4-2). Vans or trucks are not included.

The function intersection of the y-axis is influenced by studies (Ibrahim and Hall, 1994; Martin *et al*., 2000; Smith *et al.*, 2004; Agarwal *et al.*, 2005; Hranac *et al.*, 2006; Chang *et al*., 2010; Pearson and Hamilton, 2014; Zhong *et al*., 2014) about the impact of rainfall on vehicle speed, which can reduce driver visibility. Speed reduction is different for light (0.25-6.4 mm/h) and heavy (>6.4 mm/h) rainfall.

4.4.2 ADDITIONAL VIDEO ANALYSIS

To supplement the literature data, this thesis has obtained additional observations by analysing videos (uploaded on YouTube) of cars driving along flooded roads. Identifying suitable videos was very challenging because the method of extraction was constrained by: *(i)* the location (the UK); *(ii)* the type of road (urban); *(iii)* the type of vehicle (2WD car); *(iv)* the possibility to see some elements from which estimate the car velocity and the flood depth.

Flood depth was estimated in relation to wheel diameter and other objects of known dimension. Water depth was inferred from the proportion of wheel that was submerged. Vehicle speed was estimated by analysing distance covered by the vehicle over a fixed time period by using road markings (if visible) or other objects of known dimension, as reference points. Figure 4-4 gives an example of such procedure, on the basis of a video recorded in Perth (UK) in 2012, where v_{car} (km/h) is calculated using Equation 4-4:

$$v_{car} = 3.6 * \frac{\mathrm{d}_{road\ signs}}{\mathrm{t}_{elapsed}}$$ **Equation 4-4**

Figure 4-4. Video screenshot for an Audi A3 driving through a flooded street in Perth (UK) in 2012.

The nature of this calculation introduces a number of measurement uncertainties. For example, water perturbations around vehicle wheels make it harder to assess water depth, whilst inaccurate height and angle of the video lens introduce uncertainty into distance calculations. The car speed was assumed to be constant. The error bars attempted to reflect these errors (Figure 4-3), in order to provide a complementary set of observations that compare well to other sources of data.

4.5 DISCUSSION ON THE TRANSPORT FUNCTION

The depth-disruption function has been developed using best available data from the scientific and safety literature. It substantially contributes towards improved understanding of traffic flow (during extreme weather conditions), progressing from existing methods and playing a key role the impact assessment of transport schemes.

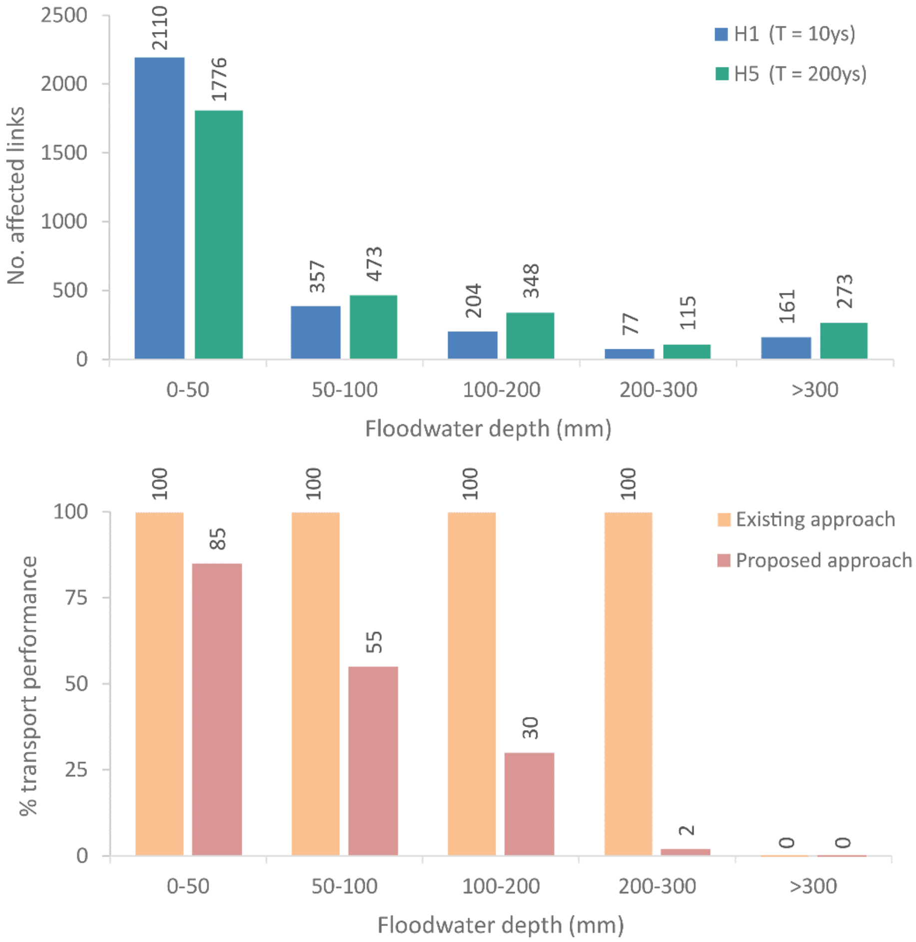


Figure 4-5. Number of road links affected by flooding for a low-profile event (H1) and for an extreme one (H5), over a total of 3023 links. Existing approaches ignore the reduction of the transport performance before reaching the ultimate threshold, *i.e.* when the road is impassable.

Current methods approach the problem of flooded roads in binary terms, *i.e.* considering them either fully operational or closed to traffic. In this way, existing approaches ignore an important part of the problem, which is the impact before reaching the ultimate threshold that determine the road closure (300 mm). Figure 4-5 shows the number of roads impacted by flooding for an urban case study (Newcastle, UK). Only few links (3.8% and 1.3% for a low- and high-profile rainfall event respectively) are not impacted by water, whereas all the rest is flooded at a certain degree experiencing disruption. The binary approach considers those roads regularly working, although their performance is far from normal business.

The curve is the first attempt to quantify flood-transport performance and, as such, limited by a range of assumptions, which includes the consideration of flood depth only as intensity measure. A future challenge is to consider not only vehicles in motion, but also the influence of flood velocities and associated debris on disruption. Expansion of the work could include consideration of other vehicle types (*e.g.* lorries) or modes of transport (*e.g*. tram, rail). Future data collection and further studies could refine this function and improve its applicability. Nevertheless, the curve developed by this study offers a significant improvement to the binary flood/transport relationships used in existing transport models.

Due to the scarcity of available information, the relationship developed in this thesis could, in future, be improved in different directions. Firstly, the curve has been built considering urban roads where drivers do not exceed 90 km/h in BAU conditions. Additional curves should be constructed to evaluate disruptions along highway or minor roads. This would enable transport planners and policy makers to more realistically represent and cost disruption.

Although the function accounts for one lower and one upper bound, uncertainties persists regarding the type of vehicles and other unpredictable circumstance, like the maintenance of the road or the driver ability. Furthermore, the uncertainty related to the observational studies is unknown, whereas error bars reflect video uncertainty. The central regression is the better estimation for the current available data. The lower and upper curves attempted to represent the uncertainty around it and they are useful to identify an area (included between the two curves) to which is it possible to refer. The knowledge of the car fleet composition is fundamental for the curve selection; if this information is missing, a conservative option could be to refer to the lowest curve, since the smallest (and slowest) cars are the ones who determine the flow in urban environments.

Increasingly local and national transport authorities are collecting data through Automatic Traffic Counters (ATCs), CCTV, and other ‘smart’ transport sensors. This information will be useful to inform the development of an improved depth-disruption function. For this purpose, traffic sensors should provide not only a count of vehicles, but also information on speed. Additionally, this should be coupled with weather sensors collecting hazard data (like flooding depth). A routine collection of information on flood depth, vehicle speed and vehicle numbers at a high density across the city would be ideal for the betterment of the function. Increasingly pervasive sensing technologies, data from other sources including geotagged social media posts, coupled with big data analytics, offer the potential to monitor and observe the disruptive effects of flooding across numerous cities and the wider road network thereby providing a vast empirical dataset to progressively refine the function or construct a set of functions according to vehicle and road type.

“Driving safety” can be considered a type of flood impact (Chen *et al.*, 2016), related to the depth of flooding for urban environments. The function could be used to raise risk awareness about safe driving depths and driving into floodwater in the community, integrating existing driving manual.

4.6 SUMMARY

Existing approaches to assess the disruptive impact of flooding on road transport are inadequate and because they fail to capture the dynamics and complex interactions between floodwater and the transport system, since a road is typically considered either fully operational or fully blocked which is not supported by observations - as highlighted in Chapter 2. Chapter 3 has described an innovative risk assessment method composed by different modules (hazard, exposure, vulnerability), and the key component of vulnerability has been developed in Chapter 4. This chapter has reviewed observational, experimental, and modelling studies of the impacts of weather on transport. A significant subset of these papers have been used to derive an empirical function that for the first time relates the depth of floodwater on a road to vehicle speed, providing a significant advance on existing practise. The depth-disruption function is complementary to the approach used by other flood impact functions in relating the magnitude of the impact to the flood loading. The maximum threshold for safe driving, stopping, and steering (without loss of control) is identified as 300 mm, on the basis of observations and driving tests; therefore, a road is assumed to be impassable only when the limit of 300 mm is reached. Incorporated into the transport appraisal calculation (see Sections 3.6 and 3.8), this function can be used to calculate the disruption, measured in cost or time, expected from flooding.

Full and reduced scale experiments have provided useful data to understand vehicle stability under parked conditions. Simulating moving vehicles is a natural progression from this work, although to cover the widest range of conditions and uncertainties would prove costly. Increased monitoring of transport systems offers the potential to improve this function by incorporating a richer set of observations. However, typical transport monitoring networks have not been established with this purpose in mind, and will need to be denser and record more than just the number of vehicles per unit of time, although other data sources may provide useful proxies.

Chapter 5 has applied the methodological framework, which includes the depth-disruption function, to a case study set in Newcastle-upon-Tyne (UK). This implementation has enabled to evaluate the flooding impact and adaptation benefits for a range of hazard scenarios, and a portfolio of adaptation options.

CHAPTER 5: THE CASE STUDY OF NEWCASTLE-UPON-TYNE

5.1 INTRODUCTION

Chapter 5 applies the methodological framework developed in Chapter 3 to a case study to evaluate its utility to assess flooding impact and adaptation benefits for a medium-size flood prone city. The case study is undertaken for Newcastle-upon-Tyne, in the North East of England (UK), which is representative of many cities in the UK, and other parts of the developed world (Wright *et al.*, 2014).

The flood disruption model is applied to city-scale simulations using rainfall and traffic inputs validated using historic flood events. The transport curve developed in Chapter 4 is applied to the urban road network of Newcastle and a range of adaptation strategies are simulated, in order to evaluate the effectiveness of interventions planned in key-spot locations. A cost-benefit analysis helps to quantify the economic return of those solutions, looking at a time-frame of 50 years. This chapter addresses objective no. 4 of this thesis.

5.2 NEWCASTLE UPON TYNE

Newcastle-upon-Tyne (North-East of England, county of Tyne and Wear; Figure 5-1) has wide records of flooding incidents, going back to at least the 14th century (Newcastle City Council, 2013; Newcastle City Council, 2016).

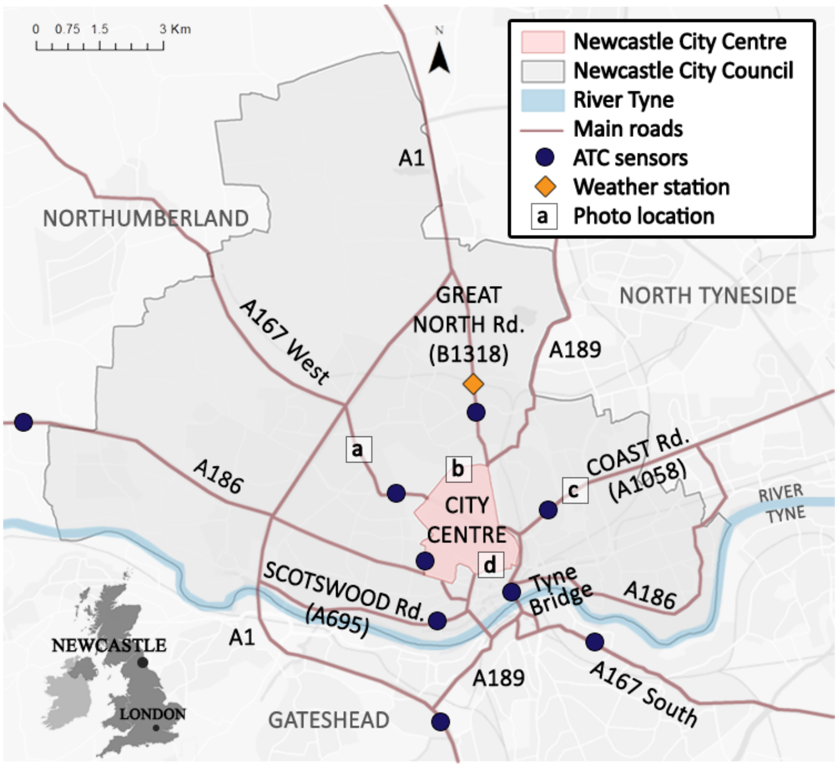


Figure 5-1. Urban features of Newcastle-upon-Tyne, including main roads, Automatic Traffic Sensors (ATCs) and the weather station location.

Recently and on multiple occasions, the city has been flooded by intense rainfalls; the most remarkable flooding event being the “Toon Monsoon” event on the 28th of June 2012, which hit the city with 50 mm of rain in two hours. The volumes of surface water caused a flash flood that overwhelmed drainage networks causing around £8 million of damage to homes, businesses, and roads; around 40% of the affected non-residential properties were temporarily forced to close and eight hour of congestion paralysed the traffic flows. (Newcastle City Council, 2016). This episode highlighted how the characteristics of contemporary cities can cause surface flash flooding, in addition to river flooding. As with most cities globally, Newcastle city centre is almost impervious without an overarching strategy for its drainage system and it provides a useful prototype in the UK for the analysis of flash floods (Wright *et al.*, 2014). The representative features that make Newcastle a good prototype of a middle-size UK city are (Everett *et al.*, 2016):

- Vulnerability to flood due to impermeable surfaces and insufficient local drainage system;

- High percentage of critical buildings and infrastructure at risk of flooding, including railway, highway, stations and hospitals;
- Extensive and highly congested road system during peak-hours;
- Presence of stakeholder groups, including Newcastle City Council and consultants;
- Council willingness to look at new strategies involving climate change adaptation and mitigation.

Partnered with the Environment Agency and Northumbrian Water, Newcastle City Council (NCC) is the LLFA (Lead Local Flood Authority) which aims to find sustainable ways to manage localised flood risk. A long-term financed programme is planned to reduce potential damages to households, commercial properties, and the "infrastructure that underpins existing local economies" (Newcastle City Council, 2016). The identification of appropriate inward investment opportunities constitutes a major challenge for the city, looking for new funding models to provide multiple benefits from one single investment.

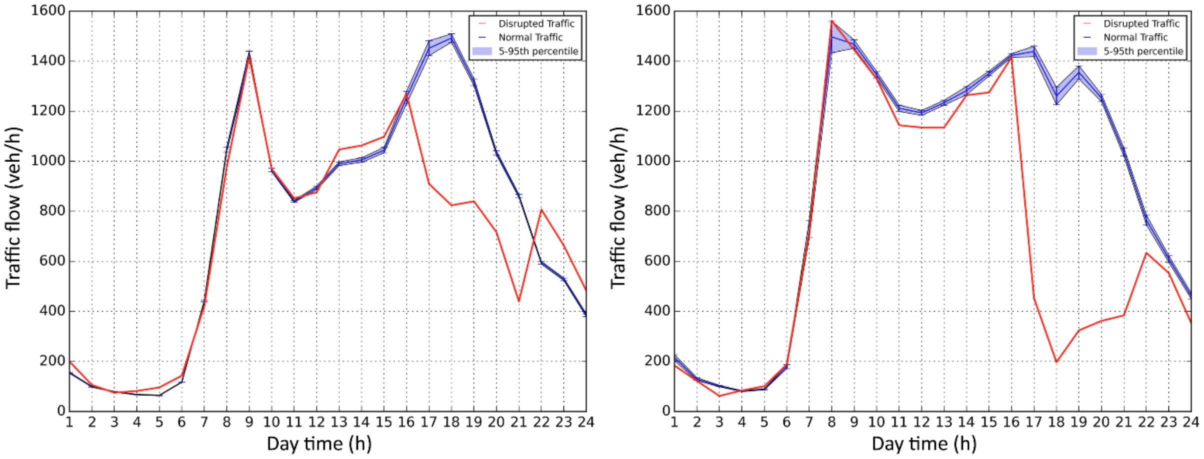
In collaboration with Newcastle University, the council and partners established the Learning Action Alliance, which commits the city to tackle flooding in a more natural way by using blue and green assets. This is achieved by providing resilient and adaptive measures to deal with flood events, and to satisfy the demands of urban drainage and planning, by generating various environmental, ecological, socio-cultural and economic benefits (Newcastle City Council, 2015).

