Political and sOcial awareness on Water EnviRonmental challenges

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Abstract

A thorough understanding of adaptation measures' costs, benefits and societal impact is required to prepare cities for the future. Since flood risk is a key climate challenge, it may serve as a focus for developing a comprehensive assessment matrix for Urban Water Cycles Services (UWCS). Accordingly, the aim of this report is to develop a framework to distinguish simple, refined, and comprehensive methods for damage assessments, identify key practical barriers and explore ways to address them. Through a three-pronged approach of literature review, expert questionnaires, and damage modelling, this report reviews methods to assess flood risks, seeks to determine the dominant flood damage types, and estimates flood risks from a pluvial flood event in Rotterdam and Leicester. This assessment matrix provides may provide the narrative for estimating costs, impacts and societal value for other UWCS. Results show that the assessment process is hindered by a lack of reliable and consistent data. This asks for continued research, especially since cost-benefit analyses, and more particularly multi-criteria analyses are key elements in risk communication and therefore form an inseparable component for constructive interaction between politicians, professionals and citizens that Digital Social Platforms aim to facilitate.

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Versioning and Contribution History

Version	Date	Modified by	Modification reason
v.01	25/01/2018	Kees van Leeuwen and Stef Koop	Comments on the draft project proposal
v.02	30/01/2018	Harry Nicklin	Finalizing the proposal
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v.08	19/09/2018	Harry Nicklin	Final draft report and Power point presentation and incorporation of the review comments of Dieperink and Van Leeuwen
v.10	15/10/2018	Harry Nicklin	Modifying the original thesis by broadening the scope of the report by adding sections on droughts and extreme heat in the introduction. Final editing
v.11	17/10/2018	Harry Nicklin	Formatting according to the POWER format
v.12	26/04/2019	Stef Koop	Formatting and language check

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Executive Summary

Europe's cities face increasing stresses predominantly related to climate change. Droughts, extreme heat and floods are expected to form key challenges for politicians, water professionals as well as urban dwellers. In particular, floods are forming one of the most threatening environmental challenge. In order to face these environmental challenges in an optimal way, a tailored integrated analysis of the key costs and benefits of adaptation measures is essential. To understand the costs and benefits of adaptation measures, two aspects are key: an adequate cost estimation and the created value of adaptation measures. Both aspects are to a large extent determined by stakeholder values and assumptions that are in turn restricted by limitations in data availability and inherent uncertainty of what the future will bring. Nevertheless, these uncertainties are unavoidably at the heart of integrated urban water management decisions. Hence, cost-benefit projections should therefore not be avoided but rather embrace these inherent uncertainties in order to enable more informed decisions. Through the monetization of created value and a proportional effort to estimate the costs over a prolonged period of time, an overall estimate of the costs and benefits can be provided for various measures. It may be particularly helpful to compare these different scenarios with the business as usual (i.e. when no adaption efforts are made). In this way, *the Costs of Inaction*, the costs that may arise if no preventative action is taken, can be quantified. By scrutinizing the various approaches for analysing the cost-benefits of measures to reduce flood risks, this report also provides insights in the possibilities to apply cost-benefit analyses for other environmental challenges that European cities face.

Increasingly, a paradigm shift has been observed from solely flood protection towards more risk-oriented management approaches. Whereas modelling techniques predominantly focus on fluvial and coastal floods, more recent studies have demonstrated that frequently-occurring pluvial flood events cause cumulative damages of a similar order. In particular, when the increase in the frequency and intensity of downpours are taken into account. In order to be useful for cities, cost-benefit analyses have to be tailored to the required level of detail, timespan and allocated budget of individual cities. Therefore, the aim of this report is to develop a framework to distinguish simple, refined, and comprehensive methods for damage assessments, identify key practical barriers and explore ways to address them. The study is based on a literature review, expert questionnaire and, in order to understand the practical implications, an application of flood damage assessment in Leicester (United Kingdom) and Rotterdam (the Netherlands).

Flood risks are a function of flood hazard and consequences; hazard is the flood probability and consequence is the damage caused. Methods of assessing flood hazards are generally more advanced than methods of assessing flood consequences and, consequently, there is a lack of comparable flood damage data to build damage models. The report's extensive literature review of flood damage assessment methods reveals that they almost exclusively focus on direct damage to buildings. Infrastructural damage, intangible damage to health and the environment, and indirect damage incurred by flooding are comparatively underrepresented. As such, the questionnaire results of 30 leading experts, emphasize the importance of infrastructural and intangible damages. The experts also prefer a multi-criteria analysis approach over a fully monetary cost-benefit analysis. Combining the questionnaire findings with the results of the literature review, a distinction between simple, refined, and comprehensive flood damage assessment is outlined. Next, a distinction between simple, refined, and comprehensive methods is provided based on data, time, and financial requirements. Simple methods have minimal data, time, and financial requirements. In practice, these can provide quick, basic first estimates of potential flood damages. Refined methods may estimate flood damage per aggregated land use class, proving more fine-tuned flood risk estimates. Comprehensive methods are often applied for local (micro) scale flood risk estimates, necessitating the effort of collecting object-level data, with the benefit of generating locally-tailored damage assessments. Additionally, a simple flood damage assessment of the city of Rotterdam and Leicester was developed from the

bottom-up. The assessment demonstrated potential pluvial flood damages of €10 million in each city from a 60mm and one hour rainfall event. Results show that there are a few limitations in the calculation process regarding data consistency and the inclusion of infrastructural and intangible damages. Considerable effort is required in collecting data in a cohesive manner in order to obtain a more thorough understanding of urban flood risks and thereby helping cities to secure a safer future.

The distinction between simple, refined and comprehensive assessments may form an important frame to apply to other climate adaptation challenges such as droughts and extreme heat. Key conclusion of this study is that not all cost-benefits can be expressed in monetary terms. In particular, indirect and intangible cost-benefits are difficult to calculate and require many assumptions. Moreover, a key lesson from institutional decision-making literature is that it is essential to strip down the deciding factors of a decision. In determining these deciding factors, that include indirect and intangibles cost-benefits, it may be an important engage multiple-stakeholder including citizens. Digital Social Platforms can have an important facilitating role in this process. Finally, climate adaptation measures often address different challenges simultaneously. For example, green roofs can reduce flood risk, enhance biodiversity, air quality and aesthetic value. In order to seize opportunities of co-benefits, it is therefore essential to formulate deciding factors that are tailored to local situations such as urban neighbourhoods which has also been the focus area of this study.

List of acronyms

BCR	Benefit-Cost Ratios
CBA	Cost-Benefit Analysis
CGE	Computed General Equilibrium
CoI	Cost of Inaction
FDA	Flood Damage Assessment
FLEMO	Flood Loss Estimation Models
FRA	Flood risk Assessments
GDP	Gross Domestic Product
GHG	Green House Gas
GIS	Geographical Information System
I-O	Input-Output
MCA	Multi-Criteria Analysis
MCM	Multi-Coloured Manual
SDC	Stage-Damage Curves
WSS	Waterschadeschatter (model to estimate damage caused by water)
WTP	Willingness To Pay

1. Introduction

1.1 Expansion of cities

In 1960, the global urban population hovered around 1 billion (World Bank, 2018a). It is now over 3 billion and by 2050, cities are expected to shelter two-thirds of the UN medium-variant projected global population of 9.8 billion (UNPD, 2017). Along with providing shelter, cities are nodes of business, communication, entertainment, and innovation, generating approximately 80% of global domestic product (World Bank, 2018b). However, the continuous growth of cities presents numerous risks and challenges for future development (Hoekstra et al., 2018; Kirch et al., 2017). Cities are rife with inequalities and there are more people living informally in city slums than ever before (UN-Habitat, 2016). Crucial services like education, healthcare, and water utilities are often inaccessible to informal city settlers. From an environmental perspective, most of all raw material consumption and production occurs in cities, putting considerable stress on air quality, soil, water resources, and waste management (e.g. Koop and van Leeuwen, 2017; Hoekstra and Wiedman, 2014). Further, at least 70% of carbon emissions originate in cities (UN-Habitat, 2016). Most cities developed in proximity to freshwater sources, as water is vital for drinking, agriculture, transportation and provides aesthetic qualities (Kummu et al., 2011). However, due to urban expansion and climate change, cities are growing increasingly prone to floods with serious socio-economic and environmental consequences. Figure 1 illustrates the increase in flood occurrence since 1980 (EEA, 2016).

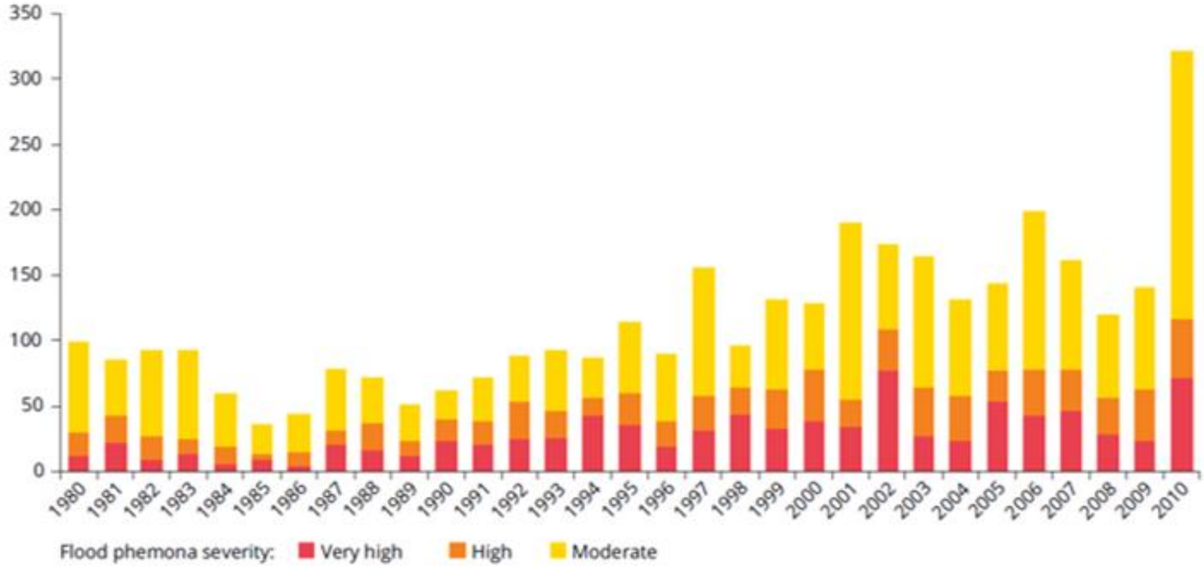


Figure 1 Number of reported flood phenomena in Europe between 1980 and 2010 (EEA, 2016)

Floods are the most frequent and economically damaging natural hazard in Europe (Rojas et al., 2013), and flood risk management is among the five research priorities set forth by European Innovation Partnerships on Water. This research investigates the societal costs of urban flooding. Other climate-related challenges designated as serious risks to Europe are droughts and extreme heat (EEA, 2012).

1.2 Climate adaptation challenges in cities

Cities are faced with serious climate adaptation challenges, most notably, droughts, heat waves and flood risk. Droughts are water shortages that occur when there is inadequate freshwater supply to meet demand, usually after prolonged periods of insufficient precipitation or insufficient snowmelt. In recent years, many places around the globe, notably Brazil, California, and the Mediterranean, have been plagued by droughts. Global warming, economic development, and population growth only exacerbate the problem. Each degree of global warming is estimated to reduce renewable freshwater water resources by 1.4%, while global freshwater consumption is expected to increase by 25% by the year 2050 (Ligtvoet et al., 2018). Without action, the number of people living in perennially drought-afflicted cities could rise to 1 billion by the end of the century (IPCC, 2014). The potential impacts of droughts include crop failures, ecosystem damage, and health risks associated with dehydration or people turning to low-quality water sources (Blue et al., 2015). Below Table 1 displays some of these drought impacts.

Table 1 Droughts impact (Blue et al., 2015; Freire-Gonzalez et al., 2016)

Impact category	Drought Impacts
Economic	- Lost worker productivity - Crop failures - Damaged infrastructure - Lost tourism revenue
Health & Social	- Dehydration - Disease from contaminated water - Loss of well-being
Environmental	- Habitat destruction - Desertification - Soil damage - Increased concentration of nutrients in water

There are numerous options available to address droughts and limit the potentially devastating impacts. On the supply side, freshwater can be made available through investments in water abstraction, treatment, and desalination technologies. On the demand side, freshwater consumption can be reduced by investing in water-efficient production technology, plugging leaky pipelines, and enacting policies to limit household water waste. Most importantly, water use in agriculture, making up most of total water withdrawals, can be made more efficient using drip-irrigation rather than conventional flood or sprinkler systems. Options for expanding water supply or limiting demand require financial investment, therefore assessments (e.g. cost-benefit analyses) are conducted to determine which option delivers the greatest net benefit. There may be knowledge about the cost of, for example, implementing drip-irrigation systems nationwide, but assessing the economic, social, and environmental benefits is more complicated. To estimate the costs of droughts, which can also be framed as the benefits of intervention, researchers use a combination of econometric techniques linking Gross Domestic Product (GDP) losses to drought-afflicted years, market valuation techniques, surveys, and other economic modelling techniques. Using these methods, studies have shown that the benefits of investments in drought management far outweigh the costs of implementation (Schreve and Kelman, 2014; Sanctuary et al., 2005). For a comprehensive review of the way drought costs are assessed, we refer to the article of Birol et al. (2006).