5.2.1 HISTORICAL EVIDENCE

When dealing with damage assessment, data collected are often related to the physical loss, such as material surface damages (Okuyama and Santos, 2014). However, losses associated with non-physical damages (*e.g.* the number of interrupted links) could have a higher impact on the urban environment (Gehl and D 'Ayala, 2016). To calculate these indirect losses requires quantification of baseline conditions as well as perturbed conditions. In the case of transport systems this can be measured in terms of traffic flows.

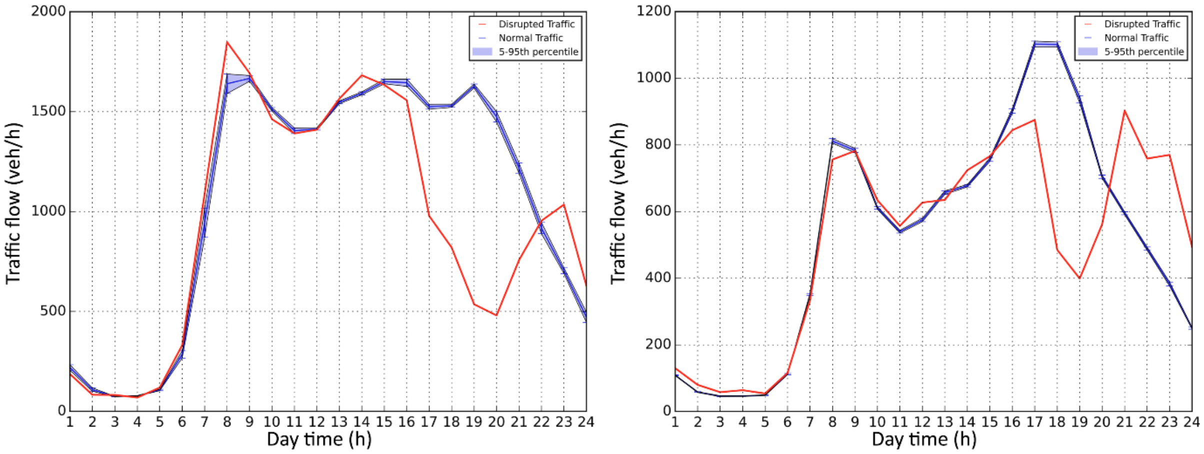
To obtain baseline traffic flows, hourly traffic flows on major road links, recorded by the Tyne and Wear Road Traffic and Accident Data Unit (TADU) by Automatic Traffic

Counters (ATCs) and stored in the Traffic Information Database (TRADS), have been used. Nine ATCs were active and providing useable data within the Newcastle City Council boundary (an area of 114 km^2, see Figure 5-1 for locations) on the 28th June 2012 and these are displayed as the red line in Figure 5-2. Baseline conditions were estimated using a total of 486 records acquired from TRADS database for Thursdays (of the months April, May, June, July) for the three years prior to the year 2012. Averages and 5th and 95th percentiles are displayed in blue to be compared to the perturbed flows (red) in Figure 5-2.



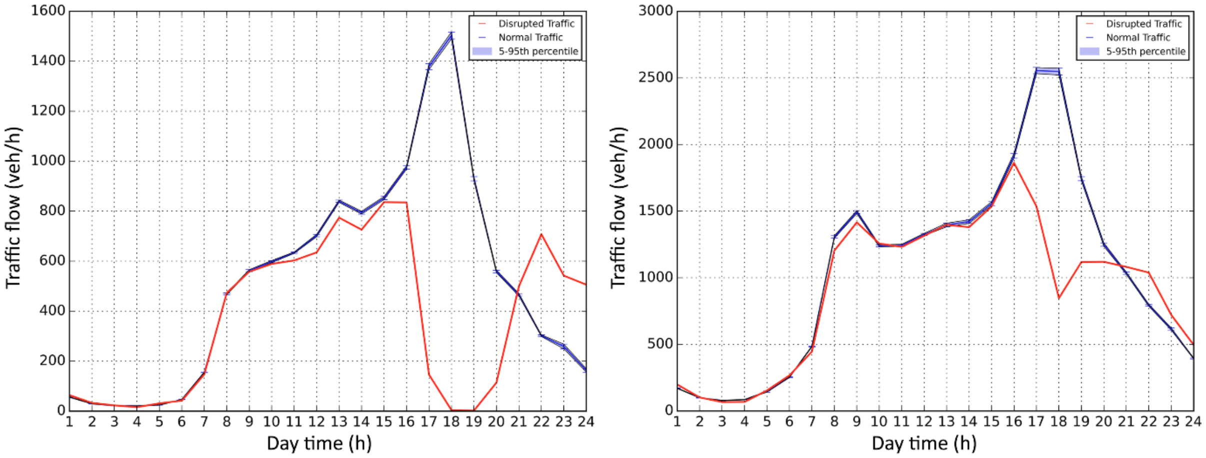
(a) GREAT NORTH Rd. (B1318)

(b) COAST Rd. (A1058)



(c) A167 Tyne Bridge

(d) A167 Southbound



(e) A695 Westbound

(f) A167 Westbound

Figure 5-2. Comparison of traffic flows (red) at six locations (measured in cars counted by each sensor per hour) on Thursday 28th June 2012 with a baseline (blue) established by the 5th-95th percentiles of traffic observations from all Thursdays, outside of school holidays from the preceding 3 years: (a) at the Great North Rd; (b) at the Coast Rd.; (c) at the Tyne Bridge;; (d) at the A167, Southbound; (e) at the A695, Westbound; (f) at the A167, Westbound.

The pattern of the ATCs data resembles the diurnal cycles of passenger car observations from other studies (Venegas *et al.*, 2011; FHWA, 2013; Roh *et al.*, 2013). Figure 5-2 shows a clear indication that traffic is impacted by flooding, as compared to average flow on Thursdays over the previous three years (of the months April, May, June, July), and that adverse weather triggers network performance. Six ATCs (on nine) were within the hazard boundary of the studied domain, and were used for data analysis and validation.

Regarding this data analysis, only the 60% of all Thursdays in the last three years for the considered months could be used to make a comparison with the "Toon Monsoon" event (Thursday the 28th June 2012). This because a proportion fell inside school holiday which have very different diurnal traffic patterns, whilst other days were affected by roadworks, public holidays, major sporting events, or a sensor failure. The pie chart (Figure 5-3) shows the proportion of the useful information, with respect to the total and the range of disregarded data.

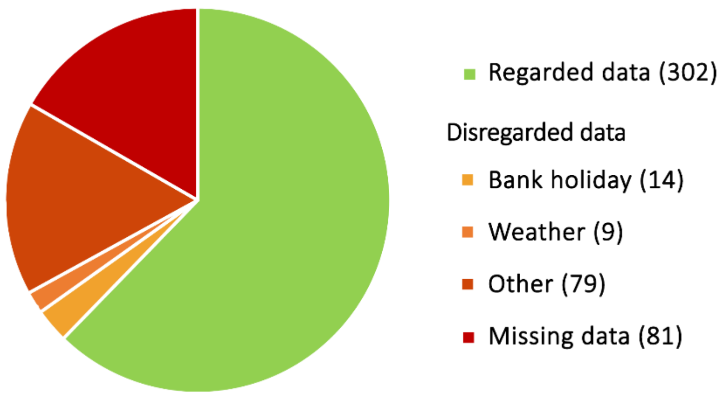


Figure 5-3. Analysis of the observations used from the TADU database. Only the 62% was suitable for processing, due to missing values and o issues. When information were not available for one sensor, date were removed from this individual sensor only and not from all.

The TRADS database stores a relevant amount of information, however downloading and handling data from it was not straightforward. The data were acquired as Excel files, one per week, showing hourly traffic volume for each day, and a script was developed in Python to undertake the analysis.

During the Toon Monsoon, one weather station (see Figure 5-1 for location) offers data that is geographically compatible with the ATCs records. Figure 5-4 plots the difference between traffic flows from baseline and flood-disrupted events, and also shows the time-series of rainfall intensity.

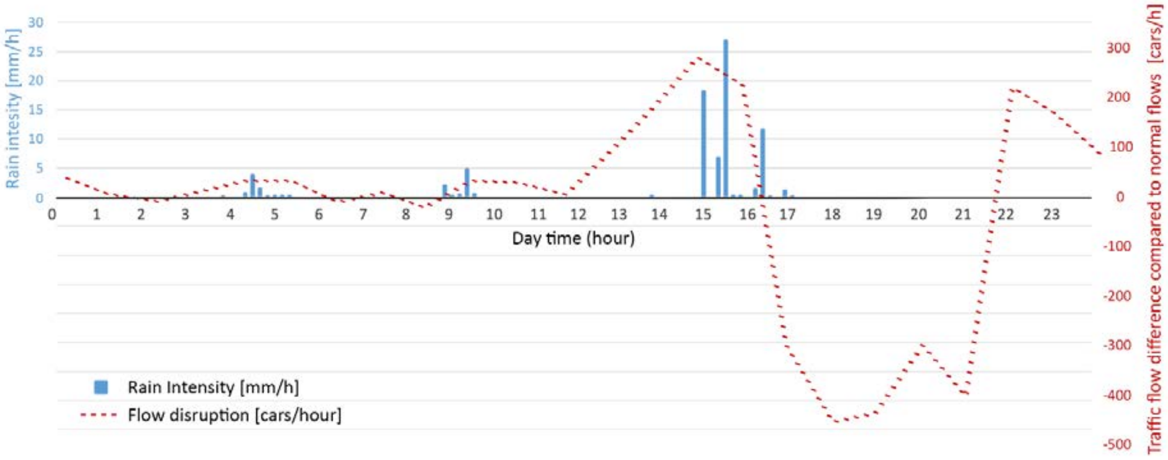


Figure 5-4. An example of rainfall record from the weather station on the Great North Road, plotted together with the variation of the traffic flow during the 28thJune 2012. Weather conditions can be considered homogenous for small cities.

The event started at 3pm, with intensity peaking half an hour later. The total rainfall within 2 hours was approximately equal to the average monthly rainfall. Interestingly, traffic volume shows a distinct increase of almost 300 vehicles per hour prior to, and peaking at the start of, the storm period. This storm was tracking from West to East across Great Britain and had already led to flooding elsewhere, and so this rise probably reflects those people who received and were able to act upon the weather forecast. An hour after the event started, just as the evening rush hour for commuters was beginning, traffic flows plummeted relative to the baseline as storm drains filled and rainfall pooled on the roads. As the accumulated surface water began to drain away traffic flow increased relative to the baseline as traffic started flowing smoothly, and people who had not tried to return home earlier took to the road. This confirmed that rainfall and flooding have different timeframe and type of impacts on the transport network.

5.3 MODEL OVERVIEW AND APPLICATION

The modelling framework (see Chapter 3) couples simulations of flooding and transport to calculate the impacts of disruption, using a transport function to relate flood depth to vehicle speed. The model simulates journeys across a transport network, defined by spatial data of links and nodes, using generalized cost of travel to assess the shortest route between an origin and destination. An effective metric to prioritize intervention options in the road network, *i.e.* a criticality index, has been developed by means of a risk matrix. A range of intervention options are tested for those locations, and a cost-benefits analysis is advanced in order to support improved business cases for adapting urban infrastructure to flooding. The framework is demonstrated on Newcastle-upon-Tyne, assuming the city and its common features are a suitable representative for middle-size UK cities.

5.4 HAZARD SIMULATION

A hydrological analysis was undertaken for the area of Newcastle to identify the surface water flow paths, and their sub-catchments, that contribute to flooding within the administrative boundary. ESRI's ArcGIS Hydrology Tool (see Section 3.3) was used to delineate the sub-catchments. The sub-catchment division was fundamental to identify the required domain of the hazard simulation, and the hierarchy of the stream links enabled understanding of flow directions and flood dynamics (Figure 5-5).

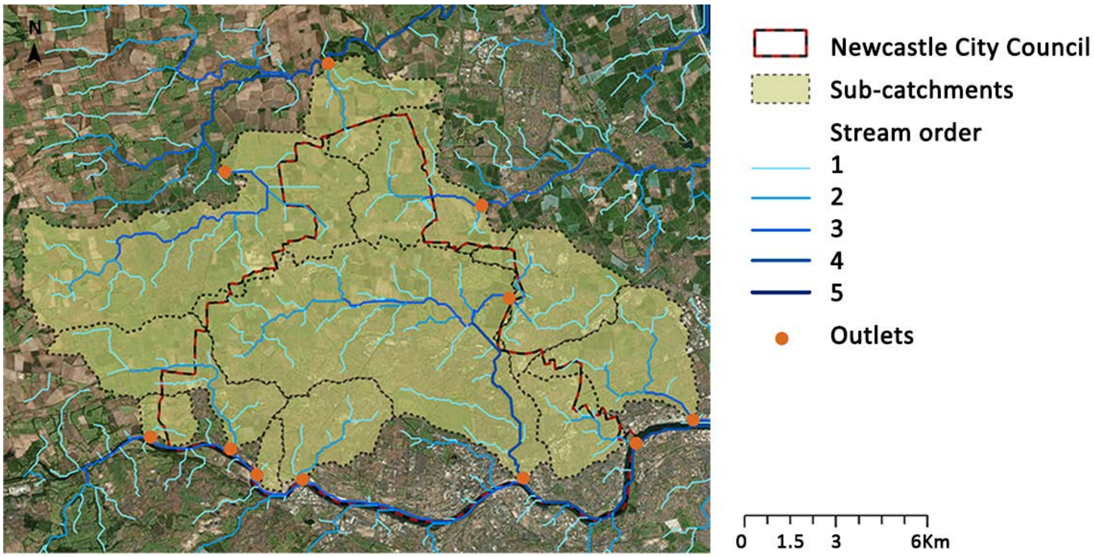


Figure 5-5. Analysis of the division in sub-catchments for the area of Newcastle, with relative stream order classification. The sub-catchments whose outlet is within the area of Newcastle defined the domain.

The hazard simulation involved in developing a range of flooding scenarios for different rainfall intensities (defined through depth-duration-frequency curves, see Section 2.3.3). Simulations of 60 minutes were undertaken for five return periods (*T* = 2, 10, 50, 100 and 200 years, that correspond to the occurrence probability of 0.5, 0.1, 0.02, 0.01 and 0.005). Although pluvial flood events can be longer than 60 minutes, this is a typical design standard as noted in Section 2.3.3.

Table 5-1. Overview of the simulated hazard events for the case study. These events were simulated using the software CityCAT.

Event	Return period	Occurrence probability	Duration
H1	2 years	0.5	60 minutes
H2	10 years	0.1	60 minutes
H3	50 years	0.02	60 minutes
H4	100 years	0.01	60 minutes
H5	200 years	0.005	60 minutes

2D simulations were undertaken using the hydrological model CityCAT (City Catchment Analysis Tool), developed by Newcastle University (Glenis *et al.*, 2013; Kutija *et al.*, 2014). This software captured the movement of the water influenced by the natural elevation of the terrain and by land use properties (including factors such as the location of streets, buildings and permeability), by solving the shallow water equations using the method of finite volumes with shock-capturing schemes (Godunov, 1959; van Leer, 1979; Harten *et al.*, 1983) and a uniform propagation of the rainfall time-series. The overland flow component is based on the solution of the full shallow water equations, obtained using the finite volumes method. The Green-Ampt method is used to estimate the infiltration over the pervious areas as a function of the soil hydraulic conductivity, porosity and suction head; representing lateral flows is an extremely difficult task that CityCAT does not account for (and no flood models can do that at present) (Glenis *et al.,* 2017).