The global mean annual surface temperature currently lies more than 1ºC above pre-industrial levels and 16 of the 17 hottest years on record have occurred since 2000 (IPCC, 2014; EEA, 2018). Maximum daily temperatures are rising even faster, and European cities are exposed to an increasing frequency of summer heat waves (EEA, 2016). Buildings and roads common in cities retain more heat than native vegetation, so cities tend to be hotter than surrounding areas and are considered urban heat islands

(Arnfield, 2003). Due to the urban heat island effect, cities experience twice as many extreme heat days as rural areas (RAMSES, 2017; Arnfield, 2003). By 2100, extreme heat days in European cities could occur 10 times more often (RAMSES, 2017). Considering this, 81% of cities designate extreme heat as a serious or very serious risk (C40 Cities and ARUP, 2014). The main threat posed by extreme heat is health-related; a 10ºC temperature rise is linked with a 1-4% increase in mortality, and 68% of natural hazard related casualties in Europe from 1980-2009 were caused by extreme heat (Luber and Mcgeehin, 2008; EEA, 2010). Other threats include air pollution, increased energy demand for cooling, reduced tourism revenue, and reduced lifespan of infrastructure (IPCC, 2014; COACCH, 2018). There is an interest in estimating the societal costs of extreme heat days in urban areas to improve the understanding of climate risks and show the benefits of heat-reducing adaptation options. Adaptation options include expansion of green zones, wind corridors, installation of green roofs and solar blinds, redesigning building codes, and upgrading infrastructure to make it more heat resilient (IPCC, 2014; C40 Cities and ARUP, 2014; RAMSES, 2017). In 2017, the Reconciling Adaptation, Mitigation and Sustainable development for cities (RAMSES) project estimated the costs of extreme heat compared with some adaptation options to calculate the net benefits of pursuing adaptation. Using national labour statistics to estimate the costs of extreme heat in terms of lost worker productivity and increased mortality rates in three European cities, the project concluded that the net benefits of adaptation range from €-314 million (cost of adaptation) to €23 billion (RAMSES, 2017). As a growing body of research indicates, preparing for the dangers of a warmer future can yield large benefits compared to costs of adaptation (COACCH, 2018).

Of the €150 billion in reported damages caused by natural hazards in Europe between 1999 and 2009, over €50 billion came from flooding (EEA, 2011). The main types of floods affecting European cities are coastal, fluvial, and pluvial. Coastal flooding is caused by rising sea levels, tidal surges, and waves. Due to the extreme nature of some coastal floods (e.g. tsunamis) and the corrosivity of saline seawater, these types of events can be highly damaging (Penning-Rowsell et al., 2014; Olesen et al., 2017). Fluvial flooding is river flooding, usually occurring at high velocities and problems are amplified if river water is contaminated or contains debris (Olesen et al., 2017). Prominent examples are the flooding of the Elbe and Danube river floods (2002, 2006), British summer-time floods (2007), and widespread river floods in central and eastern Europe (2013) (Rojas et al., 2013; Jongman et al., 2014). Pluvial flooding is caused by heavy rain events that urban drainage systems are unable to cope with. Pluvial floods are often of low depth but occurs more frequently than other types of floods, leading to high cumulative flood damages in cities where impervious surfaces stop rainwater from naturally draining (Freni et al., 2010; Spekkers, 2014). An extreme pluvial flood event occurred on July 2, 2011 in Copenhagen, Denmark, during which 150mm of rain inundated the city centre in two hours. The storm caused insured damages of over €800 million with total damages likely exceeding €1 billion (EEA, 2012; Spekkers et al., 2017). 2017 was the second costliest year on record for flood and storm damages (CRED, 2018). In Europe, annual flood losses are expected to increase five-fold by 2050 and as much as seventeen-fold by 2080, highlighting the need for cities to build flood-resilience (EEA, 2016; World Economic Forum, 2018). However, flood management policies tend to be reactive rather than proactive. For example, the Netherlands formed the Delta Commission in response to the 1953 flood disaster, and Copenhagen initiated their cloudburst management plan after heavy flooding in 2011 (Jonkman et al., 2008; EEA, 2012).

1.3 Cost of inaction and flood risk

Drought, heat waves and floods all require climate adaptation. However, in order to develop a decision-support matrix that includes costs, benefits and societal impact related to measures addressing these challenges, sufficient data is required first. For flood risk, data availability is higher. In addition, flood risk represents one of the biggest climate adaptation issues in European cities. To avoid repetition of flood events, it is best to implement flood-risk reduction initiatives in a precautionary and proactive way. Financial resources for flood-risk reduction are limited, so decision-makers need to be convinced that investments are worth it. They tend to only be persuaded once they have seen the consequences after a disaster has occurred. The concept of the Cost of Inaction (CoI) can be used to present the consequences of disasters that have not yet occurred. If decision-makers are made aware of height of the CoI, the argument for implementing proactive policies and avoiding future costs becomes more persuasive. An increased understanding of the CoI increases awareness of the benefits that can be achieved by building flood resilience, and an increased awareness is a pre-cursor to action.

The CoI can be defined as the future costs that arise if no preventative action is taken. The concept was notably used to present the costs of continuing to allow lead in gasoline in the United States. Leaded gasoline had been quantitatively associated with IQ losses, but it was not until a monetary cost (in terms of lost income) was placed on IQ losses that lead was entirely phased-out of gasoline (Needleman, 2004; Ackerman et al., 2005). Without the translation of IQ losses caused by leaded gasoline into monetary terms, decision-makers were not convinced. Years later, the CoI was well-publicized when Nicholas Stern estimated the economic costs of climate change up until year 2100 if anthropogenic Green House Gas (GHG) emissions continue unabated. Stern concluded that the CoI far exceeds the cost of carbon abatement and recommended the immediate curbing of GHG emissions (Stern, 2008). Since then, the CoI has become a useful tool for demonstrating the costs that can be avoided by taking proactive action in numerous disciplines (Andersen and Clubb, 2013). To understand the CoI, research is needed into the risks of flooding in the absence of adaptation. Flood risk is a function of flood probability and consequence, as shown in Figure 2Figure 2, from the work of Sayers et al. (2013). For example, if a flood with an occurrence probability of once every hundred years (1%) is estimated to cause damages of €100 million, then the flood risk is €1 million for that single year.

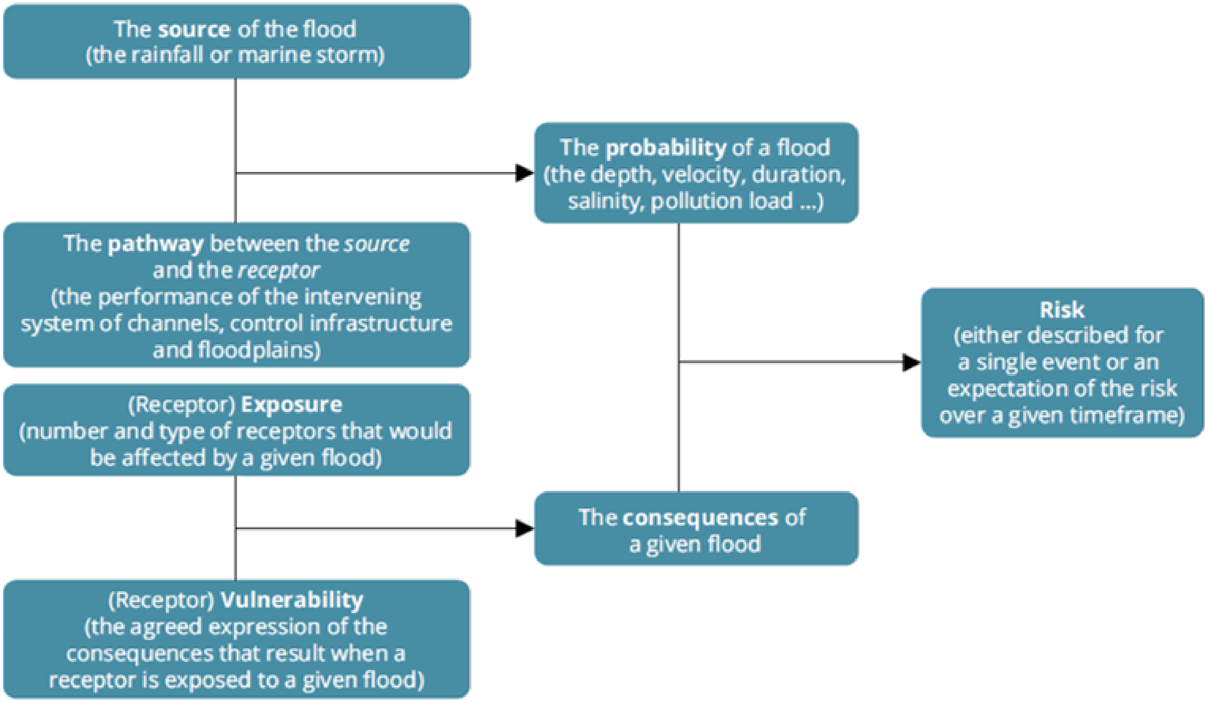


Figure 2 Flood risk concept (Sayers et al., 2013)

1.4 Research aim and outline

In order to develop a matrix to assess the costs, benefits and societal impact of adaptation measures, the CoI has great potential to support decision-makers in understanding the long-term consequences of different climate adaptation options. In order further develop the concept of CoI for urban climate adaptation decisions, it is necessary to focus on a climate adaptation challenge that has sufficient data availability, i.e., flood risk. In addition, the available resources for cost estimation vary greatly between cities, decisions and contexts. Hence, in order to be useful for a broader range of urban climate adaptation decision, the concept of CoI has to be developed in a simple, refined, and comprehensive method. Accordingly, the aim of this report is to develop a simple, refined and comprehensive approach to analyse to cost of inaction that can support climate adaptation decisions in European cities. In doing so, the focus will be on supporting flood risk decisions. The developed method will be tested for its applicability and usefulness in practice by applying it on two European cities.

Three methods are used to answer the research questions - literature reviews, expert questionnaires, and a case study. Section 2 explains the main theories used for estimating flood damages, as identified in a review of recent literature. Literature concerning is reviewed to provide an overview of existing methods and how they can distinguish into simple, refined and comprehensive assessments based on their complexity. Section 3 describes the materials and methods used in the expert questionnaires and case studies. Results are presented in section 4, followed by a discussion of the limitations and general relevance of the results in section 5. This report concludes with a synthesis and some final words in section 6. Finally, the in-depth research reported in this deliverable has a peer-reviewed scientific publication (see Appendix 1 Peer-reviewed article in in the journal of Water.

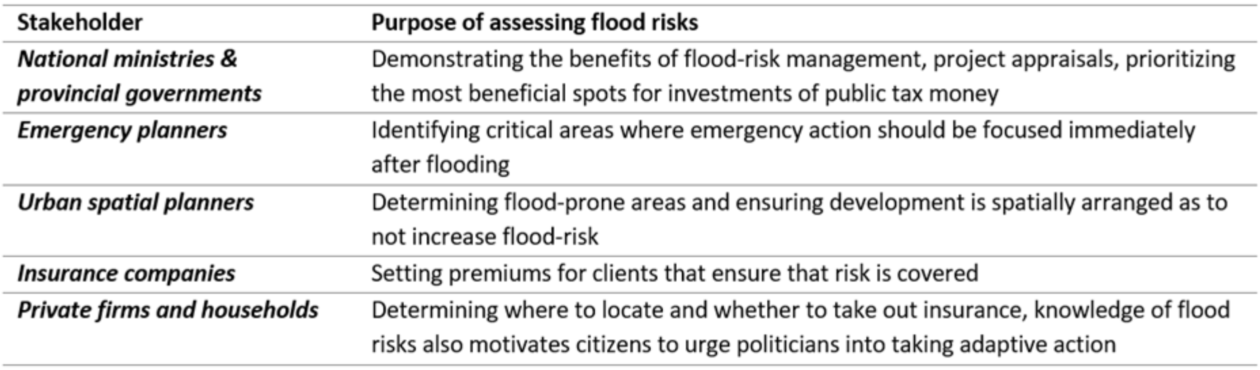
2. Flood damage assessments

In this chapter, first a brief current state of knowledge on Flood Damage Assessments (FDAs) is provided (section 2.1). Next, a conceptual distinction proposed between direct versus indirect and tangible versus intangible flood damages (section 2.2). Sections 2.3, 2.4 and 2.5 provide an overview of current FDA approaches to quantify direct damage, indirect damage and intangible damage for pluvial flooding, respectively. Based on this overview, the advantages and disadvantages of a Cost-Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA) are discussed (section 2.6). Section 2.7 provides a discussion of the how to deal with uncertainties of each method. Although the focus on FDAs, the methodological approaches and key considerations are also applicable in a broader context of analysis costs and benefits of adaptation measures in cities.

2.1 Flood risk assessments: current state of knowledge

The European Commission mandated member states to publish risk maps and implement flood risk management in national policies in the 2007 Floods Directive (2007/60/EC) (European Commission, 2007). Recently, the UN Sendai Framework for Disaster Risk Reduction 2015-2030 placed understanding and assessing flood risks as a top priority for reaching sustainable development goals by 2030 (UN, 2015). Flood Risk Assessments (FRA) are valuable to a variety of stakeholders. National ministries and provincial governments are responsible for allocating tax money for flood risk management and must decide where to prioritize investment (Escuder-Bueno et al., 2012). Without FRA, cities may encounter issues of wasting precious funds by reducing flood risks in areas that do not really need it or are failing to provide funds to the areas in urgent need. They rely on FRA to optimize decisions and to demonstrate the benefits of flood risk management in general (Messner et al., 2007; Merz et al., 2010). Emergency planners assess flood risks to designate critical first-response areas, while insurance companies assess flood risks to determine premiums (Messner et al., 2007; Merz et al., 2010). A list of reasons for assessing flood risks is shown in Table 2.

Table 2 Stakeholders and purposes of assessing flood risk (Merz et al., 2010; Messner et al., 2007)



Stakeholder	Purpose of assessing flood risks
National ministries & provincial governments	Demonstrating the benefits of flood-risk management, project appraisals, prioritizing the most beneficial spots for investments of public tax money
Emergency planners	Identifying critical areas where emergency action should be focused immediately after flooding
Urban spatial planners	Determining flood-prone areas and ensuring development is spatially arranged as to not increase flood-risk
Insurance companies	Setting premiums for clients that ensure that risk is covered
Private firms and households	Determining where to locate and whether to take out insurance, knowledge of flood risks also motivates citizens to urge politicians into taking adaptive action

Historically, a heavier focus has been placed on protecting society from flood hazards through technical means with little thought about managing flood risks (Merz et al., 2010; Sayers et al., 2013). As cities have expanded there has been increasing recognition that cities are susceptible to greater flood damages, leading to a shift in paradigm from flood protection to flood risk management (Jonkman et al., 2008). Data and modelling techniques are still crude for Flood Damage Assessment (FDA) compared to flood hazard assessments (Kreibich et al., 2010; Hammond et al., 2015). There is limited use for detailed flood hazard assessments if detailed FDA are unavailable. To undertake the effort of detailed flood hazard modelling while data input is of insufficient quality is a rather meaningless effort. There is a need to bridge the gap and deepen understanding of flood damages to strengthen knowledge of overall flood risks.

Most flood damage research has been dedicated to fluvial and coastal floods (Merz et al., 2010; Gerl et al., 2016) because these floods tend to be large-scale with more obvious consequences than pluvial floods. However, recent studies have demonstrated that frequently-occurring pluvial flood events cause cumulative damages on a similar order (Zhou et al., 2012). The inundation and damage process for pluvial floods is different than for coastal and river floods, so methods developed for other flood types cannot simple be transferred for pluvial FDA (Kellens et al., 2013). There has been relatively little emphasis placed on consistently collecting damage data and developing standardized pluvial flood damage models (van Ootegem et al., 2015). Inconsistency in data collection makes it difficult to compare estimates between models, consequently, it is harder to share results and experiences between different areas (Kemfert and Schumacher 2005; Hunt and Watkiss 2011). Efforts are needed to assess pluvial flood damages, since they are likely to increase as cities grow and hydrological patterns simultaneously intensify because of climate change (EEA, 2016).

Material damages are easy to quantify monetarily, but intangible damages like environmental and health impacts are less clear (Green et al., 2011). Despite the assumption that pluvial flood events are only small-scale, indirect and intangible damages can be significant in case flood water is contaminated or a vital infrastructure network is disrupted, which makes it important to quantify all flood damages. If only the most obvious damages are measured, then the FDA will not paint the full picture. Direct tangible flood damage like building damage can be expressed in monetary terms without much controversy. To monetize the costs of psychological trauma, or the loss of a pet, or loss of connection to water supply due to flooding can introduce uncertainties and ethical objections, as different people have different valuations of these damages. Intangible and indirect damages should not be neglected solely on that basis, so research into the optimal ways of expressing and presenting these damages to decision-makers is needed to strengthen the use of FDA as a support tool.

The current lack of data on all the factors influencing pluvial flood damages introduces uncertainties (Apel et al., 2009). These can be reduced by developing databases of flood damages and building a deeper understanding of the driving mechanisms, but until then, uncertainties should at least be identified (Merz et al., 2010). The acknowledgement of uncertainty and the limits of damage assessments ensures that users are aware of the limitations before using results to motivate policy choices.

To deepen understanding of FDA, combinations of terms relevant to urban FDA were entered in Google and Google Scholar. The purpose was to identify reports by international organisations and studies in peer-reviewed scientific literature giving detailed descriptions of the methods for damage assessments. Articles and reports published recently (later than 2000) with focus on FDA were reviewed. The keywords used in the search are shown in Table 3.

Table 3 Literature review search terms

Term 1	Term 2	Term 3	Term 4
Urban	Floods	Damage	Assessment
Pluvial	Flooding	Impact	Evaluation
Direct		Loss	Estimation
Indirect		Risk	Calculation
Intangible			

2.2 Flood damage types

Flood damage encompasses a host of harmful impacts on our health, assets, environment, and economy. Distinctions are made between direct/indirect and tangible/intangible flood damage (Thieken et al., 2005; Merz et al., 2010).

Direct damage occurs in the flooded area due to immediate physical contact with floodwater, while indirect damages arise with a time lag or outside the flooded area (Hammond et al., 2015). For example, if a flooded business halts production, the physical damage to assets is constituted as direct damage, while induced losses to supply and demand are indirect.

Tangible flood damage is damage to assets that can be easily monetized with a market price, whereas non-market priced damage (e.g. health loss) is intangible (Messner et al., 2007; de Moel et al., 2015). Some examples are shown in Figure 3.

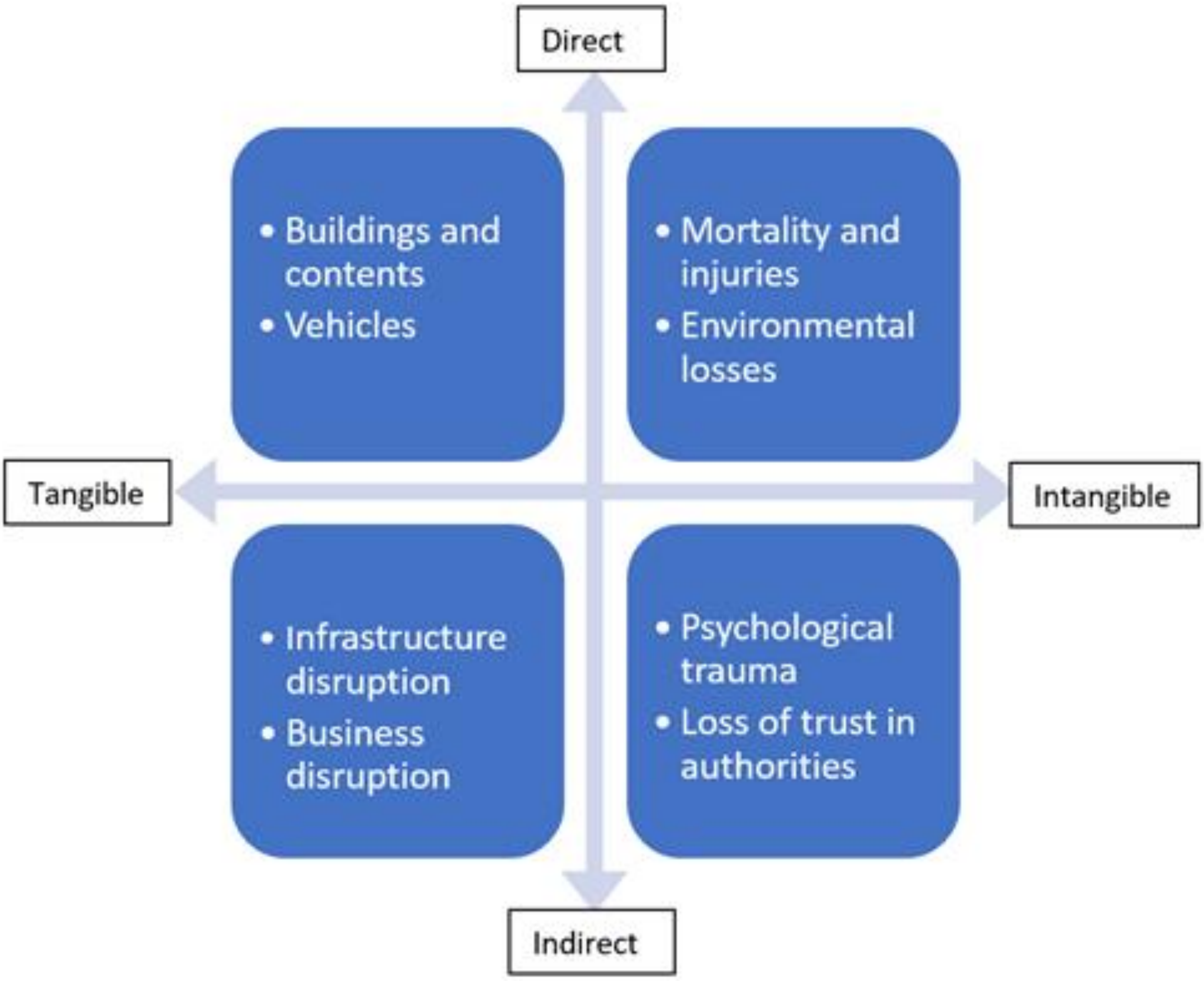


Figure 3 Direct, indirect, tangible, and intangible damage examples

2.3 Direct damage

Physical contact with floodwater is known to cause direct damage to buildings, railways, roads, vehicles, electrical equipment, and many more assets (Merz et al., 2010). Based on observed damages reflected in insurance data, Figure 4 show the contribution of each land use type to total direct flood damage from recent flood events.

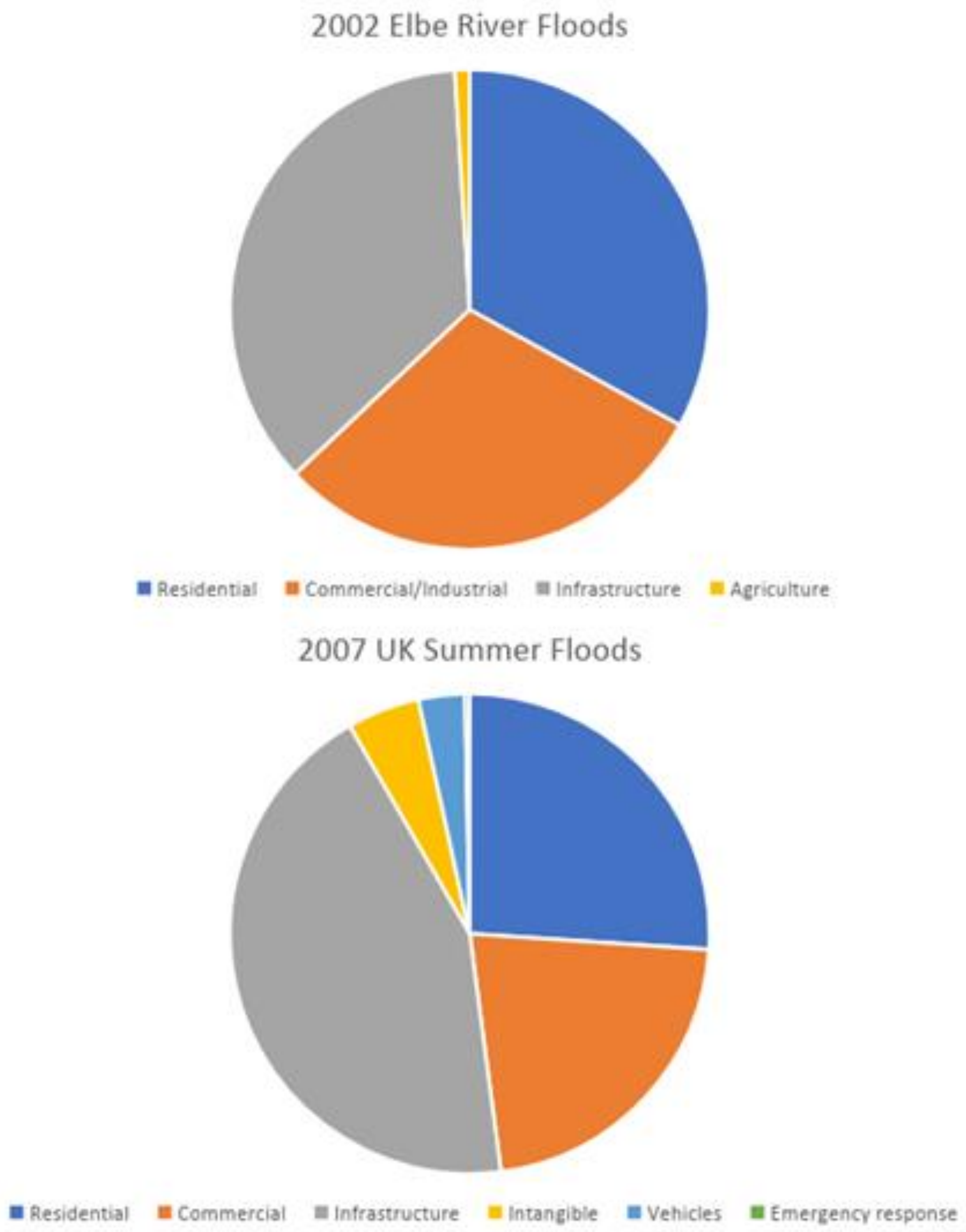
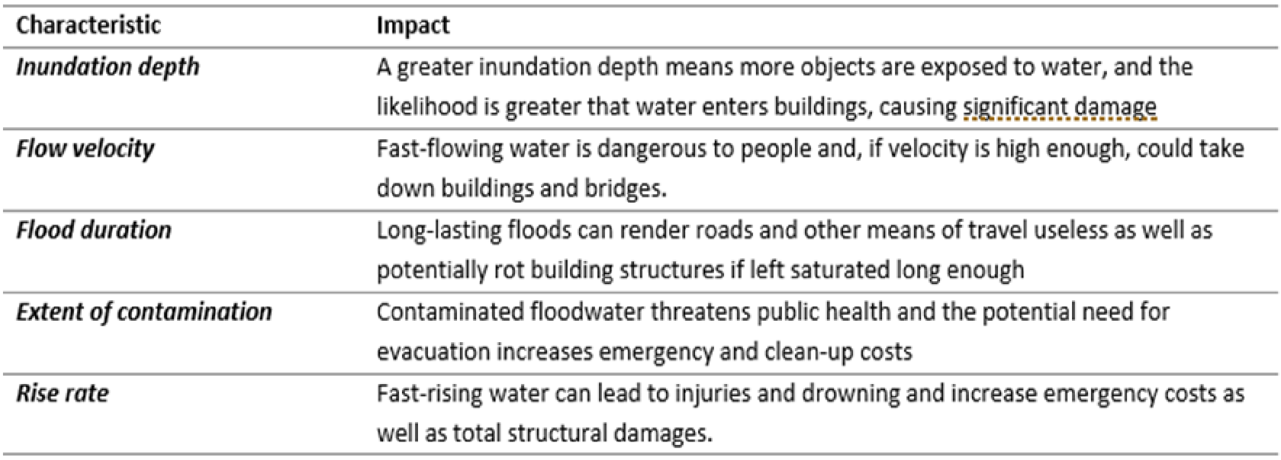


Figure 4 On Top: Insured losses from 2002 Elbe floods (Meyer and Messner, 2005). At the bottom: Insured losses from 2007 UK summer floods (Fenn et al., 2016)

As shown in Figure 4, observed losses for residential, commercial, industrial, and infrastructure sectors are the greatest. This is logical as industrial and infrastructure units are highly valuable, and residential and commercial units are predominant in cities.