In order to provide rapid analysis of urban hydrodynamics for large areas, CityCAT was deployed on the Microsoft Azure Cloud platform. Input and output data are summarised in Table 5-2.

Table 5-2. Input and Output data for the urban flood model CityCAT

INPUT	**Data**	**Sources**	**File type**
	Rainfall	Derived from FEH manual	ASCII
	DEM (4m resolution)	Environment Agency	Raster
	Buildings footprint	OS MasterMap	Shapefile
OUTPUT	**Data type**	**Software**	**File type**
	Time series of water depths	CityCAT	ASCII
	Time series of water velocities	CityCAT	ASCII

Simulations adopted a resolution of 4 m, *i.e*. each cell measured 4x4m which has previously (Glenis *et al.*, 2013) been found to provide an appropriate balance between accuracy and computational expense for simulations of a large domain, typical of transport analysis. For this setting, the run-time was of 24 hours.

The features of the built environment were extracted from the OS MasterMap data, defining roads and buildings. In particular, the effects of buildings were considered as obstacle the flow. The cells of the building footprint were excluded from the numerical domain and kept in the "buildings layer" as objects; the rain falling onto this layer was redistributed to the neighbouring cells of the building boundaries. Roads were considered as impermeable surfaces, indeed their cells had the permeability coefficient equal to 1 (Kutija *et al.*, 2014; *Glenis et al.*, 2017).

The software generated flood maps, with snapshots of water depth and velocity maps at different time-steps, for all the cells in the grid domain and for each scenario. Example of flood maps are shown in Figure 5-6, for two different return periods.

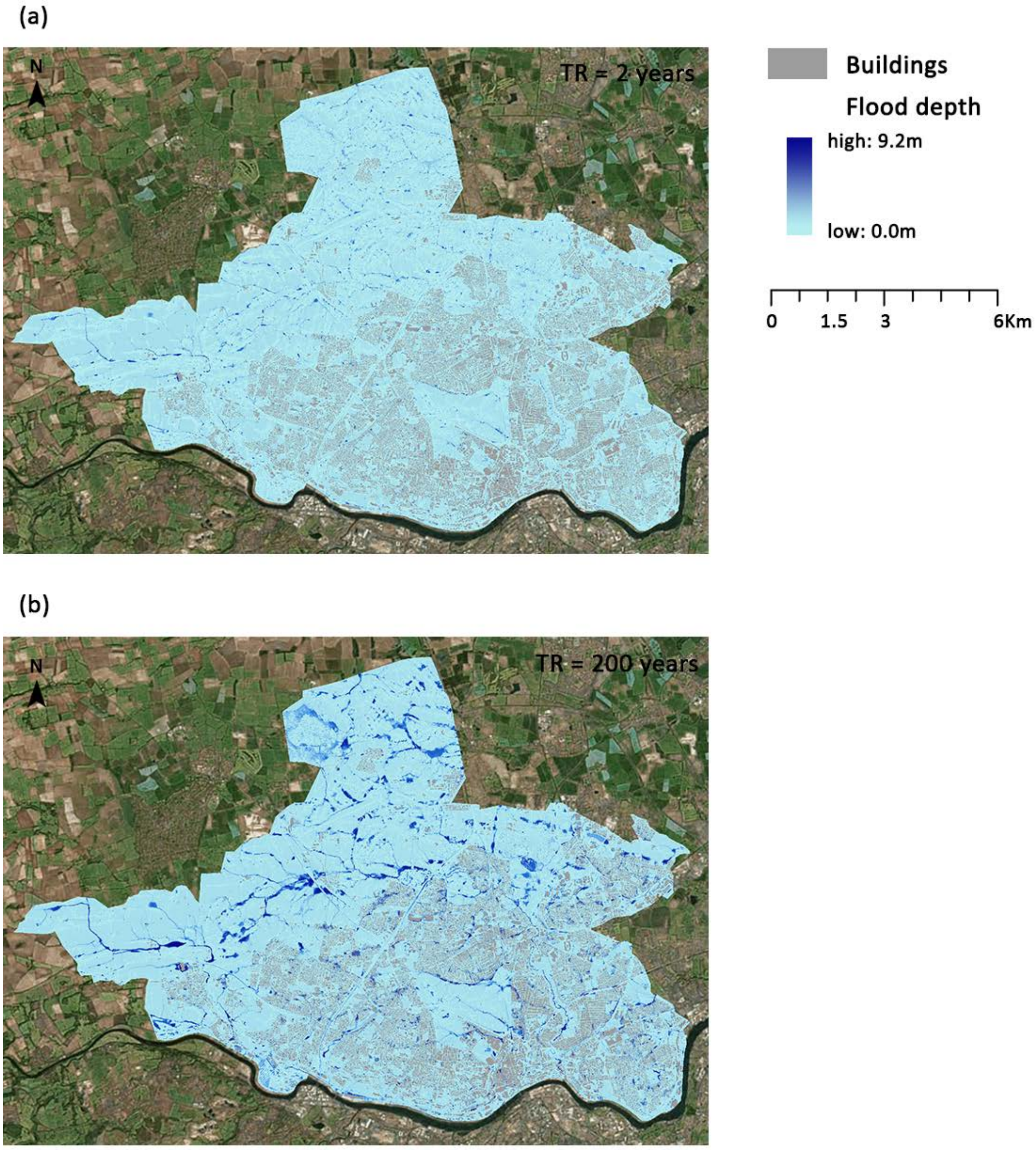


Figure 5-6. Inundation map in terms of flood depth for the domain for: (a) H1: 1-in-2-years event (probability of occurrence 0.5 in any given year), and (b) H5: 1-in-200-years event (probability of occurrence 0.005 in any given year). Differences are present both in the magnitude and in the extent of the flood footprint.

5.5 TRANSPORT MODELLING

The transport model was developed using the rationale outlined in Section 3.4, by simulating the road network of the Newcastle area in a GIS-based origin-destination matrix method model. When the model simulates journeys across a transport network, the free flow speed on the links are defined using classes from the UK COst Benefits Analysis (COBA) model (DfT, 2004c; see Section 2.5.3) inferred from attributes in Ordnance Survey MasterMap data. All the input data are specified in Table 5-3. Census data were used for the assignment of Journey-to-Work trips for the region of Tyne and

Wear, using the iterative assignment routine, in order to assess the number of users along any road in the network.

Table 5-3. Input and output data for the transport model, based on an origin-destination matrix method.

INPUT	**Data**	**Sources**	**File type**
	OS MasterMap	ITN network data	Shapefile
	ONS Census	Commuting trips data	csv
	COBA	COBA classes	csv
OUTPUT	**Data type**	**Software**	**File type**
	Commuting time (baseline)	ArcGIS	csv
	Commuting length (baseline)	ArcGIS	csv

A number of transport processes are represented at reduced complexity to ensure the model is computationally efficient, as outlined in Section 3.4.2.

The transport model was applied to simulate all commuting journeys across the metropolitan county of Tyne and Wear (538 km^2). Middle-level Super Output Area (MSOA) population-weighted centroids for the 2011 UK census (from the Office for National Statistics, UK) were used as origins and destinations for a total of 43,681 of these journeys (see Figure 5-7), with routes computed for baseline and flood conditions. The runtime of a simulation was in the range of minutes. Following the same process as Ford *et al.* (2015), the model was validated for baseline conditions against census journey flows and observations (see Section 5.7.2).

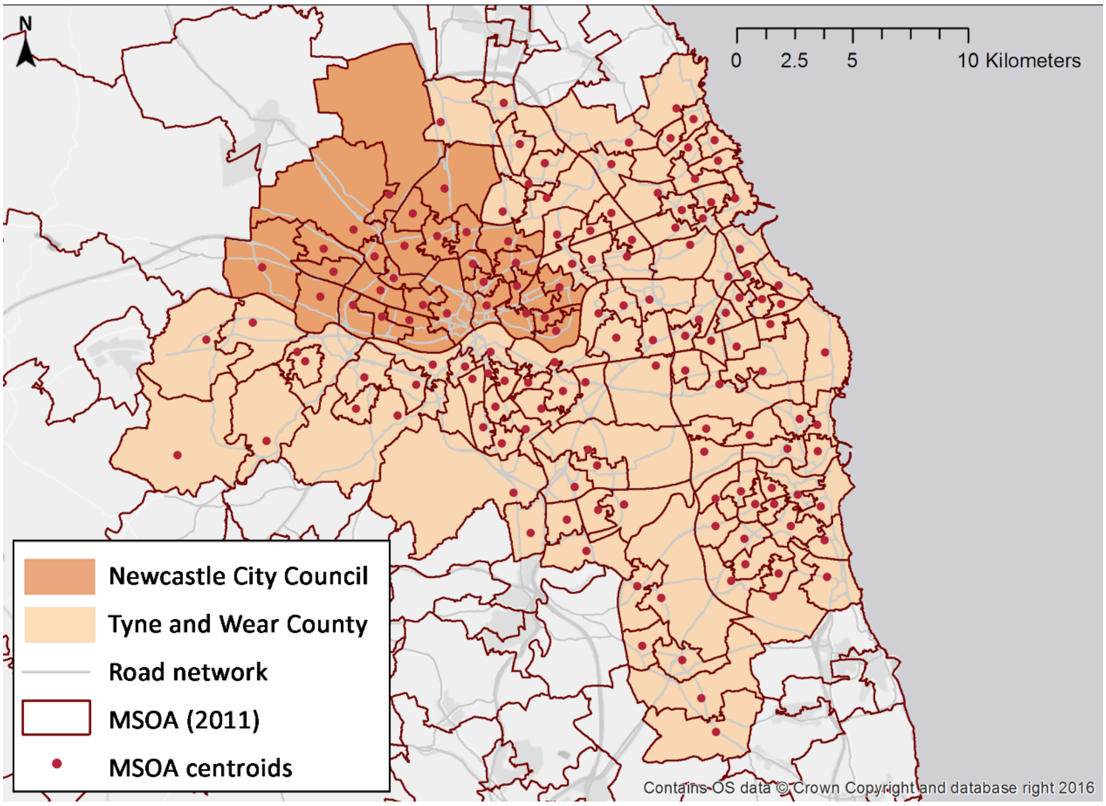


Figure 5-7. The 2011 Middle layer Super Output Areas 2011 of Newcastle upon Tyne and the surrounding area of Newcastle simplified in wards and centroids, and the road network from OS MasterMap data.

5.6 IMPACT MODELLING

The impact of a range of flood events, including those similar to the 28th June 2012 storm, on the road network were assessed for the whole urban system.

First, the flood footprints were overlaid on the network, in order to quantify the depth of flood water on the road links. This is useful to identify the roads that are likely to be closed due to flooding, and the ones in which flooding is causing higher speed reduction (Figure 5-8).

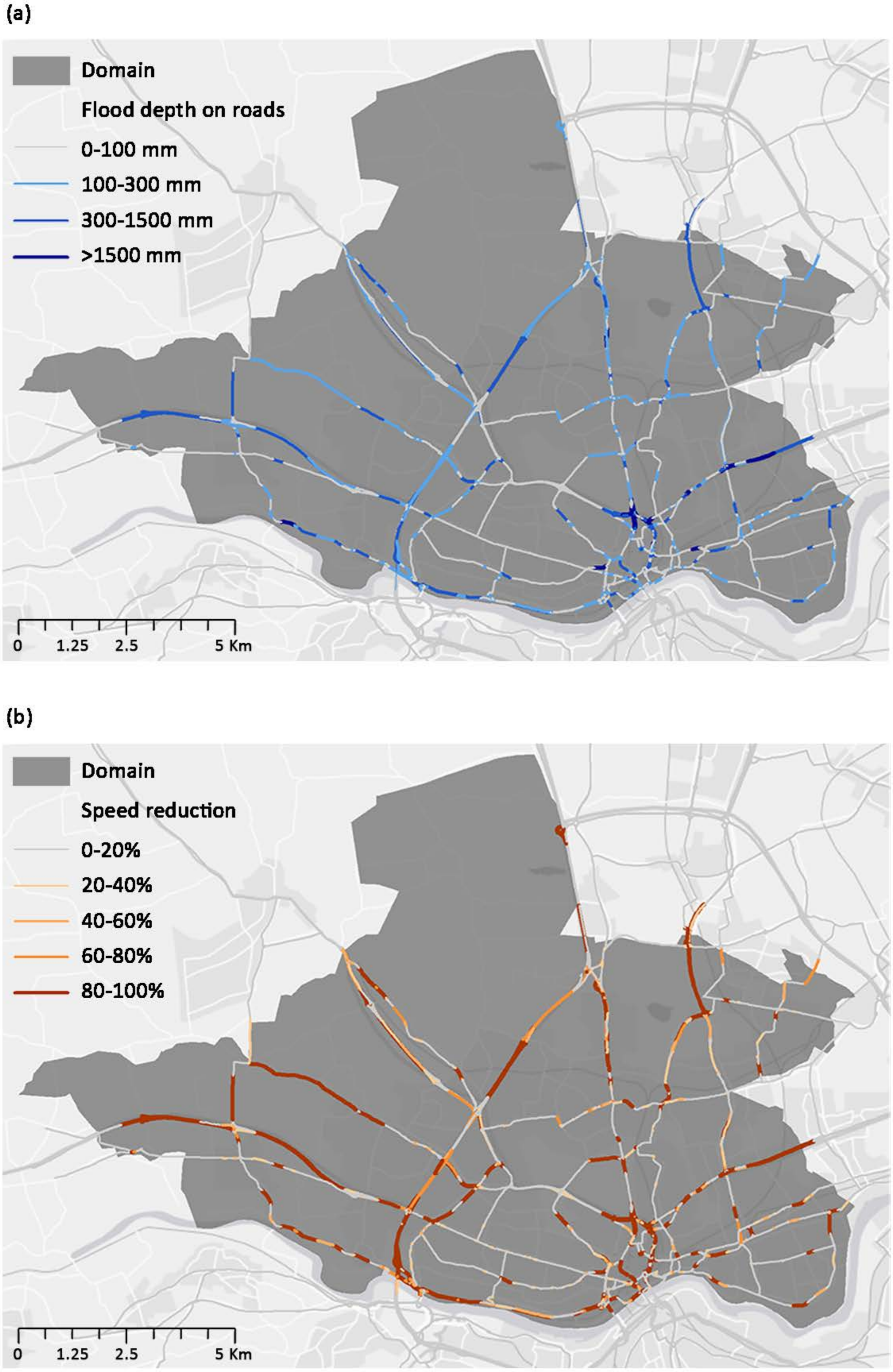


Figure 5-8. Example of map for the most extreme and impactful event (*T*=200), showing: (a) the water depth on road links; (b) the speed reduction due to that water depth.

By using the threshold of 300 mm (see Section 4.6), the increasing impact of the hazard is highlighted by an increase in the percentage of roads affected by flooding (Figure 5-9).

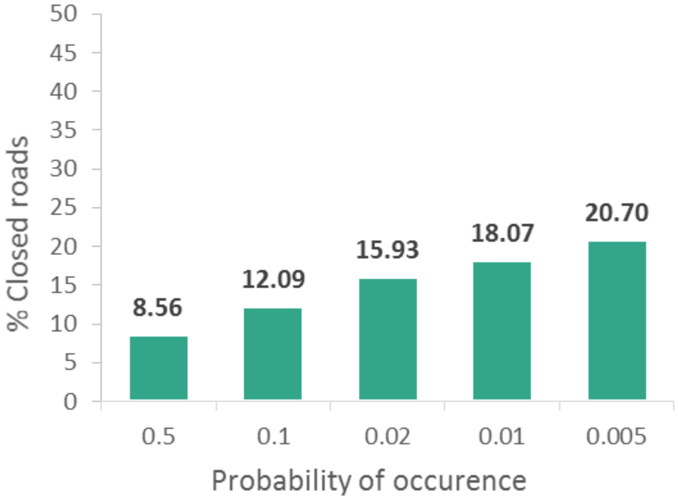


Figure 5-9. Bar chart showing the percentage of completely closed roads on the whole Newcastle network, for a range of flood events.