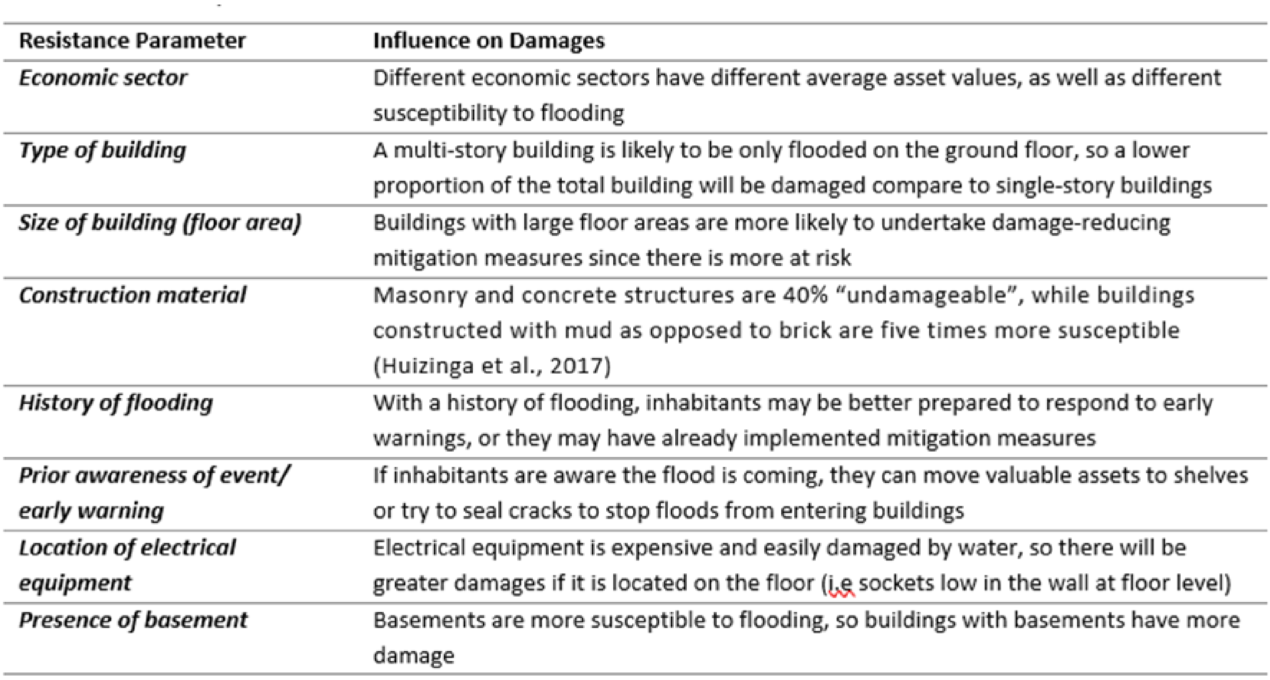
Flood damage is influenced by more parameters than just economic activity and flood depth, for example single-storey buildings and those with basements are more likely to be flooded. Other factors influencing flood damage are shown in Table 4 and Table 5, split between impact parameters describing the flood, and resistance parameters describing flood-prone objects (Merz et al., 2010).

Table 4 Impact parameters



Characteristic	Impact
Inundation depth	A greater inundation depth means more objects are exposed to water, and the likelihood is greater that water enters buildings, causing significant damage
Flow velocity	Fast-flowing water is dangerous to people and, if velocity is high enough, could take down buildings and bridges.
Flood duration	Long-lasting floods can render roads and other means of travel useless as well as potentially rot building structures if left saturated long enough
Extent of contamination	Contaminated floodwater threatens public health and the potential need for evacuation increases emergency and clean-up costs
Rise rate	Fast-rising water can lead to injuries and drowning and increase emergency costs as well as total structural damages.

Table 5 Resistance parameters



Resistance Parameter	Influence on Damages
Economic sector	Different economic sectors have different average asset values, as well as different susceptibility to flooding
Type of building	A multi-story building is likely to be only flooded on the ground floor, so a lower proportion of the total building will be damaged compare to single-story buildings
Size of building (floor area)	Buildings with large floor areas are more likely to undertake damage-reducing mitigation measures since there is more at risk
Construction material	Masonry and concrete structures are 40% "undamageable", while buildings constructed with mud as opposed to brick are five times more susceptible (Huizinga et al., 2017)
History of flooding	With a history of flooding, inhabitants may be better prepared to respond to early warnings, or they may have already implemented mitigation measures
Prior awareness of event/ early warning	If inhabitants are aware the flood is coming, they can move valuable assets to shelves or try to seal cracks to stop floods from entering buildings
Location of electrical equipment	Electrical equipment is expensive and easily damaged by water, so there will be greater damages if it is located on the floor (i.e sockets low in the wall at floor level)
Presence of basement	Basements are more susceptible to flooding, so buildings with basements have more damage

Research of direct flood damage should include more than just flood depth. Other factors can play a role, for example, the presence of basements and carpets are key for pluvial floods that occur frequently and usually at a depth below 20cm (Spekkers et al., 2011). In practice, obtaining this kind of information for all flooded buildings can be problematic.

Methods to assess direct damages

The methods of assessing direct flood damages are embedded in literature more-so than for indirect and intangible damages (Oliveri and Santoro, 2000; Apel et al., 2004; Merz et al., 2010; Gerl et al., 2016). The standard method for assessing direct damages is to link a map of the flood hazard with physical building and land use registers to assess exposure, then use a damage function to translate exposure into monetary damage (Smith, 1994; Merz et al., 2010). A visual depiction of this process provided by Rijkswaterstaat is shown in Figure 5 (Jonkman et al., 2008).

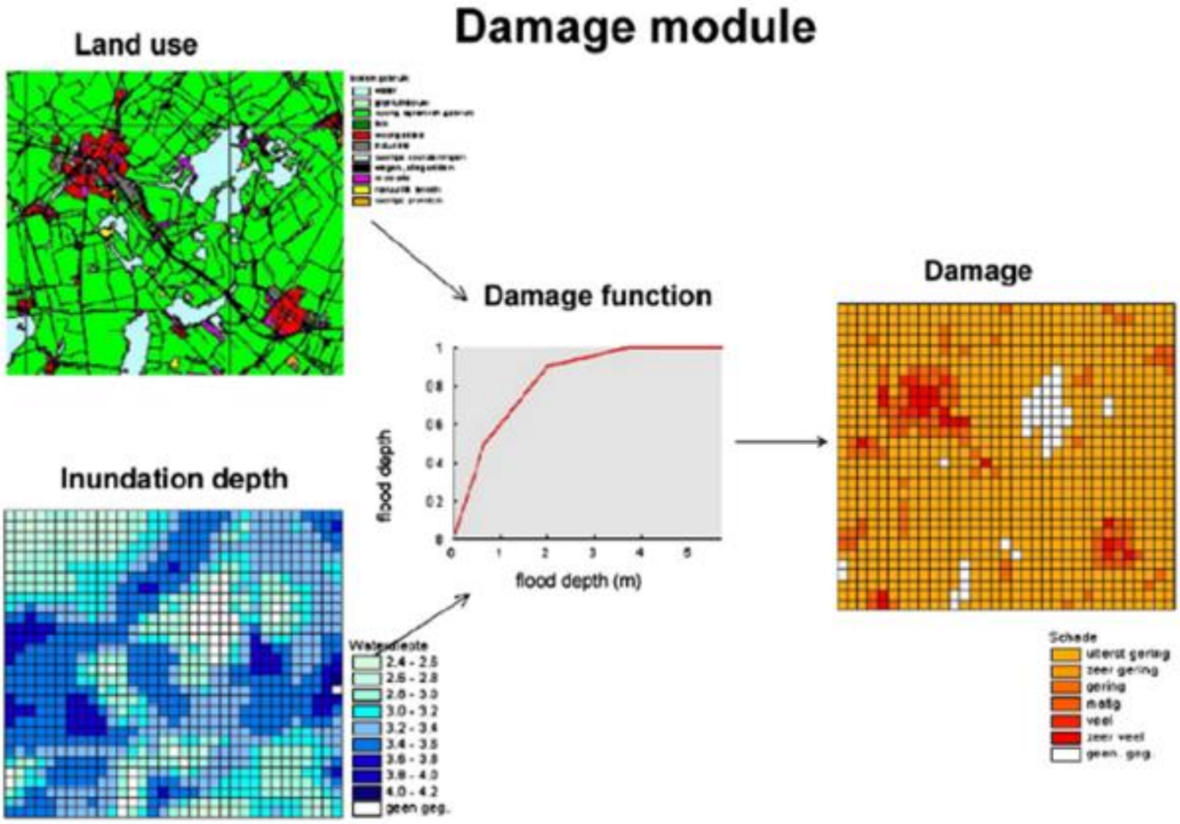


Figure 5 Scheme of the damage estimation process (Jonkman et al., 2008)

Flood hazard mapping

A flood hazard map (bottom-left of Figure 5) is the point of departure for direct damage assessments. Flood depth is usually depicted, but also flow velocity, degree of contamination, and other impact parameters can be shown (Zhou et al., 2012; de Moel et al., 2015). Depth is determined by identifying the watermark for each building, examining satellite remote sensing data of the flooded area, or simulating the spread of a flood using hydraulic modelling (Apel et al., 2009; Freni et al., 2010). Advancements in satellite imagery and hydraulic modelling have supported the development of detailed flood hazard mapping methods that incorporate urban surface water flow processes and interactions with the drainage system, capably expressing flood depth at 0.25m^2 resolution (Maksimović et al., 2009; Leandro et al., 2009). These methods are beyond the scope of this study, but suffice to say, flood hazard mapping methods are more advanced than the current methods of assessing flood damage (Hammond et al., 2015).

Exposure analysis

To assess exposure, the flood hazard map is overlaid with a map displaying each individual object or land use class to see which ones are flooded. A maximum damage value representing the total asset value susceptible to flooding is assigned to get an estimation of the total value-at-risk.

A detailed exposure analysis at the micro-scale uses object-level data to assess exposure for each individual element at risk. To obtain the asset value and flood susceptibility for each individual asset requires extensive effort in scouring real estate databases and conducting field surveys. Especially in large cities, the collection of object-level data is inefficient due to the heavy time, resource, and effort requirements (Hammond et al., 2015).

Instead, objects of similar characteristics are pooled together into groups based on land use for residential, commercial, industrial, and infrastructural sectors (Merz et al., 2010; Bubeck and Kreibich, 2011). For example, the European coordination of information on the environment programme (CORINE) has a land cover data that splits between continuous urban fabric, discontinuous urban fabric, industrial, and road and railway networks is sometimes used (Jongman et al., 2012).

Detailed multi-parameter models also split each sector into sub-classes based on size, building type, building quality, and construction material (e.g. Kreibich et al., 2010; Elmer et al., 2010). This extra layer of detail comes at a cost as it requires greater data. A detailed description of the exposure analysis is provided in the publication of Gerl et al. (2014).

Susceptibility analysis

Susceptibility is analysed with Stage-Damage Curves (SDC), which have been used in flood damage studies globally since 1945 (Smith, 1994; Hammond et al., 2015). SDC show the flood hazard on the horizontal axis with damage on the vertical axis, either in absolute terms (absolute curve) or as a percentage of the asset value (relative curve). Examples of absolute and relative damage curves for industrial damage are shown Figure 6. Note that the flood depth rises to six metres because these curves were developed for coastal and river floods, whereas pluvial flood depths rarely exceed one metre.

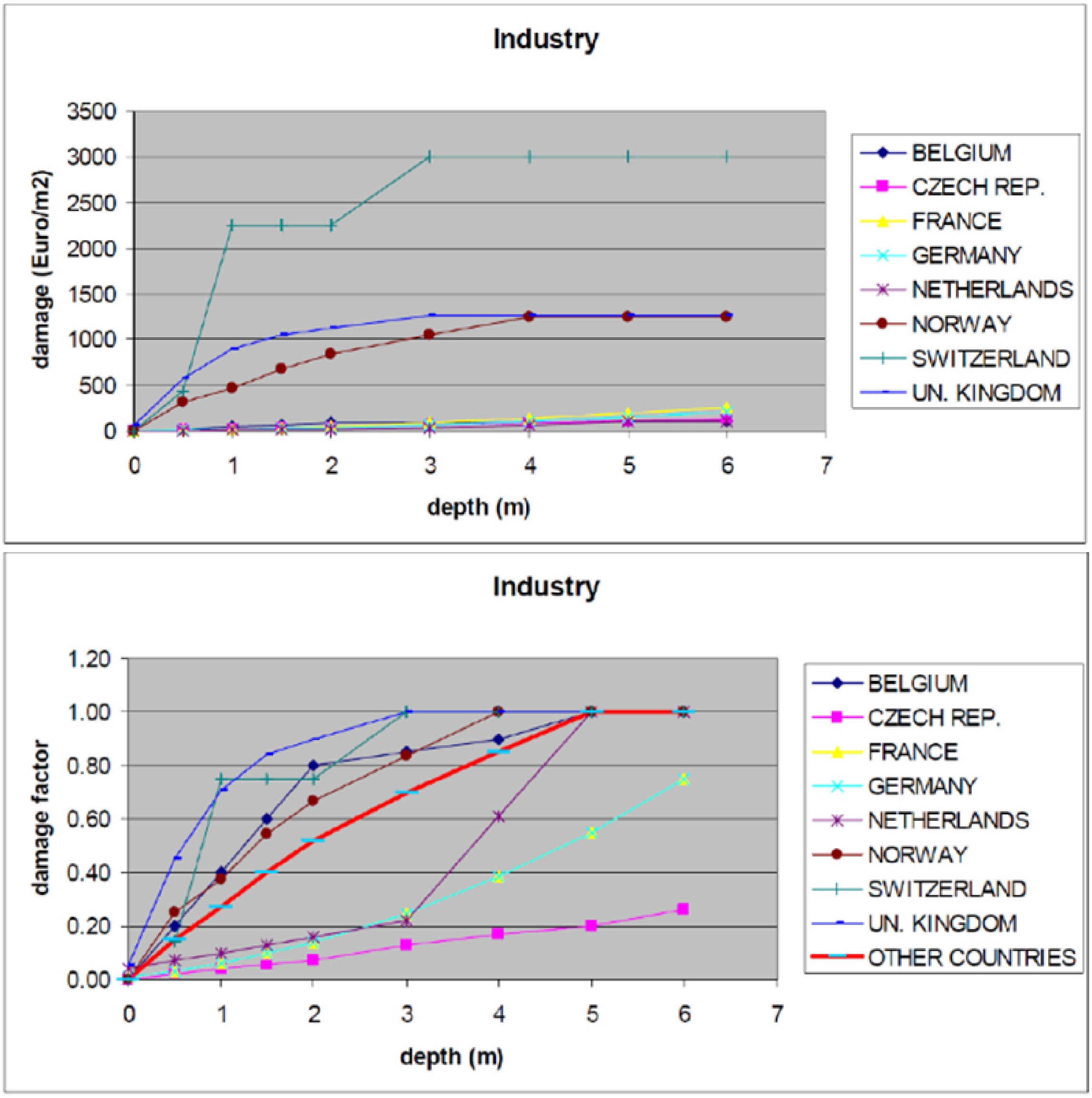


Figure 6 Absolute damage curves for European countries (Huizinga et al., 2017)

As shown above, damage curves differ widely in Europe and depth is the only flood hazard consistently associated with flood damage. It would be ideal to include all relevant impact and resistance parameters in direct damage assessments, but this is not possible due to data limitations (Messner et al., 2007). To develop SDC and define relationships between parameters and flood damage, data is required (Merz et al., 2010).

Data sources

To build pluvial flood damage models, damage data is gathered either empirically or synthetically. Empirical data comes from damage records of past flood events, which can be found in insurance databases (Spekkers et al., 2017). These databases paint a picture of losses in insured households. However, not everybody is covered by flood insurance, so data does not represent the total exposed population. Further, insurance data may not contain any information about the actual flood, only stating monetary damage (Spekkers et al., 2011).

Surveys are used to collect empirical data from flood damage victims. Surveys allow researchers to obtain information about flood damage and resistance parameters that cannot be surmised from insurance data. For example, telephone surveys were used to obtain information about flood damage and the presence of several resistance parameters in households of flood victims to support the development of the detailed multi-parameter Flood Loss Estimation MOdels (FLEMO) in Germany. Data was collected for residential and commercial losses only, and empirical data for other damage classes is still lagging (Thieken et al., 2008; Kreibich et al., 2010). A fallacy of sending out surveys is that respondents may have poor, inaccurate recollections of the flood event.

Synthetic data is generated by asking flood damage experts to estimate what damage can be expected from hypothetical flood events in “what-if” scenarios (Merz et al., 2010; Hammond et al., 2015). The use of synthetic data is commonplace in Europe, for example the Flemish, Dutch HIS-SSM, and UK Multi-Coloured Manual (MCM) damage models (Jongman et al., 2012; Penning-Rowsell et al., 2014). The MCM includes 140 SDC just for the residential class, representing the most advanced FDA method in Europe (Penning-Rowsell et al., 2014). However, it was constructed for coastal and river flooding and no such models yet exist for pluvial FDA. The comparative advantages and disadvantages of empirical and synthetic data are described in Table 6.

Table 6 Empirical and synthetic data

Approach	Examples	Advantages	Disadvantages
Empirical	FLEMO MURL Hydrotec (Germany) ANUFLOOD (Australia)	- Based on real events so more accurate and uncertainties can be quantified - Effect of mitigation measures can be quantified	- Damage surveys often inconsistent so data can be of limited quality - Lack of data for low frequency/high impact events - Difficulties transferring damage estimates as they are based on local conditions that very over space and time
Synthetic	MCM model (UK) HIS-SSM (NL) Flemish Model (Belgium) HAZUS-MH (USA)	- Damage information for any water level and land use type can be developed - Results can be general, not based on local conditions, so possible to standardize damage curves for transfer over space and time	- Considerable effort required to develop and maintain damage databases for every damage type (lots of what-if surveys needed) - Results are subjective, based on expert judgement which introduces uncertainties

Pluvial flood damage: recent findings

There has been extensive research of river and coastal floods, but data collection for developing SDC for pluvial floods is still in its infancy (Spekkers et al., 2011; Grahn and Nyberg, 2017). Stone et al. (2013) and Olesen et al. (2017) argue that due to a lack of pluvial flood data, a simple threshold method is appropriate for assessing flood damage. In the threshold method, damage is a binary function of flooded/not flooded and a constant damage value is assigned if the inundation depth exceeds a threshold (usually 20cm, representing the mean doorstep height) (Zhou et al., 2012; Stone et al., 2013). An equation is shown below (Stone et al., 2013).

IF $\text{WaterDepth}_{\text{building}}$ < Threshold THEN $\text{Cost}_{\text{building}}$ = 0
If $\text{WaterDepth}_{\text{building}}$ > Threshold THEN $\text{Cost}_{\text{building}}$ = ContentDamange + BuildingDamage
ContentDamage = €935 BuildingDamage = €1409 (2012 numbers)

Susnik et al. (2014) relied on this approach to estimate the effects installing a separated sewer system in Eindhoven would have on pluvial flood damage. They estimated damage of €3.35-€3.48 million from a two-year return period event and damage of €88.5-€89.2 million for a 10-year event, showing that separating the sewer system did not significantly reduce damage. However, damage could be underestimated since flood damage is likely to increase beyond 20cm as more building contents, electrical appliances, and power outlets are exposed.

Work is being done to define relationships between pluvial flood damage and parameters other than just depth. Pluvial floods are usually short-lived with negligible flow velocities and rise rates, so these characteristics are not considered key damage determinants (Zhou et al., 2012; Stone et al., 2013; Yin et al., 2016). In cities with connected drainage systems, storm water can be mixed with sewage, increasing health risks and direct flood damage (Thieken et al., 2005; Kreibich et al., 2010; Spekkers et al., 2017). Recent studies have gathered empirical data via surveys and insurance data (Spekkers et al., 2014; Poussin et al., 2015; van Ootegem et al., 2015; Rozer et al., 2016; Grahn and Nyberg, 2017). Key findings are that damages are most influenced by building type, whether the household has prior history with flooding, and awareness of the flood prior to impact. Further, resistance parameters are interdependent, for example, households with prior flood experience can respond more effectively to emergency flood warnings than houses with no flood experience. It is likely that resistance parameters are paramount for determining pluvial flood damage, as they are high frequency events with many opportunities for damage reduction. An overview of recent pluvial flood damage studies is in Appendix 2.

Pluvial flood damage studies are predominantly performed in residential areas, with little emphasis on other sectors. Agricultural damages can be left out since most agricultural areas are likely to be located outside city boundaries. Studies in Germany and England reported agricultural damages between 1-2% of total direct damages (Meyer and Messner, 2005; Hammond et al., 2014). Damage to infrastructure can have extensive knock-on effects, so it is considered as indirect damage in this report.

2.4 Indirect damage

Indirect damage occurs either outside the flooded area or after the flood event (Jonkman et al., 2008; Merz et al., 2010). It refers to loss in flow values rather than loss of stock value, caused by disruptions of linkages in the economic chain (Koks and Thissen, 2014).

Floods can cause severe indirect damages, particularly if a crucial node of business or infrastructure is disrupted, where indirect damages could exceed direct damages (Rose, 2004). For example, if a flour producer is disrupted by flooding, any businesses (e.g. bakeries) outside the flooded area that are reliant on the flour producer for crucial production inputs may also have to halt production. Likewise, if a central infrastructure like a telecommunications tower or power plant is disrupted, all people losing connection will suffer indirect damages. The predominant types of indirect damages are infrastructure and business disruptions. Emergency response costs can be significant for large-scale floods, but usually contributing less than 5% of total damage (Penning-Rowsell et al., 2014).

Methods to assess indirect damages stray from SDC used for direct damage. This is because indirect damage is based on economic factors that dictate the ability of the economy to revert to pre-flood conditions. Some parameters vital for determining indirect damages are shown in Table 7.

Table 7 Indirect damage determinants

Parameter	**Impact on indirect damage**
Production capacity	If business is already producing at full-capacity, they are unable to boost production to make up for flood losses
Import possibility	If importation is possible, flooded areas can receive crucial inputs from non-affected areas
Input substitutability	If business is flooded, alternative sources of crucial inputs can alleviate disruptions
Insurance coverage	Insured sectors receive pay-outs that can be used to boost recovery from flooding
Number of sectors disrupted	There will be less knock-on effects if only a few sectors/roads are flooded compared to if all sectors are unable to operate
Timing of reconstruction aid	If reconstruction aid arrives quickly, businesses will have less down-time and will be able to meet pre-flood conditions quicker
Alternative infrastructure/transport links	If crucial infrastructure/transport node is flooded, presence of alternatives will reduce disruptions

Methods to assess indirect damages

Business interruptions

If information about parameters listed above is available, detailed approaches can be used to model business interruption losses. Input-Output (I-O) models consider the economy as a system, using input-output tables from economic databases to represent production interdependencies, where sectors provide outputs that are used as inputs in other sectors based on a strict, linear relationship (Hammond et al., 2015). By capturing the interdependence between sectors, I-O models demonstrate the higher-order effects of how disruptions in trade flows ripple through the economy (Okuyama and Santos, 2014). However, I-O models overestimate indirect damages since they are strictly linear and do not allow for substitution or adaptive responses during flood recovery (Rose and Liao, 2005; Koks and Thissen, 2014). On the other hand, Computed General Equilibrium (CGE) models - multimarket simulations based on simultaneous optimizing behaviour of individual consumers and firms - are fully flexible and allow for adaptive responses to flooding. These models tend to overestimate our abilities to recover from floods, thus underestimating indirect damages (Rose, 2004; Hammond et al., 2015). Hybrids of I-O and CGE methods have been applied in recent studies to combine the simplicity of I-O modelling with the flexibility offered by CGE models (Hallegate et al., 2008; Rose and Wei, 2013; Koks and Thissen, 2016).

Despite innovations in indirect damage modelling, the use of models is limited by difficulties disaggregating data from the national to the city scale (Green et al., 2011; Okuyama and Santos, 2014). Current models are mostly only applicable at regional or national scales, and they require some expertise to operate (Hammond et al., 2015). Further, pluvial floods may not be as large-scale as other disasters, so simple approaches to estimate indirect damage in cities are used (Meyer et al., 2013). It is common to first assess the shock to the system (direct damage) and use it as an input in the indirect damage estimation (Rose, 2004; Hallegate et al., 2008). If information is scarce, a percentage of direct damage is used to assess indirect damage (Green et al., 2011; Olesen et al., 2017). An advantage is this requires no data other than a direct damage estimation, however it is still highly simplified as it does not consider any other parameters.

Stone et al. (2013) proposed estimating business interruption losses from urban pluvial floods with a threshold method, whereby if flood depth exceeds 10cm, damage is estimated as flood duration times an hourly rate derived from CBS financial data for 21 different sectors. However, this requires data on flood duration and average disruption costs, which may not be available and may add to uncertainty. Furthermore, this method is unable to count for trade disruptions and dependencies between sectors.

A unit-cost approach is used in the US HAZUS-MH MR damage model, which uses a sector-specific indirect damage value per day of disruption. This value is based on relocation expenses, capital related income losses, wage losses and rental income losses (Green et al., 2011). Similar approaches can also be used to assess infrastructural damages.

Infrastructure disruption

Infrastructure disruption is difficult to estimate, since its imprecise how many people lose connection to infrastructure and the value of each lost connection. It is standard in the Netherlands to use SDC to assess damages to infrastructures like roads, railways, electricity stations, telecommunications, and pumping stations (Jongman et al., 2012). However, the damage functions are mostly based on broad datasets that treat all infrastructure types in the same damage class and Bubeck et al. (2011) showed that the damage curves significantly underestimated infrastructural damage from a 2006 Elbe river flood.

Stone et al. (2013) developed a threshold method to estimate damage to electricity systems, whereby a flood depth beyond 30-50cm causes damage of €5,000 and €55,000 to low and medium-tension electricity stations. For indirect damage from electricity failure, a similar threshold is used where flood depth surpasses 30cm, indirect damage is a function of duration of the power outage and the average damage per hour for commercial and residential buildings derived from surveys. A similar method is used to assess costs of traffic delays. There are limitations to these approaches, however, since there is little known about the number of people affected by electricity failures and traffic delays, and the costs of these impacts are uncertain. Pregnolato et al. (2017) reviewed methods of estimating road disruptions from extreme weather, finding that methods rely on unrealistic assumptions like the design capacity of roads is never exceeded and nobody will attempt to drive through a flooded road. Due to these assumptions, monetary estimates of flood disruptions to road transport are questionable. Inconveniences caused by traffic, electricity, telecommunications, and water supply disruptions are hard to monetize, so they are sometimes expressed non-monetarily. Yin et al. (2016) assessed risks of intra-city network interruptions from pluvial flooding and expressed flood risk as the km of flooded road times hours submerged per year (km*h). They found that linkages in the road network and indirect road disruptions increase with flood extent as linking roads become inaccessible. The connectedness within an infrastructure network is important for estimating indirect damage, but it is also crucial to model the dependency between different infrastructure elements.

Pant et al. (2018) tested dependencies between different infrastructures (electricity, airports, ports, telecommunications, water towers, waste water) in the UK by estimating the number of people and networks connected to each node. They found that indirect effects of infrastructure extend beyond flood boundaries and disrupted electricity stations can cause severe knock-on effects for other connected infrastructure networks. The study was performed at the regional scale, and there are less assessments of infrastructure damages at the city-scale. Infrastructure damage is less-researched than damage to residential and industrial sectors, and there is limited data available to build damage models (Merz et al., 2010; Eleutério et al., 2013). Infrastructure tends to be specialised and site-specific, so major efforts are required to gather data to model infrastructural dependencies and damages. Pluvial floods are known to last less than an hour, with minimal infrastructure disruptions in most circumstances, so such effort has not been put into modelling urban infrastructure losses in detail (Stone et al., 2013). Alternative metrics such as number of people connected, or number of infrastructure units disrupted can be used to identify and prioritize vulnerable infrastructure networks for risk-reduction investments (Merz et al., 2010; Pant et al., 2018).