Below 300 mm, the impact of flooding in terms of indirect damage was considered by integrating the depth-disruption vulnerability function with information on the flood hazard to recalculate (lower) traffic speeds. This involved translating flood depth, via the transport network model, into journey travel time increase and ultimately an economic cost.

5.6.1 HOTSPOTS AND SCENARIOS IDENTIFICATION

The criticality matrix (see Section 3.6.2) was applied to identify and rank the criticality of road stretches in Newcastle's road network (Pregnolato *et al.*, 2016). The six most critical, where the combination of exposure (*i.e*. traffic flow) and hazard (*i.e*. water depth) is in the highest category, were selected for analysis of adaptation options. Road stretches can comprise a number of neighbouring links and nodes (for example, the intervention would protect more than just one spur of a roundabout). These stretches, shown in Figure 5-10, in order of criticality are:

- A: main A1 road bypassing the city to the west;
- B: section of the Coast Road (A1058), the main route entering the city from the east;
- C: convergence of A167, Great North Road (B1318) and the Coast Road (A1058);
- D: further section of the Coast Road;
- E: A167 Central Motorway, the main route through the city centre; and,
- F: A167 Central Motorway, north-west section.

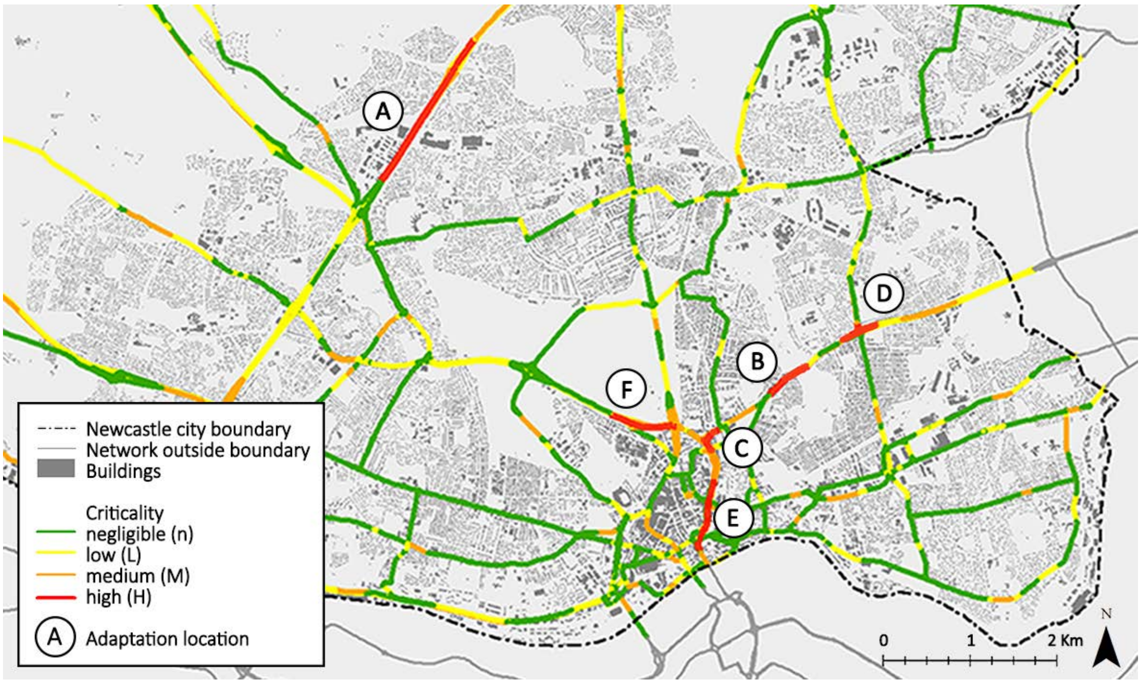


Figure 5-10. Location of the critical links in Newcastle upon Tyne's road network, identified using the criticality matrix in Table 3-7.

Eleven different scenarios of grey adaptation were considered (see Table 5-4) and simulated using the modelling framework in Section 5.7.1.

Table 5-4. The simulated scenarios to study options of grey adaptation in the urban environment of Newcastle.

adaptation scenarios	no. link hardened
LH_A	1 (A)
LH_B	1 (B)
LH_C	1 (C)
LH_D	1 (D)
LH_E	1 (E)
LH_F	1 (F)
LH_AB	2 (A, B)
LH_ABC	3 (A, B, C)
LH_ABCD	4 (A, B, C, D)
LH_ABCDE	5 (A, B, C, D, E)
LH_ABCDEF	6 (A, B, C, D, E, F)

Initially, each of the six options were tested independently (*i.e.* LH_A, …, and, LH_F). Five more scenarios considered the cumulative effect of adaptation portfolios that included increasingly critical link (*i.e.* LH_A, LH_AB, … , and, LH_ABCDEF).

5.6.2 DAMAGE MODELLING AND RISK ANALYSIS

A baseline transport scenario was initially generated, by running the transport model using the Newcastle network under normal settings (*i.e.* non-perturbed speeds defined by the COBA speed/flow curves, see Section 2.5.3). In a second stage, for every hazard scenario the speed reduction was estimated for the road network according to the vulnerability curve, and a perturbed system was built. The uncertainty bounds in Figure 4-3 capture a range of vehicle sizes, but with incomplete information on vehicles in Newcastle and their individual routes, the central estimate of the depth-disruption function has been applied to each road link.

By overlaying the water depth from flood simulations onto the road network, vehicle speeds and subsequently journey travel times were recalculated. Disrupted journeys were calculated for every pair of origins and destinations across the network, and results were computed by aggregating all of the delays to each passenger journey across the network domain.

Using the census Journey-to-Work data, the individual delay for journeys between each pair of locations were multiplied by the observed number of commuting trips between those points, obtaining the Person Hour Delay (PHD) for those journeys (see Equation 3-4). This captures the wider effects of the delay to transport links, weighting the delay to journeys by the number of people currently using those portions of the transport network. The PHDs, due to rerouting and speed reduction, were used to compare the impacts of scenarios, in order to assess the severity of the simulated events.

5.6.3 COST ASSESSMENT

The additional time required by journeys as a result of flood disruption can be can be equated to an economic cost, using a Value of Time (VoT) conversion, as outlined in Section 3.8.1. Results for the disruption scenarios with no adaptation (NA) are summarized in Table 5-5.

Table 5-5. The Person-Hour-Delays (PHD) and relative damages associated to the No-Adaptation (NA) scenarios. Costs were computed using the Value of Time (VoT) for commuters.

NA		
scenario	**PHD**	**damage**
H1	6766	£46,076
H2	13650	£92,954
H3	19446	£132,424
H4	23716	£161,506
H5	32363	£220,390

The relationship between PHD (people per hour) and damage (£) is not linear since non-linear is the relationship between flood depth and return period: a series of factors (green areas, runoff patterns, etc.) intervened in the process. Moreover, the transport network is a system and the flood impact on this related to the complexities proper of a networked asset (*e.g*. links importance, interdependencies between nodes).

The costs for each flooding event were calculated by computing the overall city-wide impact on the network applying Equation 3-6.

5.7 ADAPTATION

After considering the impact of a range of flooding scenarios, adaptation scenarios were evaluated. Low-complexity adaptation scenarios were identified on the basis of *(i)* the city council and stakeholders interests; (ii) the exploratory nature of this study.

When parameters in the model were modified to include the adaptation scenarios (see Section 3.8.2), traffic flows were recalculated, and disruptions assessed in terms of additional journey time and delays. This allowed an assessment of the effectiveness of one or more adaptation options in reducing network-level disruption from flooding.

The benefit of climate adaptation actions are usually realised over multiple years. The Net Present Value (NPV_r) of the benefits in terms of risk reduction (see Equation 3-8) was used to understand which strategy was more cost-effective, considering also the repayment time, the Return on Investment (ROI) and the initial intervention cost of each option.

Possible adaptations for link hardening include the installation of stormwater attenuation tanks, which could be provided by storm crate systems or underground tanks that manage surface water runoff. Data from a number of companies offering such systems has been collected, showing costs of around £100 per m^3 of water to be removed including excavation works and delivery cost. The cost of holding the volume of water that drains onto the road stretch (calculated from the flood model) is considered as initial investment capital cost, although these do not include maintenance costs which were not available. Regarding blue-green solutions, an average cost for normal and green roof installation has been found in the literature (Royal Haskoning, 2012) and confirmed by other sources (Keating *et al.*, 2015), equal to £93/m^2 and £63/m^2 respectively; for this research, the cost of the difference has been used (£30/m^2), considering the implementation of the strategy within planned maintenance and/or upgrades. An indicative cost for retention basins (£15-£25/m^3) was found in the SUDs manual by CIRIA (Woods Ballard *et al.*, 2015).

Input and output for the adaptation analysis are given in Table 5-6.

Table 5-6. Input and output data for the adaptation modelling.

	Data	**Sources**	**File type**
INPUT	Storm crates cost	Various company	na
	Green roof cost	Royal Haskoning (2012)	pdf
	Retention basin	Woods Ballard *et al.* (2015)	pdf
OUTPUT	**Data type**	**Software**	**File type**
	Adaptation cost	Excel	csv
	Net Present Value	Excel	csv
	Repayment time	Excel	csv

5.7.1 GREY ADAPTATION

The model was used to calculate the damages associated with the delays when the links (identified in Section 5.6.1) were protected from flood events up to a 1 in 200 year standard by: *(i)* considering them in isolation, or *(ii)* in series, within an increasing degree level of adaptation. An overview of the results is offered in Table 5-7.

Table 5-7. The Person-hour-Delays (PHD) and relative damages due to flooding impact for each scenario. Damage costs were computed using the Value of Time (VoT) for commuters.

GREY ADAPTATION: SINGLE INTERVENTIONS												
scenario	LH_A		LH_B		LH_C		LH_D		LH_E		LH_F	
	PHD	damage	PHD	damage	PHD	damage	PHD	damage	PHD	damage	PHD	damage
H1	4515	£ 30,747	6150	£ 41,882	6737	£ 45,879	6733	£ 45,852	6707	£ 45,675	6712	£ 45,709
H2	9265	£ 63,092	11987	£ 81,631	13517	£ 92,051	13615	£ 92,718	13515	£ 92,037	13635	£ 92,854
H3	14637	£ 99,680	17727	£ 120,721	19161	£ 130,486	18885	£ 128,607	19364	£ 131,869	19442	£ 132,400
H4	17244	£ 117,432	21921	£ 149,282	23422	£ 159,504	23150	£ 157,652	23621	£ 160,859	23710	£ 161,465
H5	20617	£ 140,400	30526	£ 207,882	32099	£ 218,594	32264	£ 219,718	32264	£ 219,718	32356	£ 220,344

GREY ADAPTATION: COMBINED INTERVENTIONS												
scenario	LH_A		LH_AB		LH_ABC		LH_ABCD		LH_ABCDE		LH_ABCDEF	
	PHD	damage	PHD	damage	PHD	damage	PHD	damage	PHD	damage	PHD	damage
H1	4515	£ 30,747	3953	£ 26,921	3880	£ 26,423	3862	£ 26,302	3730	£ 25,401	3344	£ 22,772
H2	9265	£ 63,092	8066	£ 54,929	7783	£ 53,002	7746	£ 52,750	7406	£ 50,435	6850	£ 46,649
H3	14637	£ 99,680	13160	£ 89,620	13160	£ 89,620	12586	£ 85,711	12461	£ 84,859	12256	£ 83,463
H4	17244	£ 117,432	15630	£ 106,440	15630	£ 106,440	15043	£ 102,444	14906	£ 101,511	14599	£ 99,417
H5	20617	£ 140,400	18920	£ 128,845	18920	£ 128,845	18296	£ 124,596	18158	£ 123,656	17726	£ 120,714

The cost of adaptation varies according to the number of locations protected, and on the volume of water storage required to protect it. The results also demonstrate that the scale of impacts are not directly proportional to the number of interventions, but a function of more complex properties of the flooding-transport system. For example, for the worst case scenario (H5: 1-in-200-years event) the difference between implementing one or three interventions is 9.2%.

For the scenarios that combine the protection action of multiple nodes, the benefits brought by adaptation were considered in light of the initial capital investment (needed for the realisation of the intervention) and of the repayment time from this investment. The addition of individual adaptation measures provides benefits but these are much higher for the two most critical stretches of road than the other four locations.

The NPV_r for the combined scenarios is shown in Table 5-8 and underlines that even just one intervention could significantly alleviate the impact of flooding, if the location has been correctly identified.

Table 5-8. The Net Present Value in terms of risk reduction (NPVr; discount rate = 3%) for the six scenarios in which the network has been made more robust to flooding; the Return on the Investment (ROI) and the repayment (payback) time give respectively the amount and the timeframe of the economic risk.

adaptation scenario	intervention cost	ROI %	NPV_r	payback time
LH_A	£717,336	746%	£5,353,318	after 3.7 ys
LH_AB	£919,284	711%	£6,535,173	after 3.9 ys
LH_ABC	£1,276,732	517%	£6,599,462	after 5.5 ys
LH_ABCD	£1,520,408	455%	£6,920,655	after 6.4 ys
LH_ABCDE	£1,801,076	394%	£7,088,859	after 7.5 ys
LH_ABCDEF	£2,365,464	314%	£7,429,349	after 9.6 ys

The return in terms of reduced risk improves as more intervention options are considered, although it takes longer to realise the return on investment. From these results it is even evident that intervening across the entire road network is not recommended, both for repayment time and initial investment. For instance, the LH_ABCDEF scenario brings a slightly additional benefit with respect to LH_AB, however both initial costs and repayment time are almost three times higher. Overall, the net benefit that accounts for the initial capital costs is greatest for just two interventions (LH_AB).

A number of complexities are also highlighted in the results, demonstrating the need for system-level analysis of the transport network. For example, hardening Links A, B, and C provides the same benefit as hardening just A and B, because Link C feeds directly into Link F. Any benefit from hardening Link C is only returned if Link F is also hardened. Particularly effective is the hardening of Link A, the strategically important city bypass road. This is most beneficial for more extreme events, because a number of alternative high capacity routes remain open during less severe events, therefore avoiding this road during such events is a possibility for drivers. Under more extreme events those alternative routes also become severely disrupted and thus protecting Link A becomes a more effective option once more.

5.7.2 GREEN ADAPTATION

Two adaptation strategies were tested against the five hazard events to explore the effectiveness of blue-green infrastructure within adaptation: the installation of green roofs and of retention basins (for labels, see Table 5-9).

Table 5-9. Adaptation scenarios tested for blue-green strategies.

adaptation scenario	adaptation type
GR	green roof
RB	retention basin

For the first option, each roof in the city is assumed to have a 50 mm of depth. The roof storage delays the release of rain water onto the urban surface, reducing both peak flow rates and total runoff volume of rainwater (Figure 5-11a). The cells of the building footprint were kept as object by the flood model and were used for simulating roof retrofitting. When roof storage is specified, then the rain falling onto the buildings layer is accumulated until the water depth on the roof reaches the specified storage depth (50 mm). Any further rainfall is redistributed to the neighbouring cells of the overland flow domain.