2.5 Intangible damage

There are numerous intangible flood impacts including fatalities, injuries, and traumas, cultural, religious, and environmental losses. Drowning is the leading cause of flood-related mortality, but pluvial floods rarely reach depths high enough to cause drowning (Fewtrell et al., 2008). Environmental losses from flooding can be significant, especially losses to ecosystem functions (Green et al., 2011). However, floods can have positive environmental effects like increasing soil fertility, thus boosting agricultural production (Kummu et al., 2011). Due to these balancing effects and since environmental areas are limited in cities, this report focuses on intangible health losses.

Studies in the UK and USA have reported high incidences of mental-health illness in flood victims, particularly development of post-traumatic stress disorder (Fewtrell et al., 2008; Hammond et al., 2015). Physical injury is also a threat, influenced by the ability of people to resist flood impacts. Factors like age, social status, and neighbourhood characteristics can reflect the social vulnerability of households (Figure 7).

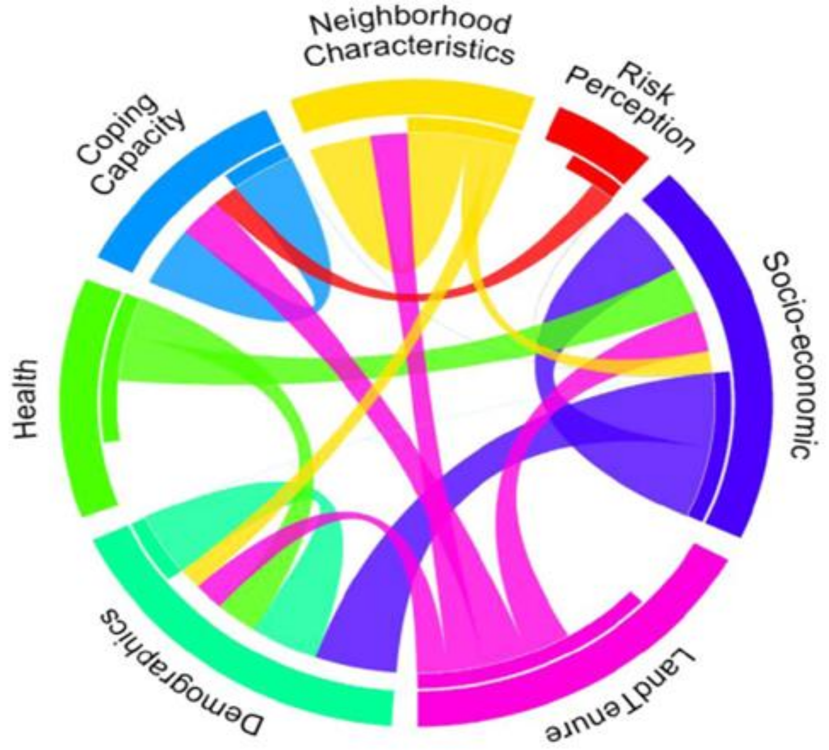


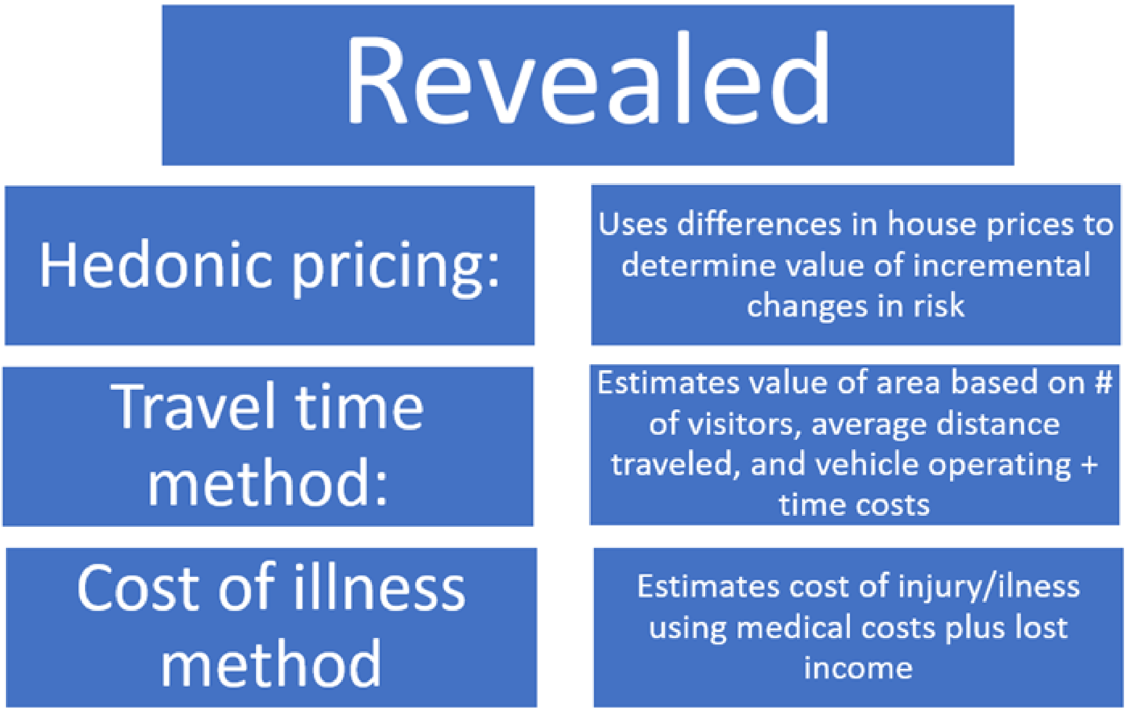
Figure 7 Factors like age, social status, and neighbourhood characteristics can reflect the social vulnerability of households, from the review of Rufat et al. (2016)

In assessing health risks from flooding, traditional means of intersecting a flood hazard map with land cover or building register maps and applying SDC are insufficient. Such methods are used to assess direct damage based on the physical vulnerability of buildings, however health risks are based on the social vulnerability of people (Koks et al., 2015). To assess exposure, demographic and building register data spatially representing the population are intersected with flood hazard maps (Koks et al., 2015).

Mortality functions can relate flood exposure to mortality in the same way SDC relate exposure to monetary damage. One mortality function should not be used to represent the entire population since there are variations in the ability to resist flood hazards (Koks et al., 2015). For example, children and the elderly are more at risk because they are less mobile (Rufat et al., 2015). Social vulnerability indices have been developed to show how variations in socio-economic conditions can determine our ability to resist both health and economic risks from flooding (Cutter et al., 2013; Rufat et al., 2015). Due to mobility issues, not only does an elderly person suffer from a higher health risk from flooding, they are also less capable of effectively responding to early warning signals and saving valuable items. Thus, the incorporation of social vulnerability indices into flood risk management can improve both the estimation of economic and intangible losses, albeit coming at an expense as it requires socio-demographic data at the household level.

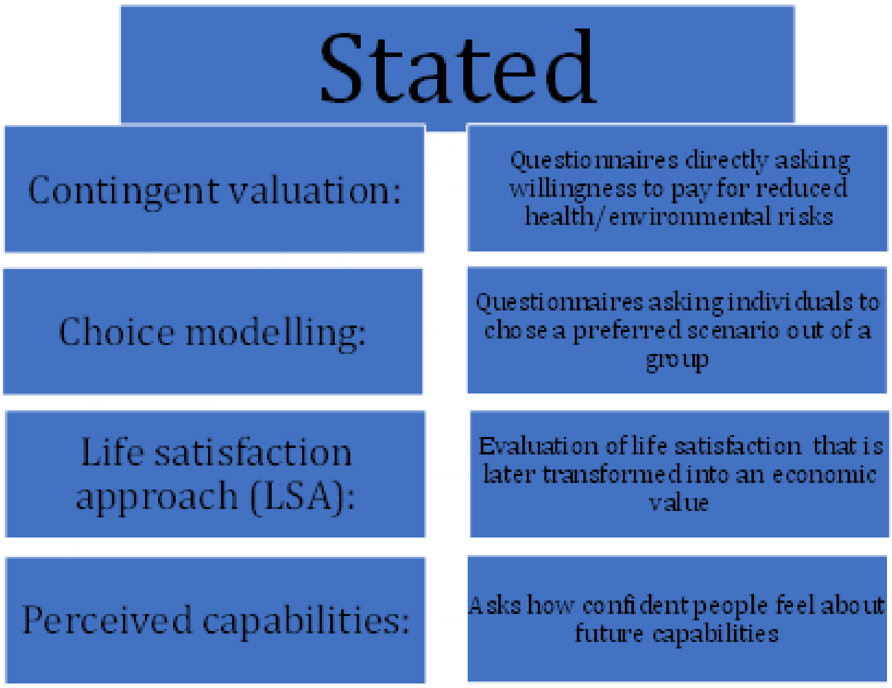
Methods to assess intangible damages

To quantify environmental and health impacts in monetary terms, for example the cost of a sprained ankle or destruction of a national park, environmental economists search for instances where the good is implicitly traded in the market (revealed preference) or ask households to directly state their preference (stated preference). An example of a revealed preference technique for assessing health damage the cost-of-illness approach. This approach considers medical costs, time spent in the hospital and opportunity costs (lost income) to place a value on a given illness. Another example is hedonic pricing, which relates increases in real estate values with reduction in risks to deduce people's Willingness To Pay (WTP) to reduce flood risks. Stated preference methods are surveys that determine the value of an environmental good or health impact based on hypothetical statements made by people. A prime example is the contingent valuation method, in which respondents are directly asked their WTP to reduce health risks. Contingent valuation was used to derive a valuation of £225/household/year for the benefits of eliminating all flood-induced health risks in the UK (UK Environment Agency, 2010). Such a method was also used to ask individuals their WTP to reduce mortality risk and estimate the value of a statistical life at €6.7 million (Hammond et al., 2015). Below, some common revealed and stated preference techniques are described in Figure 8 and Figure 9, adapted from Green et al. (2011).



Revealed	
Hedonic pricing:	Uses differences in house prices to determine value of incremental changes in risk
Travel time method:	Estimates value of area based on # of visitors, average distance traveled, and vehicle operating + time costs
Cost of illness method	Estimates cost of injury/ilness using medical costs plus lost income

Figure 8 Revealed preference method (Green et al., 2011)



Stated	
Contingent valuation:	Questionnaires directly asking willingness to pay for reduced health/environmental risks
Choice modelling:	Questionnaires asking individuals to chose a preferred scenario out of a group
Life satisfaction approach (LSA):	Evaluation of life satisfaction that is later transformed into an economic value
Perceived capabilities:	Asks how confident people feel about future capabilities

Figure 9 Stated preference method (Green et al., 2011)

Most stated preference methods rely on WTP estimates, which may not consider realistic budget constraints. To overcome this limitation, life satisfaction methods were developed whereby flood victims rate their level of well-being according to an ordinal scale which is monetized by researchers later, overcoming the problem of inaccurate declarations of what people are willing to pay in surveys (Luechinger and Raschky, 2009). Van Ootegem and Verhofstadt (2016) compared the results of life satisfaction and future capabilities surveys to pluvial flood victims in Belgium and the Netherlands. They found that there are negligible changes in life satisfaction due to flooding compared to changes in regarded future capabilities. This suggests that pluvial flood victims worry more about future floods than grieve over past floods as also reported by Lamond et al. (2015), which is not reflected in the life satisfaction method. To avoid controversy monetizing the health impacts of flooding, it may be preferable to use non-monetary metrics like number of people affected to express intangible flood damage.

2.6 Cost-Benefit Analysis versus Multi-Criteria Analysis

Stakeholders need to be informed of flood risks, as without risk awareness they may not be worried enough to act (Raaijmakers et al., 2008; Bradford et al., 2012). The researcher conducting an FDA will gain awareness of economic, environmental, and health-related risks. However, the question remains, how to convey these results to stakeholders responsible for flood-risk reduction?

The traditional method of conveying flood risks is in monetary terms, allowing for an easy comparison with capital investments (ten Veldhuis, 2011). This is done within the framework of a Cost-Benefit Analysis (CBA), whereby the implementation costs of a flood-risk reduction measure are compared with the benefits. This can be expressed as a relative ratio between benefits and costs, or in absolute terms of net benefits. Relative Benefit-Cost Ratios (BCR) are favoured for supporting the prioritization of investments in flood-risk reduction, as projects with high BCR are maximizing the ‘bang for the buck’. Schreve and Kelman (2014) reviewed BCR of risk-reduction measures reported in natural hazard studies. While studies varied in the methods used to assess benefits and costs of risk-reduction, the

BCR reported indicate that the benefits of risk-reduction outweighed implementation costs. In flood studies, the reported BCR ranged from 1.3 to 60 with nearly 50% of BCR above 10. However, it is frequently noted in literature that the usefulness of CBA for conveying flood risks is constrained by several limitations (Meyer et al., 2009; Schreve and Kelman, 2014). Social and environmental flood consequences are often left out of CBA, so these analyses place heavy weight on physical building damage and do not paint the full picture of flood risks (Meyer et al., 2009; Veldhuis, 2011). Brouwer and van Ek (2014) reported that investments in flood-risk reduction via floodplain restoration are not supported by CBA unless fatalities are monetized and included. Also, CBA place no emphasis on the spatial distribution and may be used to only support flood-risk reduction investments in rich areas with the most valuable physical assets. This is ill-suited for supporting decisions in flood-risk reduction, in which the poor and socially vulnerable are considered the most at-risk (Rufat et al., 2015).

Pluvial floods are characterized by relatively low flood depths and high frequencies, so it is likely that damage to building structures is low compared to other flood damages (ten Veldhuis, 2011; Zhou et al., 2012). Intangible damages may contribute heavily to total flood damage, so Multi-Criteria Analysis (MCA) methods are used. MCA express flood risk with multiple metrics, allowing comparison of flood risks across economic, social, and environmental domains without the forced quantification into monetary terms (Raaijmakers et al., 2008). By using MCA, different risks can be weighed and considered in a more balanced way (ten Veldhuis, 2011). This is advantageous when intangible damages are likely to significantly contribute to total damage. The use of MCA to inform flood-risk reduction decisions has skyrocketed in recent years, as noted in a literature review conducted by de Brito and Evers (2016). There is no single method of conducting a MCA, and different studies vary in the metrics considered and weighing factors used. The standard form is to first classify the risks, usually economic, social, and environmental/ecological risks (Kubal et al., 2009; de Brito and Evers, 2016). For each risk type, evaluation criteria and sub-criteria are chosen. For example, the criterion for economic risk may be monetary damage, with sub-criteria for each land use type (Meyer et al., 2009). Social risk can be evaluated in terms of the number of people affected, with sub-criteria identifying vulnerability hot-spots like schools, elderly homes, and hospitals (Kubal et al., 2009: ten Veldhuis, 2011). A conceptual diagram of the process of setting risk criteria is shown in Figure 10, adapted from Kubal et al. (2009).

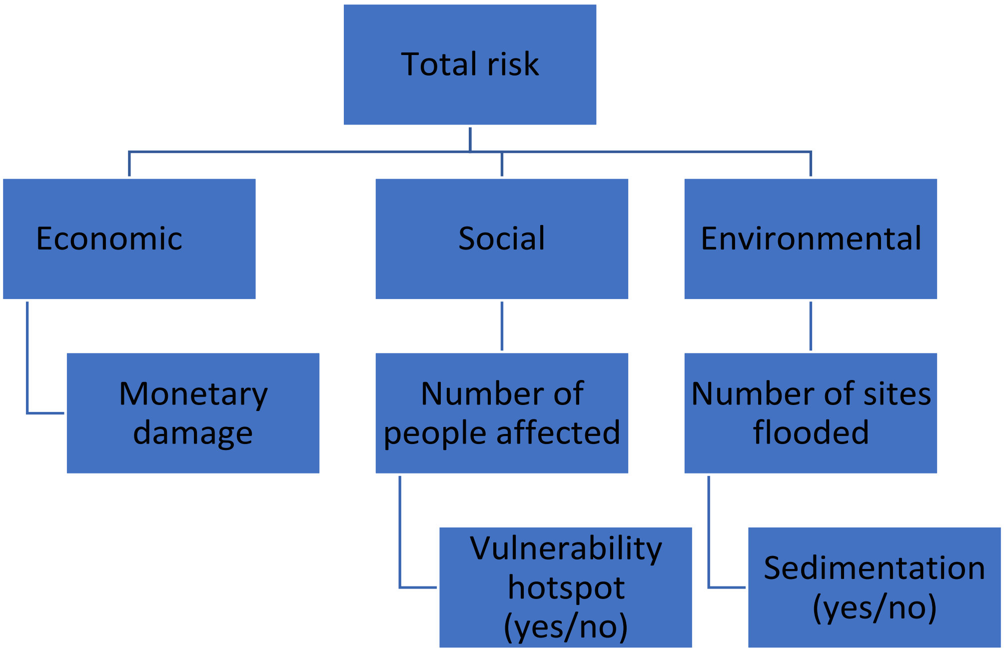


Figure 10 MCA criteria examples (Kubal et al., 2009)

Once damages are assessed for economic, social, and environmental dimensions, the challenge remains of integrating this into an assessment of total damage. All respective criteria need to be assigned weights representing their assumed contribution to total damage. Several approaches have been developed for this, such as analytical hierarchy process, multiple attribute utility theory, and simple additive weighing. For a detailed review of the relative advantages and disadvantages of each weighing method, refer to the article of de Brito and Evers (2016).

The choice of weighing factors can dictate MCA results and is regarded as a core issue of the MCA (Meyer et al., 2009). The weighing approach can be influenced by the perspectives of the researchers or by the results they seek to achieve, which diminishes trust in the outcome (Raaijmakers et al., 2008). The flexibility of MCA can deliver benefits as it allows stakeholders to deliberate until they agree on an acceptable weighing system. It is a more participatory process and dialogue between stakeholders can result in identification of improved alternative options (Green et al., 2011). Such involvement of stakeholders is largely missing from the CBA framework. However, de Brito and Evers (2016) note that few approaches for selecting weighing criteria were based on reaching a consensus, with most only based on majority vote. They also note the presence of stakeholder participation in the MCA procedure is fragmented. Some decisions in the MCA are made solely by experts, which causes problems as experts have greater awareness of flood risks than most people and thus tend to place a higher value on risk-reduction (Raaijmakers et al., 2008).

A concern in both CBA and MCA is the setting of an appropriate discount rate that reflects the relative importance of future well-being compared to the present. Many flood damage studies set a discount rate of 10%, assuming current well-being is 10% more valuable than well-being a year from now (Schreve and Kelman, 2014). In setting a high discount rate, the estimated future benefits of flood-risk reduction are reduced and the case to build resilience is weakened. Further, ethical objections can be raised if too little emphasis is placed on the well-being of future generations. A lower discount rate may overstate the benefits of flood-risk reduction, which may not necessarily be a negative outcome. The discount rate equation is shown Appendix 3.

2.7 Uncertainties

Despite efforts to develop and improve FDA methods, there are still considerable uncertainties remaining. De Moel and Aerts (2011) comment that uncertainties in direct damage modelling are substantial, largely due to a lack of adequate data for the construction and validation of detailed damage models. In the exposure analysis, assets at-risk are spatially represented with low resolution land use maps, and asset values are estimated based on aggregated data that are generalisations of reality. Uncertainties in the application of SDC are even greater as there are many explanatory variables still missing due to data limitations. Attempts of developing detailed decision-tree and Bayesian network to include more explanatory variables and improve predictive capacity of direct damage models are limited by a lack of data relating damages to all explanatory variables (Merz et al., 2013; Schroter, 2014).

Indirect damage assessments are also hindered by the lack of knowledge on economic and infrastructural interdependencies. There are substantial uncertainties about the relation between flood depth and duration with infrastructure damage and disruption (Eleutério et al., 2013; Pregnolato et al., 2017). A lack of available data on direct infrastructure damage as well as infrastructure network dependencies cloud damage estimates in uncertainty.

Intangible damage assessments are limited by the methods used to express damage in monetary terms. Neither revealed nor stated preference methods can place values on intangible impacts without controversy (Merz et al., 2010). Uncertainty can only be reduced by incorporating non-monetary assessments of intangible damages in MCA approaches. However, the usefulness of MCA is constrained by uncertainty regarding the selection of relative weights to assign to each risk dimension.

All aspects of FDA involve uncertainties, mainly caused by a historical lack of focus on assessing flood damages and collecting consistent data to develop predictive models. To better understand the way uncertainties limit damage assessments, questionnaires were distributed to experts and FDA were performed in Leicester and Rotterdam. Materials and methods used to do so are described below.

2.8 Syntheses

Flood risk damage can be distinguished into direct, indirect, tangible and intangible damages. For *direct damages*, a combination of flood hazard mapping, exposure analysis and susceptibility analysis through Stage-Damage Curves is commonly applied. For pluvial flooding, data availability can however be limited. Due to this lack of data, a simple threshold method is often applied. Here damage is a binary function of flooded/not flooded and a constant damage value is assigned if the inundation depth exceeds a threshold (usually 20cm, representing the mean doorstep height). Damage is likely to be underestimated since flood damage increase beyond 20cm as more building contents, electrical appliances, and power outlets are exposed. *Indirect damages* refers to loss in flow values rather than loss of stock value, caused by disruptions of linkages in the economic chain. There are several methods to quantify both business interruptions and infrastructure disruption. However, data availability and assumptions are often problematic. *Intangible damage* is even more difficult to monetise. Intangible health risk can be considered the most relevant intangible damage in cities. Both the revealed preference and stated preference method can be applied through questionnaires to quantify these intangible damage. However, in this discussion it seems that a multi-criteria analysis is more appropriate to properly account for intangibles.

3. Materials and methods

3.1 Expert questionnaires

A questionnaire was developed to supplement literature and reveal outside perspectives about the crucial aspects of flood damage. This method is suitable for accompanying the literature review in identifying the most important flood damage types and preferred method for presenting FDA results.

Suitability, reliability and validity

A reliable method should produce repeatable results, if not, then how can responses be trusted over responses gathered on the next day? To dampen the effect of moods on the questionnaire results, this study considers the median responses for each damage category. In this way, the results should not be influenced by outliers. The questionnaire is meant to supplement the literature review, so results are cross-checked with existing knowledge to ensure results are not unfounded.

Validity concerns the extent to which the method answers the research question. A similar questionnaire method has been used to sufficiently guide research in past studies. As part of the Methods for the Evaluation of Direct and Indirect flood losses (MEDIS) project, Thieken et al. (2008a) distributed questionnaires to 55 experts asking them to rate the usefulness of diverse types of information for assessing flood risks. The results were used to develop a manual for flood damage data collection and a set of criteria for flood loss documentation (Thieken et al., 2008a). This research will follow a similar structure; the results of the questionnaire are used to identify the flood damage types that are indispensable to any FDA. Especially, the policy demands for decision-support tools for pluvial flood risk have been targeted in the questionnaire. As such it continues the discussion in chapter 2 about direct, indirect, tangible and intangible damages, how to deal with uncertainty and what type of analysis is preferred for policy support, i.e., a CBA or a MCA.

To obtain insight in the water management requirements, a questionnaire was distributed to members of the Koninklijk Nederlands Waternetwerk and employees of KWR Water Research Institute. The questionnaire was developed using the Google Forms app and distributed via link sent by email. A total of 30 responses were collected from consultants, environmental economists, ecologists, policy-makers, and other professionals in the water sector.

Topics addressed

Respondents first stated their name, role, and occupation in the water sector. They were then asked to rate the importance of several types of flood damage, sources of uncertainty, uses for FRA, and adaptation measures from a score of 1 (not important) to 5 (urgent). The purpose was to reveal the perspective of experts not represented in literature about the most significant aspects of flood damage. By using a 1-5 ranking scale, the damage types with the highest median rankings could be identified. The last question of the questionnaire asks whether a CBA or MCA is preferred to express total flood damage. This was to get insight into the optimal ways that flood damages can be expressed from the point of view of diverse experts. Results of the flood damage type's questions and this last question are presented in Section 4. The full questionnaire is presented in Appendix 4.

3.2 Comparative case study

A FDA comprised of 3Di hydrodynamic flood mapping and the WaterSchadeSchatter (WSS) damage estimation tool was performed for a 60mm/1hour rainfall event in Lombardijen (in Rotterdam, NL; Figure 11) and Belgrave (in Leicester, UK; Figure 12). The purpose was to understand the nuances of the process and identify any limitations. Two flood vulnerable neighbourhoods in Leicester and Rotterdam were selected because these areas cover the range of variety of European flood risk challenges. Rotterdam being a Delta city representing major urban areas such as London, Hamburg or the Po valley. Leicester being a typical for riverine flooding such as the Elbe, Arno or the Seine. The vulnerability for pluvial flooding is in both hydrological settings high but may have different flood damage characteristics and different adaptation measures may be more effective. In a practical sense, the results can be used to inform inhabitants of Lombardijen and Belgrave about the potential damages that may arise from a single severe rainfall event. In this way, the most effective climate adaptation measures can be selected.

The approach is to model the flood depth of a 60mm/hour rainfall event. Important here is to connect flood depth map with the sewer drainage system for a better simulation. Next, both neighbourhoods are divided into land-use types, each with different damage characteristics depending on the flood depth. Finally, such detailed flood-damage information can be easily shared with the inhabitants by email, social media or through a web application such as a Digital Social Platform.

Site description: Lombardijen

The area includes some arterial roads, a cemetery to the west, and a large park in the centre/north. There is also a train/bus station and six main shopping streets. It is mainly residential, with a high percentage of elderly citizens. It was chosen for analysis because it is a particularly low-lying area prone to pluvial flooding with many vulnerable elderly residents.

Figure 11 Lombardijen is a neighbourhood in IJsselmonde in Rotterdam (marked Green)

Site description: Belgrave

Belgrave is mainly a residential area, bordered by train tracks on the east and the River Soar on the west. It includes shopping streets, religious centres, and schools, which could be vulnerable to heavy flood damages. This area was chosen for analysis because it is a low-elevation area at high risk from pluvial flooding and is designated as a critical drainage area by the Leicester City Council (Leicester City Council, 2012).

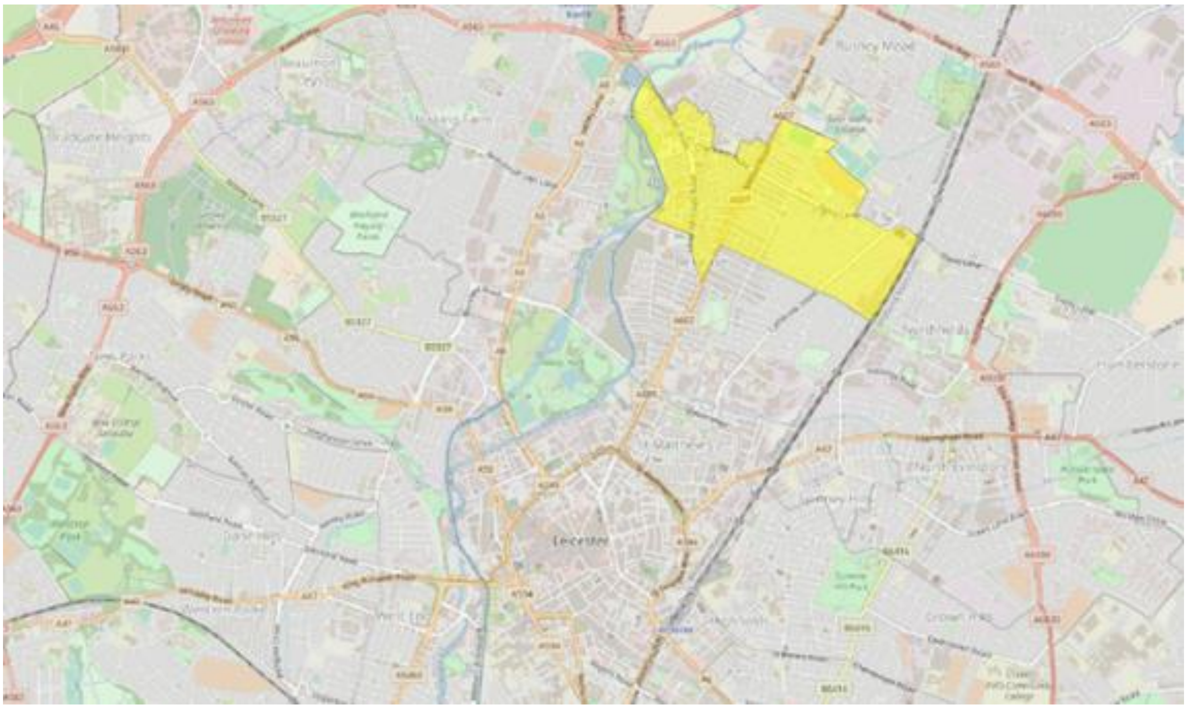


Figure 12 Belgrave is a ward of Leicester in England. The location of Belgrave within the greater Leicester area is highlighted in yellow

3Di flood model

The 3Di flood modelling software was developed by a combination of Stelling Hydraulics, Deltares, TU Delft, and Nelen & Schuurmans. It is a physically-based model designed to simulate the passage of water through urban areas during pluvial flood events. According to Van Dijk (2014), the sewer and surface water systems should be coupled in dual drainage models for realistic flood simulations. Using a sub-grid method, 3Di simulates dual-drainage provides fast and accurate results (Nelen & Schuurmans, 2017). The governing equations of 3Di are given in Appendix 5.