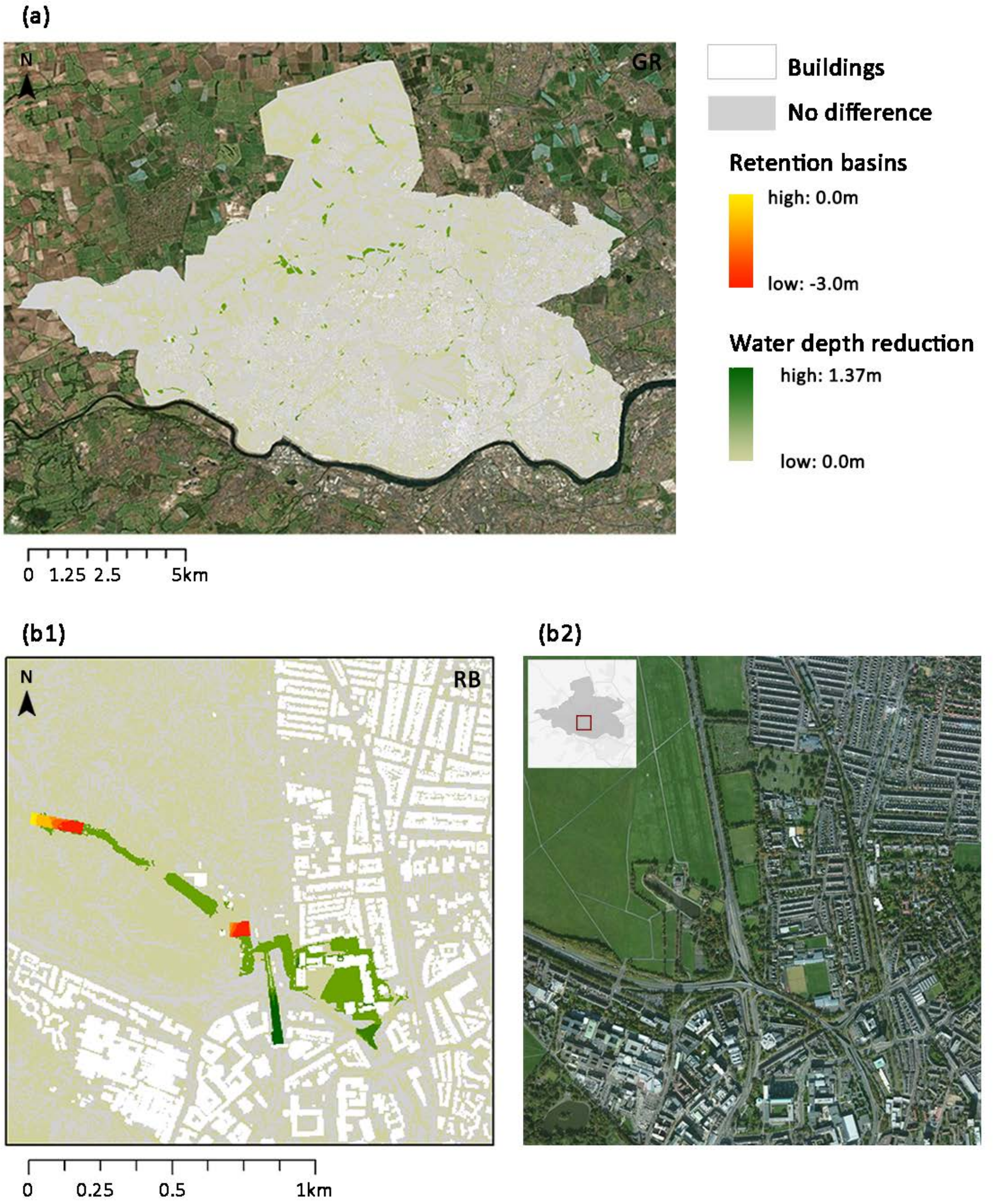


Figure 5-11. Raster maps showing the water depth difference between the normal flood simulation and simulations including (a) green roofs or (b1) retention basins; (b2) satellite map showing the area of the retention basins, with the Town Moor.

The Town Moor at the North of Newcastle is flood-prone common land close to critical stretches of road (Lomax *et al.*, 2011). This was identified as a suitable location for the installation of retention basins. Two ponds were designed to be of sufficient size to store the water volume present at the intersection between nodes F and C (Great North Rd. and main highway) during extreme flooding scenarios. This was done in the model by modifying the DEM, input of the flood model, for the areas of the retention basins. The basins reduced the quantity of floodwater (see Figure 5-11b1), however they were not sufficient to reduce the flood depth below the 300 mm threshold that would allow any passage of vehicles (see Chapter 4). This was due to the contribution of multiple runoff sources (see Section 6.2), that could not be intercepted by the ponds.

The intervention was not at all cost effective, since although flood depths are reduced, the transport disruption damages due are almost equal to those without adaptation (see Table 5-5 compared to Table 5-10).

Table 5-10. The Person-hour-Delays (PHD) and relative damages associated for the green adaptation scenarios. Damages were computed using the Value of Time (VoT) for commuters (GR is Green Roof; RB is Retention Basin).

GREEN ADAPTATION				
hazard scenario	**GR**		**RB**	
	PHD	**damage**	**PHD**	**damage**
H1	5136	£ 34,976	6755	£ 46,002
H2	10321	£ 70,286	13649	£ 92,950
H3	16113	£ 109,730	19442	£ 132,400
H4	18702	£ 127,361	23711	£ 161,472
H5	23336	£ 158,918	32361	£ 220,378

The simulation for these two adaptation options underlined that: *(i)* the benefits brought by the installation of retention basins is almost null (see Table 5-11); and *(ii)* the installation of green roofs makes a substantial difference on the flooding impact, comparable to grey adaptation. Therefore, the cost-benefit analysis was advanced for the latter option only.

Table 5-11. Comparison between the simulated benefits for the different hazard scenarios. The benefits associated with the installation of retention basins (RB) are almost null, whereas the presence of green roofs (GR) brings a relevant contribution to flood alleviation in Newcastle.

benefit (per event)								
hazard scenario	**GR**	**RB**	**LH_A**	**LH_B**	**LH_C**	**LH_D**	**LH_E**	**LH_F**
H1	£11,100	£75	£15,329	£4,195	£197	£225	£402	£368
H2	£22,668	£4	£29,862	£11,323	£903	£236	£917	£100
H3	£22,694	£24	£32,744	£11,703	£1,938	£3,817	£555	£24
H4	£34,145	£34	£44,074	£12,224	£2,002	£3,854	£647	£41
H5	£61,472	£11	£79,990	£12,508	£1,796	£672	£672	£45

Looking at the benefits of adaptation, green roofs represent the second best option after the hardening of Link A (the most critical stretch of A1). However, the hypothesis of retrofitting every roof of the city is not realistic, from both a feasibility point (*e.g.* structural issues) and capital cost of intervention (hundreds of millions of pounds), as outlined in Table 5-12.

Table 5-12. The results of intervention cost and NPV$_r$ for the green roof scenario, considering a timeframe of 50 years. Clearly, a capital cost of intervention of approximately £440m is not feasible nor realistic. This was due to the simplistic hypothesis to consider a futuristic Newcastle with 100% of green roofs.

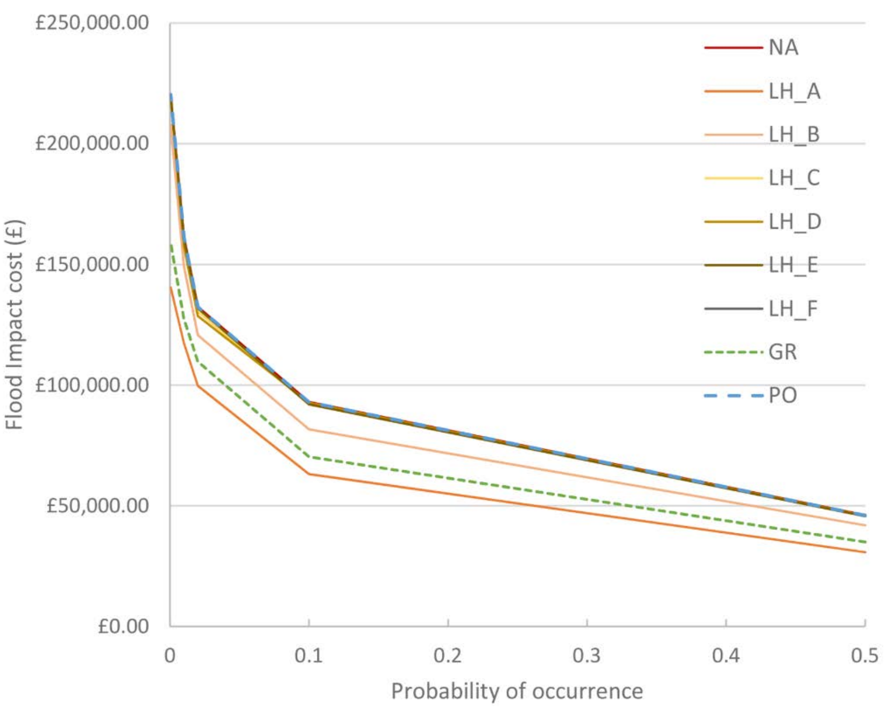
adaptation scenario	intervention cost	ROI %	NPV$_r$	payback time
GR	£61,455,689	7%	£4,030,363	never

Nevertheless, green roofs include a series of co-benefits (biodiversity, heat island or pollution reduction, etc.) that are not accounted for in this analysis and could strongly contribute to the quality of the built environment (Everett *et al.*, 2016).

5.8 KEY RESULTS AND SUMMARY

Chapter 5 implemented the modelling framework and the depth-disruption function, outlined in Chapter 3 and Chapter 4 on a case study in Newcastle upon Tyne in the UK. An analysis of the impacts and benefits of adaptation for a range of hazard scenarios was undertaken, looking at the effectiveness of the different solutions. The implications of this work are discussed in Chapter 6.

(a)



(b)

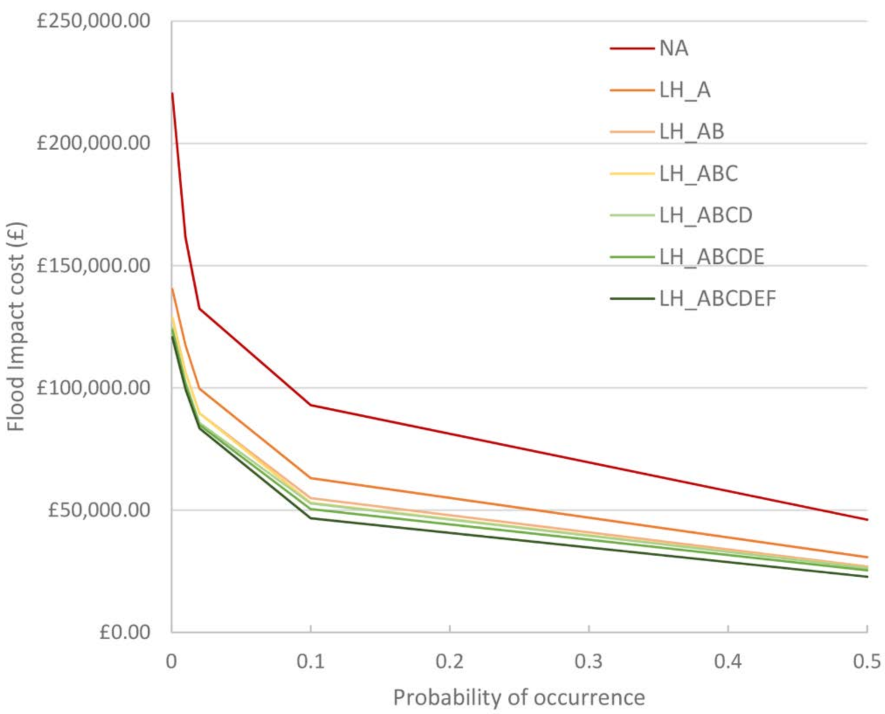


Figure 5-12. Impact cost summary for all the scenarios: (a) considering the single interventions in isolation; (b) considering combined interventions. The data underpinning these graphs were presented in Table 5-7 and Table 5-10.

The benefits brought by grey and green adaptation options are shown in Figure 5-12(a); Figure 5-12(b) highlights the synergies underpinned by hardening a series of links. Adaptation interventions drastically reduced the impact for extreme events (occurrence probability = 0.005) and provided alleviation also for lower-profile events (occurrence probability = 0.5), determining the curved shape of the function.

In summary, results showed that:

- even low-profile rainfall events (*e.g*. 1 in 10 years event) could bring significant disruptions and associated costs to travellers (Figure 5-12);
- the effectiveness of the adaptation options varies depending on the number of junctions protected, and this highlights the need for an understanding of the importance of particular "hotspots" in the road network;
- green adaptation does provide an effective but unrealistic option (green roofs), or a realistic but ineffective (retention basin) strategy for flood alleviation (Figure 5-12);
- grey adaptation decreases delays to travellers under all scenarios, however larger benefits are brought when strategies are implemented in combination, within a system-wide perspective;
- the importance of considering system-scale analysis of network disruption, rather than link-based disruption, is also demonstrated by a number of complexities underlying the results;

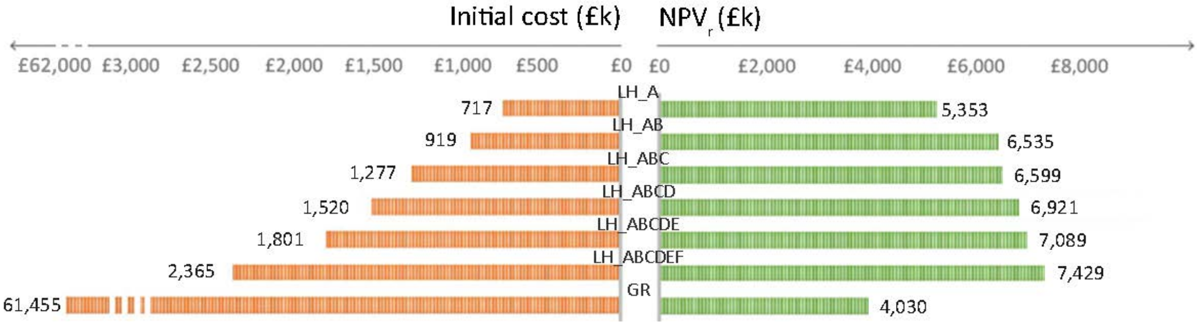


Figure 5-13. Repayment time and the capital cost of the investment to implement the intervention considered in this study. The data underpinning these graphs were presented in Table 5-8 and Table 5-12.

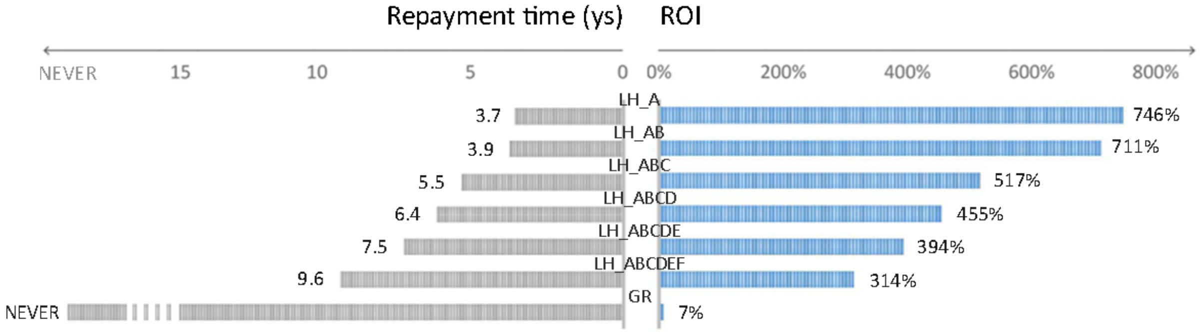


Figure 5-14. The repayment time and the Return on Investment (ROI). The data underpinning these graphs were presented in Table 5-8 and Table 5-12.

- the return in terms of reduced risk improves as more intervention options are considered, although it takes longer to realize the return on alleviation (Figure 5-13 and Figure 5-14). However, the net benefit that accounts for the initial capital costs is the greatest for just two interventions (LH_AB).

The Net Present Value, the repayment time and the hotspots location can provide fundamental risk-based information to prioritize adaptation investments. Although different cities will exhibit different properties, the framework and principles for prioritizing adaptation are transferable, and the outputs have been shown to be compatible with existing infrastructure appraisal processes.

Chapter 6 summarises more briefly the key concepts and processes of this study, discussed the results outlined above; it also underlines their implications for practitioners and transport managers. Chapter 7 finally integrates and synthesises the issues raised in the previous sections, while reflecting the introductory thesis objectives.

CHAPTER 6: DISCUSSION AND IMPLICATIONS

6.1 INTRODUCTION

Chapter 5 reported on a case study of the methodology developed by this thesis, demonstrating the applicability of the concepts. It was shown that the method was useful to identify vulnerable locations in the transport network and prioritise interventions to improve its resilience. Chapter 6 discusses the results obtained in the case study and identifies cross-cutting themes that underpin the key concepts and processes described throughout the thesis. Then, it underlines the aspect of novelty and the main contributions of this work. Validation and uncertainty are also discussed, providing a complete and critical discussion.

6.2 GREEN VERSUS GREY ADAPTATION

This study provides the basis for a more comprehensive approach to appraise the impact from flood events and the benefits of adaptation in the urban environment. The model is shown to provide many benefits to a transport and flood risk manager, to explore the implications of investment decisions.

A number of adaptation options were tested, from “grey” and “green” engineering. The capability of green infrastructure of reducing flood impact in urban environments is presented in literature as highly controversial (Lawson, 2014), and largely discussed. This research confirms the complexity of evaluating the benefits, when flood alleviation only are appraised.

The green roof strategy provided an overall greater improvement in network performance, comparable with the junction hardening. However, while the green roof strategy considered here represented an absolute upper bound (*i.e.* 100% of all roofs) on the potential of this intervention strategy, only one hardened junction is evaluated and this provides a disproportionate return. Furthermore, implementing a ‘universal’ green roof strategy was unlikely to be a realistic option in an established city, at least in a short timeframe, as many roofs are unsuitable to be retrofitted at reasonable cost (or even at all). The percentage of water retained can also vary consistently, depending from roof structure, vegetation type, pre-existing soil level of saturation, and rainfall magnitude.

The system of retention basins simulated in Section 5.7.2 did not alleviate the impact of flooding, since the floodwater depth remained over the maximum threshold for a safe driving (300 mm).

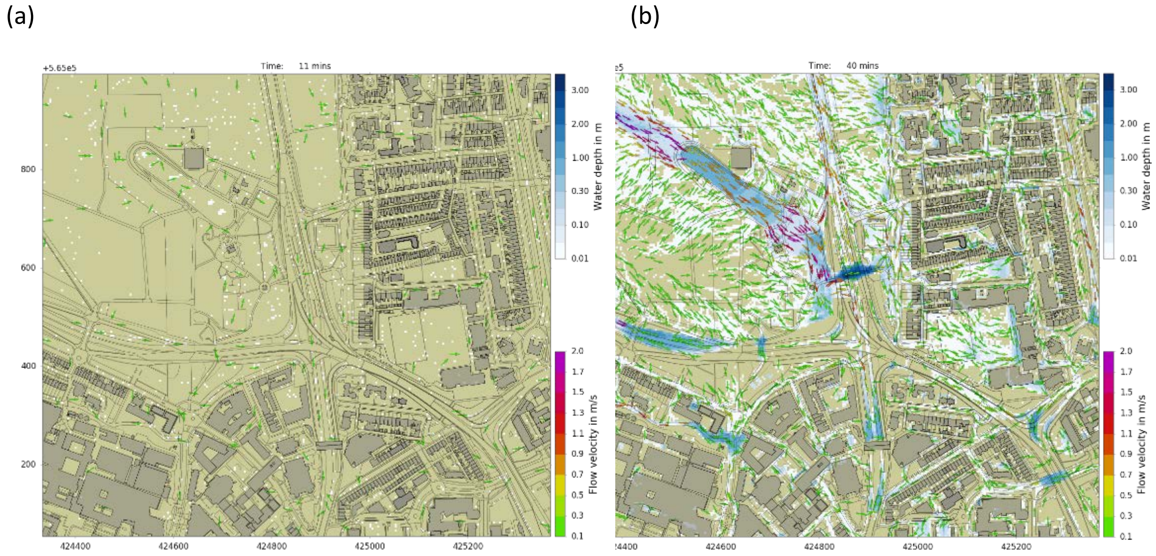


Figure 6-1. Flood modelling output after11 minutes (a) and after 40 minutes (b) the event started. The arrows indicate the velocity of water at that instant.

As Figure 6-1 shows, analysing the source of surface water flooding for an area of interest was not a simple task. The main contributions of runoff were shown to derive from the Town Moor (where the ponds were located), however additional water flows could come from North and from the East neighbourhood zones. This exposes the inefficacy of the retention basins in this case and the need to develop more sophisticated flow analysis for complex urban environments.

Regarding grey engineering adaptation, the results show that just one grey infrastructure intervention in a critical location provides a substantial reduction in transport disruption, and that two options have the ideal combination of NPV_r and initial cost. The benefits varies according to the number of locations protected, and results also demonstrate that the scale of impacts are not directly proportional to the number of interventions, but a function of more complex properties of the flooding-transport system. In fact, hardening Links A, B, and C provides the same benefit as hardening just

A and B, because Link C feeds directly into Link F. The synergies due to the combination of F and C resulted in obtaining benefits from hardening Link C if Link F is also hardened.

The hardening of two critical parts of the road network (links A and B) was estimated to bring up to 17% more benefit than the green roof solution, in a repayment time of four years only. This highlights the importance of understanding the structure, capacity, connectivity, and flows that determine the vulnerability of the transport network. When finances are limited, identifying key nodes and links on the road network can have a disproportionate benefit.

Green infrastructure, however, typically provides other benefits beyond flood risk management, such as improving wellbeing, biodiversity and providing a cooling effect during heatwaves, without being limited by a storm design frequency. This suggests that green infrastructure can have a role in a more integrated flood risk management, even though it cannot resolve a flooding issue in isolation. Future approaches should focus not only on traditional measures of hard interventions, but look at multi-faceted approach to planning, design and management of public spaces, as investments to mitigate storm impact and improve urban quality. A portfolio of carefully targeted green and grey engineering investments would deliver the widest and benefit in the face of uncertainties and sustainability.

Adaptation economics includes several aspects of criticality for both green and grey adaptation. For infrastructure project appraisal costs are usually underestimated while benefits overestimated (Flyvbjerg, 2006). In the case study presented in Chapter 5, adaptation costs have been based on real data from a number of companies, however, they remain estimates because costs are very site specific. Considering the expected increase of extreme events and frequency of flooding episodes, and also that transport damages represents only one of the flooding losses, it is likely that benefits could be underestimated for a long timeframe (>50 years).

6.3 CROSS-CUTTING THEMES

The research covered a full range of topics linked to flooding impact, transport resilience and urban adaptation. Multiple cross-cutting themes can be identified and discussed around the main overarching research question, namely: what are the most effective adaptation strategies to maximise the robustness of infrastructure networks and hence make the best contribution to urban resilience with respect to flooding?

6.3.1 TRANSFERABILITY

This research investigated the impact of flooding on the transport sector, looking at potential interventions within the case study of Newcastle (UK). The models and data used in this study (*e.g.* DTMs, ITN data) are readily available for other UK and worldwide locations, enabling the approach to be readily transferred to any other city in the UK. This data is typically available (albeit possibly in different formats) in other developed world cities and so it is expected that the approach could be readily transferred to such cities. However, many cities and countries do not routinely collect, or make readily accessible, this data but emerging global data sources such as OpenStreetMap may make transferability further afield a possibility in the near future. One challenge for transferability is the consideration of the local conditions of the selected case study; for example, American cities would be expected to have a higher percentage of SUV cars and so the upper bound of the depth-disruption curve might be more representative. Different socio-economic conditions can be tested by modifying the number of users (private cars) of the network, assuming new behavioural choices such as more tele-working or cycle commuting. This could also include the investigation of the role of transport mode (*e.g*. public or private transport) in flooding impact and transport performance during adverse weather events. The camber and quality of roads, typical tyre age and other factors will also need to be reflected in setting up non-UK case studies.

For Newcastle, adaptation options were selected on the basis of those most of interest to local stakeholders, such as the Newcastle City Council. It is not expected that this rate of return from the adaptation interventions would be the same in every city because the transport network structure and level of redundancy, travel patterns, and topographies will be different, but application of the criticality analysis is shown to prioritise investment interventions effectively. The criticality index is particularly useful to identify the weakness portions of the network, such as bridges connecting two sides of a city, on the basis of hazard magnitude and number of users.

6.3.2 IMPLICATIONS OF THE MODELLING ASSUMPTIONS

A number of transport processes were represented at reduced complexity to enable large-scale analyses at reasonable computational cost.

Hazard simulations were run at 4 m of resolution using the flood model CityCAT (Glenis *et al.*, 2013). Although higher resolution could be employed (*e.g*. 1 m), the implications were limited: the threshold of 300 mm was usually overpassed by much more than few centimetres. Therefore, 4 m of resolution represented a reasonable compromise between accuracy and modelling run-time, even considering potential camber variations.

CityCAT is a deterministic and physical-based model; it produces the best-possible solution based on physics and the parameters defined in the settings. The model provided rigorous solutions for complex free-surface flow over the terrain by using the Osher-Solomon Riemann solver, one of the most accurate solver (Erduran *et al*., 2002). Uncertainty in the results could be due not to the solving equations, but to the uncertainties in the input (*e.g*. frictions coefficients, topography, etc.).

Sub-surface drainage was not considered, although its effect could be relevant for a range of rainfall events. However, this would require a complex and demanding fully-coupled model, not available at the time of this study for the considered domain. The implementation of sub-drainage is indeed matter of future studies (see Section 7.3.1).

Finally, rainfall curves were calculated by CityCAT using the FEH methodology. This method is best for long-duration rainfall and return periods up to 200 years; for large domain, the analysis cannot include regional variation (this could be problematic for wider areas, such as London) (Kjeldsen, 2007).

Regarding the transport model, the simplification of the road network in wards removes the ‘start’ and ‘end’ of the journey; this significantly reduced the computational cost. For smaller wards this error distance is negligible (less than 1 m); for larger wards the error distance may be higher, but the number of people affected is far smaller due to lower densities. Indeed, the ward simplification has a relatively small impact on the disruption calculation. However, this would be less appropriate if considering emergency response where redundancy of emergency planning routes may be crucial.

Travellers were considered to have complete knowledge of the road network. Vehicle-to-vehicle interactions, non-flood incidents and traffic signals were ignored. This provided a computational advantage, whilst still capturing the macro-scale transport interactions. Moreover, the computed damages regarded the indirect transport costs (delays) only and were limited to the ones caused by flooding (*e.g.* the loss of visibility due to the bad weather). Considering all these assumptions, it is likely that the results represent a lower estimate of delays.

6.3.3 MODEL VALIDATION

The study develops a framework in which hazard, network and damage modelling are integrated. Given its complexity and research breadth, an overall validation was not possible. The approach taken has therefore been to validate the individual components.

Regarding the hazard modelling, and CityCAT in particular, whilst the mathematical equations underpinning the simulations of surface water flow in the CityCAT model (*e.g.* the Green-Ampt method, see Glenis *et al.*, 2013) have been tested and utilised for over a century, the complex interactions of surface water in an urban environment are more difficult to validate. Uncertainty also arises from the input data (such as the rainfall, DEM, permeability). In order to undertake such validation, observations of water depth and velocity during a real-world high rainfall event must be taken across a large urban area. The pluvial flood hazard resulting from the Toon Monsoon (120 min of duration, 100 years of return period) was used as a means to validate the simulations of urban surface water flow. Data regarding spatially-referenced photographs taken during the flood event and other comments witnessing the flood, were gathered about the 2012 event using crowd-sourcing techniques. Alongside this data, Newcastle City Council also utilised questionnaires to gather a description from local residents of flood conditions in and around their properties. The data gathered from these sources were used to validate and calibrate the flood model CityCAT. Figure 6-2 shows some of the validation results from this process.

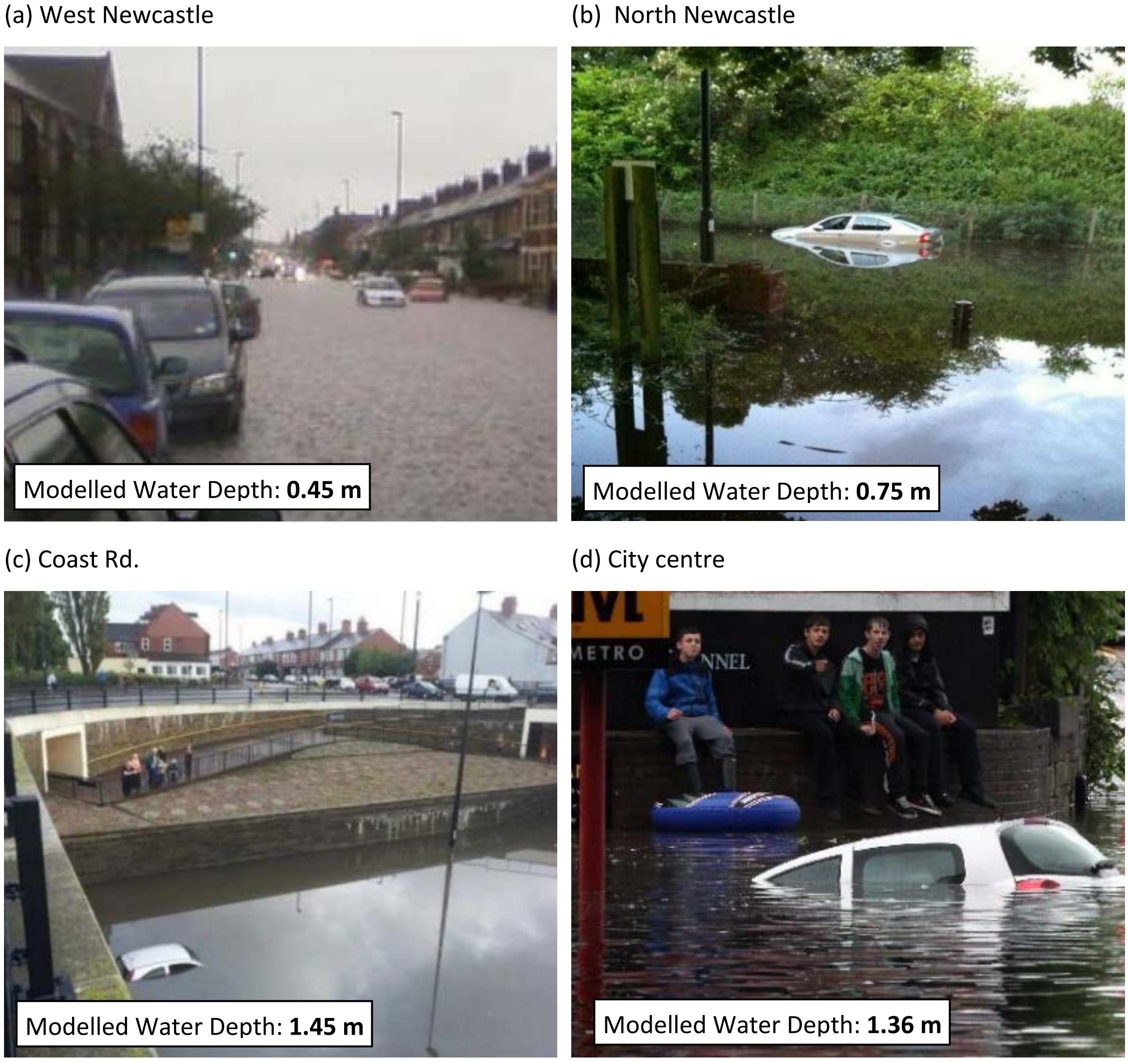


Figure 6-2. Examples of validation photographs used to assess the accuracy of CityCAT simulations (see Figure 5-1 for locations). Photos are from a Newcastle University website, set up the day after the flood to allow people to upload photos and observations: http://ceg-morpethflood.ncl.ac.uk/toonflood.

The depths at locations in CityCAT, where photographs or reports were provided, were compared with those visible in the real June 2012 event. Agreement between the survey data (photographs and reports) and modelling results show good correspondence (Glenis *et al.*, 2013). Moreover*,* the recent work of Glenis *et al.* (2017) supported the CityCAT validation even further via lab experiments.

Regarding the network modelling, the baseline of the model was validated using 2011 Census data of commuting flows and observations from Automatic Traffic Counters (ATCs); the 2011 Census data are the last available. By analysing the commuting flows and data available regarding traffic flows on peak times (Figure 6-3), the simulated busiest roads from the simulation corresponded to the busiest observations from

Google Maps and other sources, such as the traffic analysis by TADU (2017) and Butcher (2015).

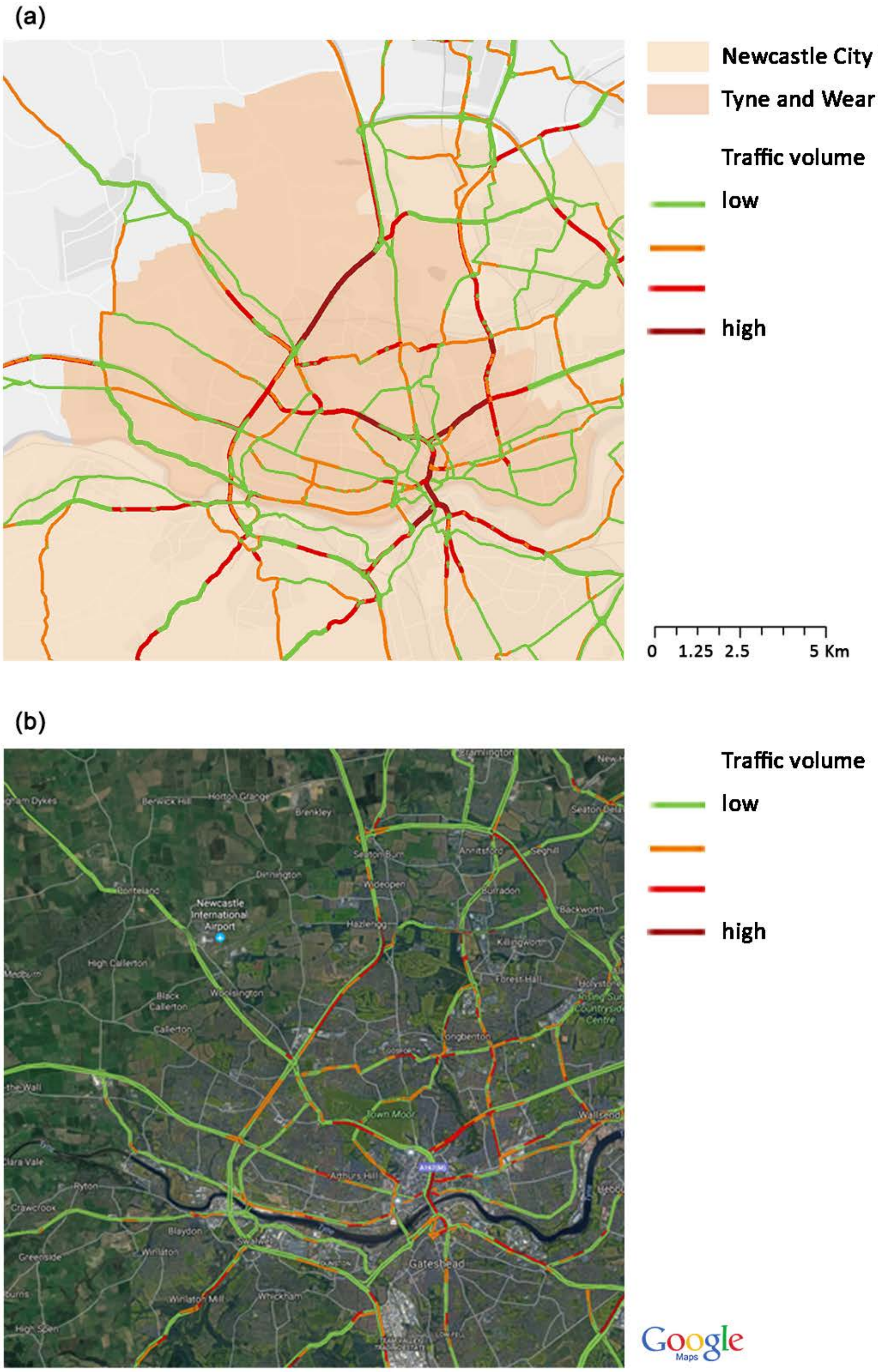


Figure 6-3. Comparison between simulated and observed traffic flows: (a) simulated traffic flows, using the JtW data and the model; (b) traffic flows in real time from Google Map at 17:15 of a normal weekday.

Validation of disrupted traffic flows is especially challenging because of limited observations due to the low frequency of extreme weather events. One set of information was collected for the Toon Monsoon, however this was not in a format directly compatible (traffic flow in vehicle/hour) with the modelling output (PHD, Person Hour Delay) and this is only measured in a few locations. Nevertheless, the relative extent of the disruption observed by the sensors is comparable with the model results (Pregnolato *et al.*, 2016; Pregnolato *et al.*, 2017).

Despite the progress of recent years in data collection, it is noted that the quality of databases may significantly vary. Information often belongs to databases associated with important quality issues (see for example the percentage of missing data from the TADU dataset, Figure 5-3), which include low level of details or scarcity of observations, especially at high flood intensities. Improved protocols for the collection of data in pre- and post-flood scenarios could integrate hazard and damage information in order to provide a sound basis for derivation of future empirical vulnerability relationships. Improving data collection is on the agenda of many UK cities (*e.g*. the Newcastle Urban Observatory, https://research.ncl.ac.uk/urbanobservatory/), and the integration between different datasets is a necessary step for monitoring the overall system and to support empirical research. Incorporating this data, and other emerging datasets from driver monitoring systems, offers the potential for a far richer understanding of vehicle response during disruptive events and should greatly improve the validation and calibration of this type of model (Batty, 2013; Kermanshah *et al.*, 2014).

6.4 NOVELTY OF THE RESEARCH

The research is innovative from multiple perspectives:

i) the *integrated framework:* a novel and integrated modelling method for the assessment of the impact of rainfall-induced flooding is formulated, combining hazard and network analysis, impact and adaptation assessment - as opposed to silo-based approaches, which frequently separate climate and transport analysis;

ii) the depth-disruption function: in order to overcome the current binary approaches of modelling flood disruption to roads, a new depth-disruption function is developed.

The function provides the relationship between the depth of floodwater on a road and the vehicle speed, representing a significant advance on existing practise;

iii) an improved business-case for adaptation analysis: adaptation measures is investigated to improve the resilience of transport infrastructure. A criticality score provides indications to target hard engineering strategies (grey adaptation) and soft engineering ones (green adaptation) in the city-system.

6.4.1 THE INTEGRATED FRAMEWORK

Data from traffic sensors and video during floods confirmed that the traffic continued to move in flooding conditions, highlighting the need for the more sophisticated approach to disruptive impacts of flooding advanced by this thesis. A new framework is advanced, alongside the standard CAT modelling practice. CAT modelling is currently applied for computing direct losses to building stock, within the insurance and reinsurance industries. However, in the context of infrastructure losses are more widely linked to the performance loss of the system and not limited to direct monetary ones (*e.g.* road pavement damages), but do include indirect losses such as transport disruption or business interruption.

CAT modelling is re-thought expanding the exposure elements to infrastructure systems and losses to indirect losses, within a new approach to threat and risk analysis. A "next generation" of CAT models could improve infrastructure resilience at urban level, considering wider consequence- and performance-based assessments, arriving at multi-hazard assessment and cascading effects (Pregnolato *et al*., 2017c). Assuming a more systematic and integrated collection of information in future years, data could contribute to develop empirical damage curves for additional hazards or to "update" the existing ones, like the depth-disruption function developed by this study.

6.4.2 THE DEPTH-DISRUPTION FUNCTION

Flooding, especially as a result of intense precipitation, is the predominant cause of weather-related disruption to the transport sector. Existing approaches to assess the disruptive impact of flooding on road transport fail to capture the interactions between floodwater and the transport system, typically assuming a road is fully operational or fully blocked, which is not supported by observations.

In order to transition from a binary view of a flooded road being considered 'open' or 'closed', this study developed a relationship between depth of standing water and vehicle speed. The function that describes this relationship has been constructed by fitting a curve to a range of quantitative data that has be extracted from existing studies and other safety literature, supplemented by video analysis. The proposed relationship is a good fit to the observed data, with an R-squared of 0.95. The significance of this research is that it is simple to incorporate the function into existing transport models to produce better estimates of flood induced delays.

The depth-disruption function is complementary to the approach used by other flood impact functions in relating the magnitude of the impact to the flood loading. The maximum threshold for safe driving, stopping, and steering (without loss of control) is identified as 300 mm, on the basis of observations and driving tests; therefore, a road is assumed to be impassable only when the limit of 300 mm is reached. The function can also be used to raise driver awareness about safe driving depths.

6.4.3 AN IMPROVED BUSINESS CASE FOR ADAPTATION

The proposed method overcomes current siloed approach to managing transport and flood risks by integrating flood modelling, network simulations and adaptation in a holistic model. By integrating across multiple agencies of transport and flooding, one investment could favoured a joint benefit. The model provided: *(i)* a mechanism for city-wide screening of priority locations for flood adaptations based upon analysis of road networks and traffic properties; *(ii)* a means of assessing floods impact and adaptation benefits, in terms of reduced disruption, for better flood risk management. To date this has not been considered in flooding appraisals in such a comprehensive way.

This work provides a means of prioritising limited financial resources to improve resilience. This is particularly important as flood management investments must typically exceed a far higher benefit-cost threshold than use, provided the original transport infrastructure investments. By capturing the value to the transport network from flood management interventions, it is possible to create new business models that provide benefits to, and enhance the resilience of, both transport and flood risk management infrastructures.

A cost-benefit analysis of adaptation strategies is crucial for a consistent decision-making. This research compares a portfolio of hazard scenarios and adaptation options in order to understand which combinations provide the best return, by including indirect benefits on traffic and circulation. Considering a range of flood events (thus different flood footprints and depths) enables to take into account how viability is altered and possible travel speed of different routes. Furthermore, by considering multiple events it is possible to identify a balance of the costs and benefits from the size of adaptation at each road stretch.

Green infrastructure deployed widely provides notable benefits in terms of flood depth reduction across the city. Targeted interventions can provide more localised benefits, but in the example of the retention ponds considered in Section 5.7.2, although water depths are reduced, there is no benefit to the transport system. However, as this analysis only considers the benefits in terms of disruption and no other benefits associated with urban flood management (*e.g*. urban amenity, pollution reduction), it is likely that the overall returns would be higher.

The cost of interventions were estimated from academic and grey literature. Such costs could be fixed (*e.g*. green roofs) or be in relation to a designed return period (*e.g*. drainage system). The benefits were considered in terms of delays reduction to commuters using the road networks. The NPV of the benefits in terms of risk reduction, NPV_r, was used to compute the long-term costs and benefits, accounting for inflation and the life-span of infrastructure (3% discount rate). Although designing for more extreme events is more costly, the returns are greater and provide greater resilience to projected changes in rainfall.

6.5 UNCERTAINTIES

At present, all data and information are characterized by uncertainties, and projections into an uncertain future (Hallegatte *et al.*, 2012). This section considers the uncertainties in the analysis.

The major sources of uncertainties are ranked in Table 6-1 and can be identified in relation to: (1) the transport model; (2) the flood-transport curve; (3) the breadth of adaptation scenarios; (4) the flood model; (5) the rainfall design. (1) and (4) are 'structural' uncertainty, related to the model choice and modelling assumptions; (2), (3) and (5) could be reduced by better information or analysis.

Table 6-1. Uncertainties ranking for the major sources of this thesis.

Rank	Uncertainty	Issue	Potential solution
1	Macro-transport model	Representation of simplified traffic processes; commuting and private cars only.	A more sophisticated transport model could be used, in order to better address queuing effects and bottlenecks. For peak times, commuting travels are probably dominant, but do not capture all congestion.
2	Flood-transport curve	Uncertainty regarding car type, people behaviour, road conditions.	The extreme parts of the curve are reasonably well-defined, the central part could be more influenced and shaped by the availability of further data. The collection of data (experimental and observed) could help to refine the damage and define different curves for a range of vehicles.
3	Breadth of adaptation scenarios	Extreme options adopted: 100% green roof or the invulnerability of selected stretches of road.	The interpretation of the results is pivotal for judging a model. The tested options were meant to be indicative. More realistic hypothesis could be tested (*e.g.* green roof retrofitting for flat roofs only); for SUDS, potential viability study could be undertaken beforehand.
4	Flood model	Uncertainty regarding outputs (depth, flood extent).	Adopt a higher resolution (*e.g.* < 1m) to refine the outputs, even if this would increase the modelling run-time.
5	Rainfall design	Large domains do not consider regional variation and assume uniform rainfall.	Larger areas can be investigated by dividing the domain into smaller sub-domains.

Regarding uncertainties in the transport model, different factors could determine a complex effect on the demand and flows: *(i)* people's behaviour, including postponing or cancelling the trip, switching motorised mode or willingness to drive into floodwater; *(ii)* weather-related parameters, such as low visibility, rain, pavement condition, illumination; *(iii)* socio-economic development, that could potentially lead to either an increase or a reduction of motorists. Some reasons related to trip adjustments (journey importance, destination relevance, trip length) are related to the uncertainty of discretionary trips; however, their influence is weaker for commuting journeys, which follow more rigid schedules even in adverse-weather conditions (DfT, 2016a).

At a decision-making level, it is possible to account for uncertainty by: *(i)* considering flexible adaptation, involving strategies that can be modified once new lessons are learnt (Hallegatte, 2009); *(ii)* developing robust strategies that operate well over a range of alternative futures (Wilby and Dessai, 2010); *(iii)* planning by scenario, including multiple sets of input (Jenkins *et al.*, 2012). A portfolio of measure based on a mixture of adaptation strategies (*e.g.* green and grey adaptation) is an example of effective approach to reduce the impact of flooding risk and exploit opportunities. The introduction of adaptation measures would be more effective if combined with planned maintenance and/or upgrades of existing structures (*e.g.* green roof) or infrastructure.

In addition to the complexity related to the built environment, uncertainty makes flood risk management more challenging. Targeted and cost-effective solutions are pivotal to design resilient solutions and forward-thinking cities. Adaptation measures should be introduced incrementally, considering today and future needs to cope with the climate variability and extremes. Especially for the hard-to-reverse investment (with a long design life, like transportation infrastructure), flexibility and robustness should be integrated in the design.

Another aspect of the decision-making under uncertainty relates to the long-life of infrastructure, which relates to the “generational gap” (Turner and Zolin, 2012; Invernizzi *et al.*, 2017): who is going to pay (for the initial investment) and who is going to benefit (from the implementation of the strategy) could span generations. The rationale of NPV has been challenged as the best measure of the investment goodness, however the topic is still under-studied in engineering (Sartori *et al.*, 2014). NPV and risk analysis should be supplemented with additional evaluations (*e.g*. a multiple-criteria decision analysis), in order to inform long-term decisions.

6.6 SUMMARY

Chapter 6 has discussed the results and research contributions of this thesis, considering their implications for academia, practitioners and transport managers in the area of flood management and network resilience. Multiple cross-cutting themes were identified related to the transferability and scalability, the assumptions and the validation of the model. The research has been demonstrated as novel since it developed an integrated framework for flood impact assessment on roads and an innovative depth-disruption curve, which overcomes existing approaches. Implications for transport and flood risk managers were discussed, underlining key differences between green and grey adaptation, and the uncertainties present in the overall work.

Chapter 7 draws overall conclusions from this work outlining the main achievements and considering the potential direction of future study.

CHAPTER 7: CONCLUSION

7.1 INTRODUCTION

Following discussion of the research and its wider implications in Chapter 6, Chapter 7 briefly summarises the research presented in this thesis, highlights the main achievements and novel contributions, before reflecting on its key limitations to date and the potential direction of future research.

Previous studies in the literature have shown that the relationship between adverse weather and traffic flow is complex and has been poorly understood. The new results here assess the impact of a range of flooding, climate and adaptation scenarios, showing that the impacts of traffic disruption from extreme flooding can be effectively mitigated through targeted adaptation along key stretches of the road network. The findings presented demonstrate that increases in rainfall intensities lead to a nonlinear increase in journey time as a result of the spatial heterogeneity of the flood hazard and the many network interactions of journeys across the transport system. The complexities of the urban environment and of the network underlined the importance to undertake system-level analysis, integrating hazard and transport modelling.

Without adaptation intervention in the transport system, Newcastle (and cities with similar urban properties) is likely to experience transport disruption leading to an increase in travel time of more than 50% for more extreme events (1-in-200 years), associated with a cost of more than £220,000. Adaptation does contribute to flood impact alleviation, and two drainage improvement interventions (grey adaptation) in specific vulnerable locations, for a timeframe of 50 years resulted to provide the best return. The effectiveness of green adaptation in reducing flood impact remains uncertain, although additional co-benefits are related to this type of strategy.

7.2 REVIEW OF OBJECTIVES

Cities are becoming increasingly vulnerable to damage and disruptive impacts of adverse-weather events, due to their high concentration of people and assets.

This thesis developed an integrated framework for assessing system-scale impacts of surface water flooding on transport networks, and evaluated potential adaptation strategies to enhance urban resilience. To achieve this, the broader issues of flooding in urban environments were investigated and the gaps in current capabilities of flood risk assessment of urban transport systems were identified in Chapter 2. An integrated modelling systems framework was developed to quantify the impact of flooding on transport systems in Chapter 3, where the key relationship between flood characteristics and transport system performance were discussed in Chapter 4. The framework was applied to a representative urban case study, validating the model with historic flood events; the case study was also functional for assessing the effectiveness of green and grey adaptation interventions to manage flood risk to transport disruption (Chapter 5).

7.2.1 A BETTER UNDERSTANDING OF FLOODING IMPACT IN CITIES

Surface flooding is a major risk to urban environments. Transport networks are fundamental for the functioning of a city and a key element in emergency management. Indeed, ensuring resilience to such networks would provide robustness to the whole system “city”. An increasing body of evidence recognises that probabilistic methods are necessary to develop an appropriate estimation of risk; however, they are mainly applied to buildings and direct damages.

New models and new tools are necessary in order to tackle the impact of flooding on urban areas in a more complete way, especially in light of climate change and demographic increase. Chapter 2 successfully identified methodological limitations in the literature and needs related to the assessment of flooding impacts in urban environments, in particular regarding the absence of criteria for quantifying the effects of flood waters on vehicle motion/speed. Existing approaches to assess the disruptive impact of flooding on road transport are inadequate and fail to capture the dynamics and complex interactions between floodwater and the transport system, since a road is typically considered either fully operational or fully blocked which is not supported by observations.

7.2.2 THE DEVELOPMENT OF AN INTEGRATED MODELLING FRAMEWORK

The research addresses the identified issues by developing an integrated risk analysis framework (Chapter 3), based on catastrophe modelling. The hazard component of the modelling consists of developing flood maps via hydrodynamic modelling for a range of rainfall events. The exposure element involves the development of a transport network using available information regarding road geometry, speed and flows.

The method assessed the impact of a range of flooding, climate and adaptation scenarios, and test the effectiveness of a portfolio of adaptation options on the impacts of traffic disruption from extreme flooding. The disruptions take into account indirect costs, related to the interruption of the normal circulation, in function of several factors (*e.g.* travelling distance and speed). The baseline model of BAU commuter flows can be "disrupted" by hazardous events as well as "adapted" to target different urban interventions, permitting the simulation of a set of analysis to support decision-making.

The method provides a mechanism for city-wide screening of priority locations for flooding adaptations based upon analysis of road network and traffic properties, indeed objective no. 2 was achieved. Furthermore, it enables the peak disruption impact to be assessed, thereby providing important information to policy makers to determine the benefits of adaptation options on the transport network. Finally, by targeting adaptation interventions at the most critical stretches of road network, in terms of traffic flows and flood depth, the framework is used to propose a cost-effective prioritisation of the intervention options.

7.2.3 A NEW FUNCTION FOR FLOOD DISRUPTION TO TRANSPORT SYSTEMS

Vulnerability was incorporated in the modelling framework through the development of an original depth-disruption function that relates the floodwater depth with vehicle speed reductions (Chapter 4). By reviewing observational, experimental, and modelling studies of the impacts of weather on transport, an empirical function was derived, providing a significant advance on existing practise. The depth-disruption function is complementary to the approach used by other flood impact functions in relating the magnitude of the impact to the flood loading. The maximum threshold for safe driving, stopping, and steering (without loss of control) has been identified as 300 mm; beyond which a road is assumed to be impassable. Incorporated into the transport appraisal calculation, this function can be used to calculate the disruption, measured in cost or time, expected from flooding.

Although the curve includes a series of uncertainties, it is currently the best-fit to the available data and fulfilled the set objective.

7.2.4 THE CASE STUDY OF NEWCASTLE (UK)

The model has been applied to Newcastle upon Tyne in the UK to assess the disruption due to flooding on commuting journeys, by comparing travel times with those for unperturbed conditions. The same model is also used to evaluate the effectiveness of adaptation strategies in protecting the city from the adverse consequences of flood events. The model is applied to a UK case study, due to data availability and its representative urban characteristics (Chapter 5), and validated using historic flood events. The transport curve is applied to the urban road network of Newcastle and a range of adaptation strategies are simulated, in order to evaluate the effectiveness of interventions planned in key-spot locations. A cost-benefit analysis helps to quantify the economic return of those solutions, looking at a time-frame of 50 years. Overall, the model was applied with success.

With no adaptation of the transport system, a 1-in-200-year rainfall event increases travel times by more than 50%, with an associated economic impact of over £220,000. Adaptation measures contribute significantly to flood alleviation. Application of a risk-based ‘criticality assessment’ has been shown to enable effective targeting of grey (traditional engineering) adaptation, and only six carefully sited locations can reduce net present flood risk by £6m in less than 10 years’ time. This compares to £4m for a green adaptation strategy, in a non-realistic lapse of time (centuries). Although the green strategy would provide additional co-benefits, such as enhanced biodiversity and air quality improvements, deployment of green infrastructure at a city-wide scale would require an unprecedented scale, and likely high cost, of intervention.

Combining flood and network analysis is shown to improve engineering decision-making and prioritisation of adaptation investments in urban areas. The findings and methodology are of interest to transport policy analysts, planners, economists and engineers, as well as communities affected by disruptive events. Although a number of challenges remain to reduce some of the uncertainties in the integrated framework, this work has provided an important first step to improve the understanding of transport disruption from flooding and the efficiency of adaptation interventions, and it demonstrates an effective approach to prioritising adaptation investment.

7.2.5 IMPLEMENTING ADAPTATION TO MANAGE FLOOD RISK

When limited resources for flood risk management are available, the method introduced in this work enables quantification of the indirect impacts of flooding on transport delays and provides a strategy for prioritising investment to maximise returns. The effectiveness of the adaptation options varies depending on the number of junctions protected, and this highlights the need for an understanding of the importance of particular “hotspots” in the road network. Grey adaptation decreases delays to travellers under all scenarios, however larger benefits are brought when strategies are implemented in combination, within a system-wide perspective. Green adaptation does provide an effective but unrealistic option (green roofs), or a realistic but ineffective strategy (retention basin) for flood alleviation. A combination of green and grey strategies would couple the effectiveness of the first and the co-benefits of the second, providing more resilient and sustainable urban environments.

Although the implementation of adaptation and the consequent cost-benefits analysis could be improved in different directions in the future, this stage of the study was functional for providing a qualitative overview about some options of flood management. With respect to the limits identified for this study stage, objective no. 5 can be considered achieved.

Calculation of the Net Present Value, the repayment time and the hotspots location provides fundamental risk-based information to prioritise adaptation investments. Although different cities will exhibit different properties, the framework and principles for prioritizing adaptation are transferable, and the outputs have been shown to be compatible with existing infrastructure appraisal processes.

7.3 FUTURE RESEARCH

The methodology developed by this work could lead the way towards a range of future research. The potential of this research is not limited to just flooding impacts on infrastructure, and additional dimensions of urban environments and systems could be incorporated.

7.3.1 REFINING THE METHODOLOGICAL FRAMEWORK

Future development of this approach could reduce uncertainties by increasing the accuracy and complexity of a number of the represented processes, although this comes at a computational expense.

In relation to the hazard modelling, a higher resolution (*e.g*. 1x1 m) could increase the accuracy of the output, although this would imply longer simulations. This modelling could also be improved by accounting for the sub-surface drainage network when modelling flood areas, and by spatially considering non-uniform rainfall.

Increasing the sophistication of the transport model, *e.g.* use of an agent-based transport model could better capture micro-effects (*e.g.* acceleration, deceleration, car-following, lane changing) of disruption, albeit at additional computational cost. A micro-model could be adopted to model congestion and queuing effects, alongside the implementation of data on the basis of past records in order to account. Dynamically linking an inundation and transport model would allow a simulation of disruption over the course of the flood event, and to understand when transport patterns return to normal after the rain (recovery timeframe), which would vary according to the magnitude of the flood. Similar approaches have already been implemented to understand the risk of drowning (Dawson *et al.*, 2011).

The impact analysis could incorporate future urban development, land-use and socio-economic changes; this would consider future traffic flows and testing of alternative adaptation options, such as a behavioural shift away from private cars, increased home working, or adding redundancy to the road network. The impact modelling, and outputs such as the maps of flooded roads for different scenarios, could be particularly suitable for analysing the accessibility of critical structures in the city (*e.g.* schools, hospitals), the recovery time of the network and emergency plans.

Other combinations of adaptation scenarios could be simulated to optimise investment decision. For example, the scenarios of grey adaptation ABCF could be run in order to assess the synergies between node C and F. Additionally, a more realistic combination of roof retrofitting (*e.g*. flat roofs whose surface is higher than a certain threshold) and node hardening could be verified too.

The trend towards the gathering of more data in cities could lead not only to a better understanding of the urban dynamics, but also to the development of more refined damage curves and more realistic impacts models.

7.3.2 DATA AND VALIDATION

Complete and consistent datasets would provide better information to support more accurate models and analysis. The analysis of hazard data (*e.g*. rainfall rate, flood depth) and impact data (*e.g*. traffic flow during floods) could be useful for: *i)* monitoring and analysing trends looking at different events and locations; *ii)* identifying stronger relationship between hazard and consequences; *iii)* performing risk analyses and model validation. Collecting data and gathering information in a complete and reliable way is a complex and demanding task. Lack of standardised methodologies in current data collection imply inconsistency in their interoperability and the lack of integration typical of current siloed approaches (that separate hazard and damage data).

A focus priority should be on accessing and analysing the increasingly available big data from flood events in cities around the world to produce better validation data on the relationship between flooding and traffic disruption. Current observations are limited due to the low frequency of extreme weather events and the partial geographical extension of traffic sensors and weather stations; their format is also not directly compatible with the modelling output. The next frontier of big data should include a more systematic installation of sensors all over the city, looking at coordinating the location for collecting hazard and impact data (*e.g*. traffic sensors and weather stations). More information could be included in the data gathering in addition to traffic volume and rainfall rate, including travelling speed and flood depth. Such progress would enable to completely validate models like the one proposed by this thesis.

7.3.3 EXTENSION TO OTHER SCALES AND SECTORS

The integrated method developed in this thesis includes the three general elements of hazard, exposure and vulnerability (CAT modelling). Although this study focuses on flood risks to the road network, the potential of this research is not limited to just flooding impacts on infrastructure and could be scaled up in a number of ways.

The models and data used in this study are readily available for many locations around the world, enabling the approach to be readily transferred to other cities. Analysis could be carried on looking at particular critical elements of the network (like bridges) or at a national scale; options for upscaling would focus on the main road arteries such as the Strategic Road Networks (SRNs). Other transport networks or transport means (*e.g.* the railway network, public transport) could be considered, in combination with flooding or a different hazard. The vulnerability element would be the most critical step in this context, since few data could be available for some hazard-related impacts and new disruption functions would need to be developed. More systematic data collection in the next years could support that stage.

Transferring the framework to other infrastructure sectors and/or hazards could provide the basis for the development of a "next generation" of CAT models for infrastructure resilience (Pregnolato *et al.,* 2017c). Examples of applications could be: *(i)* the impact of wind gusts on electrical distribution systems; *(ii)* the impact of heat waves on railway system; *(iii)* the impact of volcanic ashes on aviation; *(iv)* the impact of groundwater flooding on the metro system. Such type of models are valuable for the management of existing complex systems, considering wider consequence- and performance-based assessments. Further study could also include the interconnections between the transport network and other lifelines (*e.g.* energy system), looking at cascading interdependencies and failures.

Potential practical development could be represented by *(i)* applying the curve in a study of flood risk on England's Strategic Road Networks; *(ii)* implementing the method to analyse business interruption; *(iii)* considering the integration with council town planning for green infrastructure; *(iv)* applying the research outcomes to transport models for consultancy.

In addition to PHDs, additional impacts within urban systems could be assessed. The transport sector can affect also health and environment, with key issues around air and urban quality, such as particulate concentrations or pleasantness of the commuter journey. Those metrics can be considered in function of re-routing and additional travel time and distance, and appraised within the model to compute other type of impact. Business interruption could be particularly relevant for the economic sector. Finally, the model could be employed to assess emergency routes and planning (Green *et al*., 2016).

7.3.4 IMPLEMENTATION OF DECISION-MAKING APPROACHES

This research has proven to be of relevance, and interest, to practitioners and engineering consultants. The criticality method (Section 3.6.2) helps to prioritise particular types of flood management investments. However, other uncertainties, and multiple spatial combinations of measures and their sequence of implementation poses significant challenges for decision-makers. Planners could address this by adopting a multidimensional and spatial optimization in order to explore potential tradeoffs, and investigate the complex relationship between risks and other objectives (Caparros-Midwood *et al.,* 2017). Risk and sustainability targets could be analysed by planners who require decision support tools to manage a set of priorities and criteria for optimal planning decisions.

7.4 IMPACT OF THE RESEARCH

The UK extensively suffers from widespread disruptions and losses (£1.3bn in 2013/14 and £1.6bn in 2015/16) due to floods. Flood damages are projected to increase to £27bn by 2080 due to the ageing of assets and more severe weather events. This evidence illustrates the need to re-think infrastructure and to support the near future of our cities through resilient national measures against extreme events, including a broader range of changes and policy responses. This research has started to highlight the critical role of transport networks for urban resilience, in particular in light of the flooding impact on roads (*e.g*. rerouting, delays) and therefore urban functioning.

As infrastructure has long-term implications for a city’s functioning, any future adaptation must be both effective and sustainable. The delivery of quantified evidence of the impacts of flooding and associated costs, alongside the benefits of adaptation strategies, is of interest to a wide range of sectors and stakeholders.

Risk Analyst: this work provides new understanding to existing approaches in urban transport analysis, by setting a new direction of research for flooding impact and adaptation assessment. The proposed method overcomes the current silo-based approaches by integrating flood and network simulations in a holistic model. The methodology draws principles from CAT modelling (typically applied to assess the risks to buildings), and originally applies them to the transport sector. This is of interest for risk analysts, and- disaster and risk reduction management specialists (including engineers, water companies).

Transport Modeller: this model used a depth-disruption function to compute transport disruptions due to flooding avoiding the binary consideration of roads (either open or closed), typically assumed in existing studies. The function is aligned with current flood risk and could be integrated in current transport appraisal models, such as the national WebTAG (DfT, 2014c). Local and national government, consultants and modellers could apply the function when investigating transport appraisal and urban investment. Moreover, it could also be applied to inform safety-driving guidance and stimulate community awareness about the danger of driving into floodwaters.

Local authorities: this work proposes an overarching framework which could allow different organisations to work together and develop a shared understanding of the most suitable solutions to surface water flooding problems. The model's output can assist local authorities to make a risk assessment based on the flood hazard and the network elements at risk, supporting decision-makers in designing adaptation measures.

The investment prioritisation method has been designed with existing approaches in mind in order to be compatible. The proposed cost-benefit analysis is based on manuals and data already adopted by industry and governmental links (*e.g.* HM Treasury's Green Book, the MCM, the CIRIA manual), ensuring the possibility of integration with current methods. This work adds to existing approaches in urban transport analysis, by setting a new methodology for flooding impact and adaptation assessment. The policy relevance and engineering legitimacy of this research is ensured by the end users, which include: (1) infrastructure operators and urban planners, (2) industries and business, (3) investors and insurers, and (4) the urban development community (planners, decision-makers).

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