To model urban drainage, a sewer network map displaying the locations of pipelines, manholes and storm drains in Lombardijen was included by Nelen & Schuurmans. This was not available for Belgrave, so infiltration rates of 120mm/hour in parks, 25mm/hour in gardens, 12mm/hour in parking and 0 in buildings and roads are assumed.

The 3Di output displays the maximum water level at the end of the rain event throughout the study area. Subtracting elevation from the water level results in a water depth map. The water depth maps created for Lombardijen and Belgrave are shown below in Figure 13.

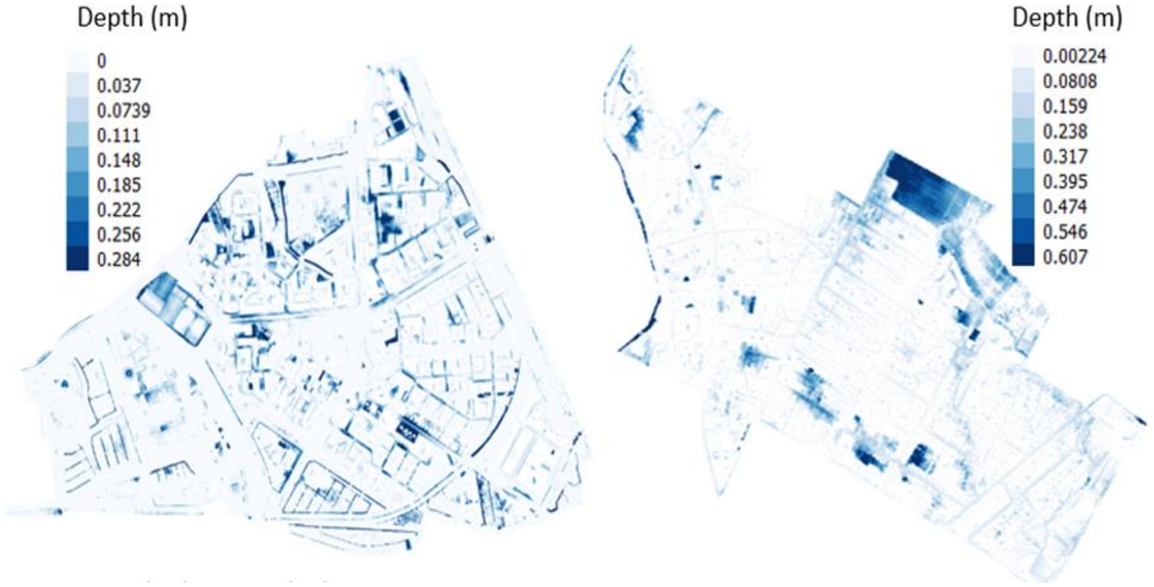


Figure 13 Inundation level for Lombardijen (left) and Belgrave (right)

As shown in Figure 13, both areas have some pools of water, but the water depth in Belgrave is noticeably deeper. This is probably due to a lack of a sewer network in the Belgrave flood model.

WSS

The resulting maps were inputted into the WSS online FDA tool. This is a cloud-based tool that runs on dedicated servers in Amsterdam, enabling computationally intensive flood damage estimations. It was developed by the STOWA consortium of Dutch water companies and was designed to estimate damages from pluvial flooding up to 30cm, later upgraded to estimate damages up to 2.5m.

The water level map was the only input needed to estimate damage in Lombardijen since the WSS already includes elevation data, land use information from CBS, BAG, BGT, TOP10NL, and BRP data sources, and damage functions throughout the Netherlands. For Belgrave, a LIDAR DTM elevation map at 1m^2 was attained from the UK government environmental data online portal. A land cover map was not freely available, so it was created by transposing a satellite map of Belgrave over an empty layer in QGIS and manually forming land use classes. Land was only split between buildings, parking lots, parks, roads, and gardens. The land cover and elevation maps used in the Belgrave study are shown in Appendix 6. Damage functions for Belgrave were also not freely available, so the Dutch damage functions default to the WSS were applied.

The WSS calculates damage with relative SDC, taking the following aspects into account: value of land use class (Ddd), factor for flood depth (Yd), factor for flood duration (Yt), and factor for the month (Ys). All relations between these variables and flood damage were derived synthetically. In this study, flood duration is one hour, and the month of flooding is inconsequential since this only influences agricultural damage, which is not part of this FDA. The equation used for damage calculations in the WSS is shown below in

Table 8, with examples for the six land use classes included in the Belgrave damage assessment.

Table 8 WSS damage equation

$$D_d = D_{dd} * Y_d * Y_t * Y_s$$

Land use class	**Max (D_{dd})**	**Flood depth (Y_d) (0cm, 1cm, 5 cm, 15cm, 30 cm)**	**Flood duration (Yt)**	**Month (Yt)**
Residential	271	(0,0.1,0.5,1,1)	1	1
Educational	271	(0,0.1,0.5,1,1)	1	1
Parks & greens	0.1086	(0,0,1,1,1)	0.8	1
Parking lots	0.076	(0,0,1,1,1)	1	1
Secondary roads	0.076	(0,0,1,1,1)	0.5	1
Gardens	0	0	0	0

The flood depth column shows the damage factor for each incremental water depth value. For example, if a residential building is flooded by 1cm of water for one hour, then direct damage/m^2 (Dd) = 271*0.1*1*1 = 2.71€/m^2. If water depth reaches 5cm, the damage factor (Yd) increases to 0.5, and if water depth reaches 15cm, then Yd becomes 1 and direct flood damage is equal to the maximum damage value. The SDC implementing these equations are shown below, Figure 14 shows the SDC used for all buildings (left) and the SDC applied to parks, roads, and parking lots (right).

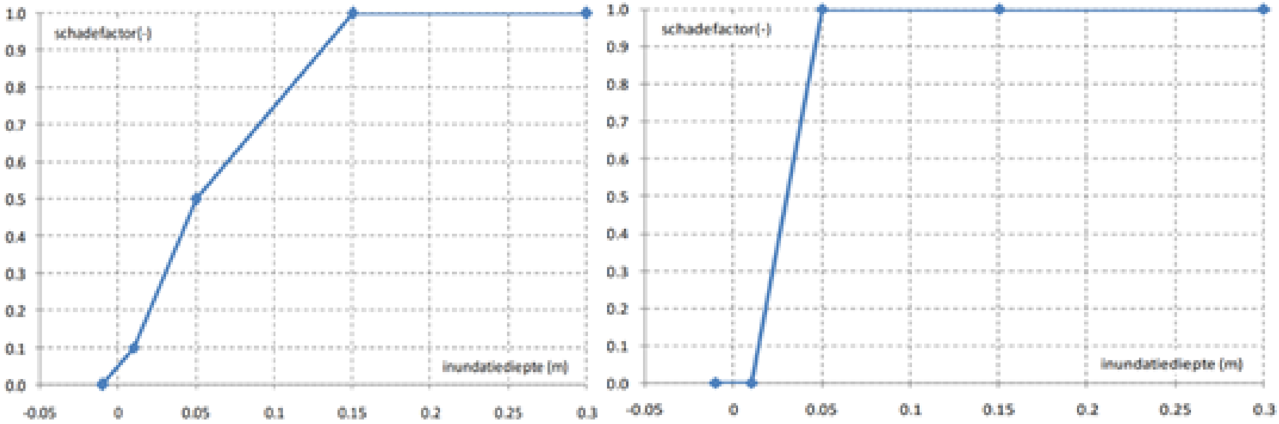


Figure 14 Stage Damage Curve left of buildings, right of parks, roads and parking lots

The SDC shown above were developed for Dutch land uses, but were applied to Belgrave. It is important to note that this transfer of SDC between the UK and Netherlands is not optimal, as their buildings differ in materials and characteristics that influence damage susceptibility.

With these damage functions, the WSS calculates damage per pixel, sums up results per m^2 and sends them as a link via email. The user is given the option of downloading the results in spreadsheet (.csv) or GIS format.

4. Results

In this chapter, we will first present the results of the expert questionnaire (section 4.1). Based on the questionnaire results and the results of the extensive literature study in chapter 2, a seven-step approach for assessing flood damage is proposed (section 4.2) and a distinction is made between simple, refined and comprehensive flood damage assessment (section 4.3). Section 4.4, provide an assessment of the direct flood damage costs in of a neighbourhood in Leicester and in Rotterdam in order to test the practical feasibility of the direct flood damage assessment proposed in chapter 3.

4.1 Questionnaire results

Questionnaire responses are shown in Figure 15, Figure 16 and Figure 17. The horizontal axis shows the rating of importance from 1-5 (1 is low, 5 is high), and the vertical axis shows the frequency of responses. In Figure 15, Figure 16 and Figure 17, it is noticeable that the direct damage types with the highest importance ratings are infrastructure and transportation. Business interruption inside the flooded area is the most important indirect damage. Injuries and casualties are the highest rated intangible damages. For every damage type, the most answered response was either 3 (somewhat important) or 4 (very important), as shown in Table 9.

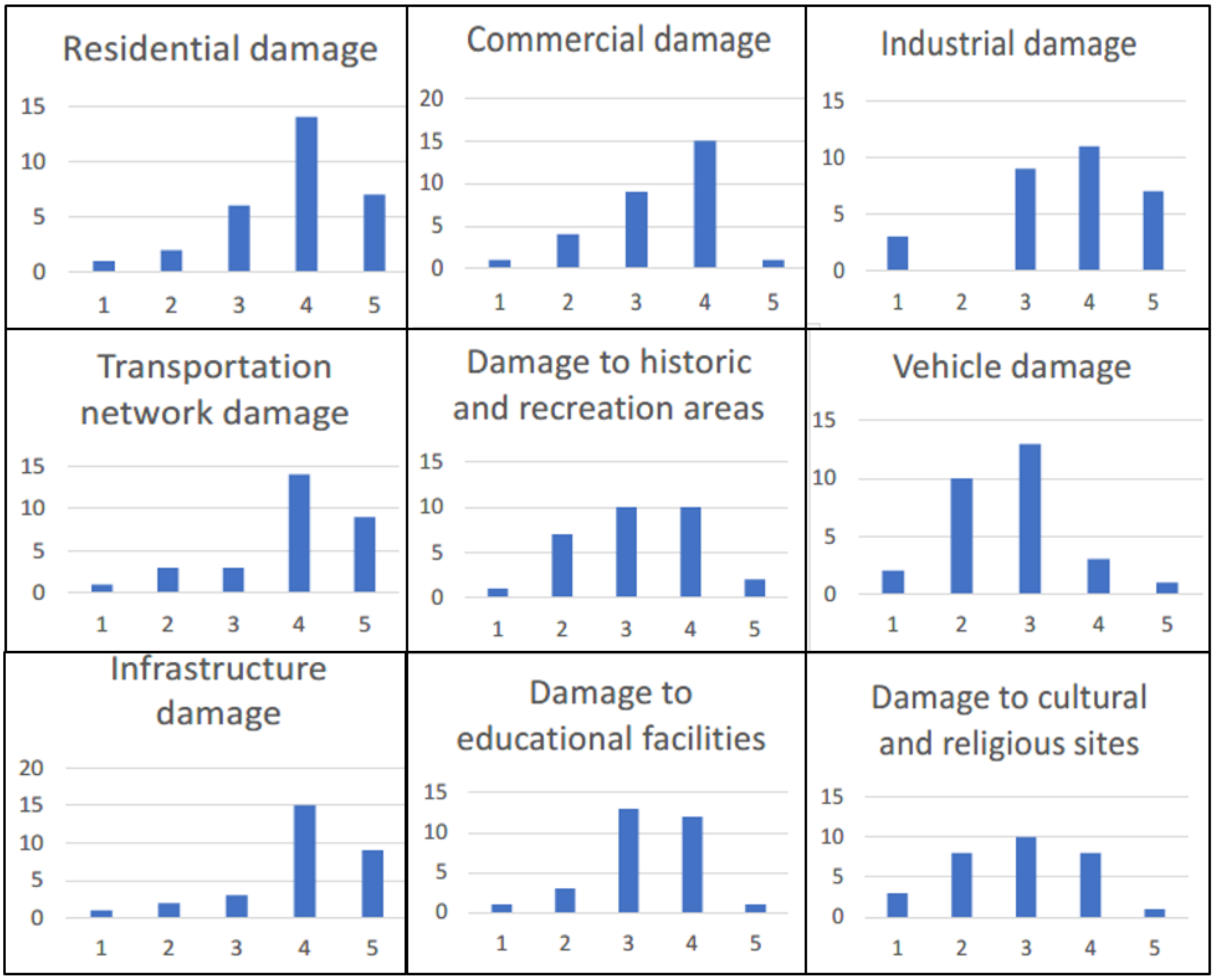


Figure 15 Expert rating of importance from 1-5 (1 is low, 5 is high) for different direct flood damages. Y-axis shows the number of experts. The X-axis shows the importance rating

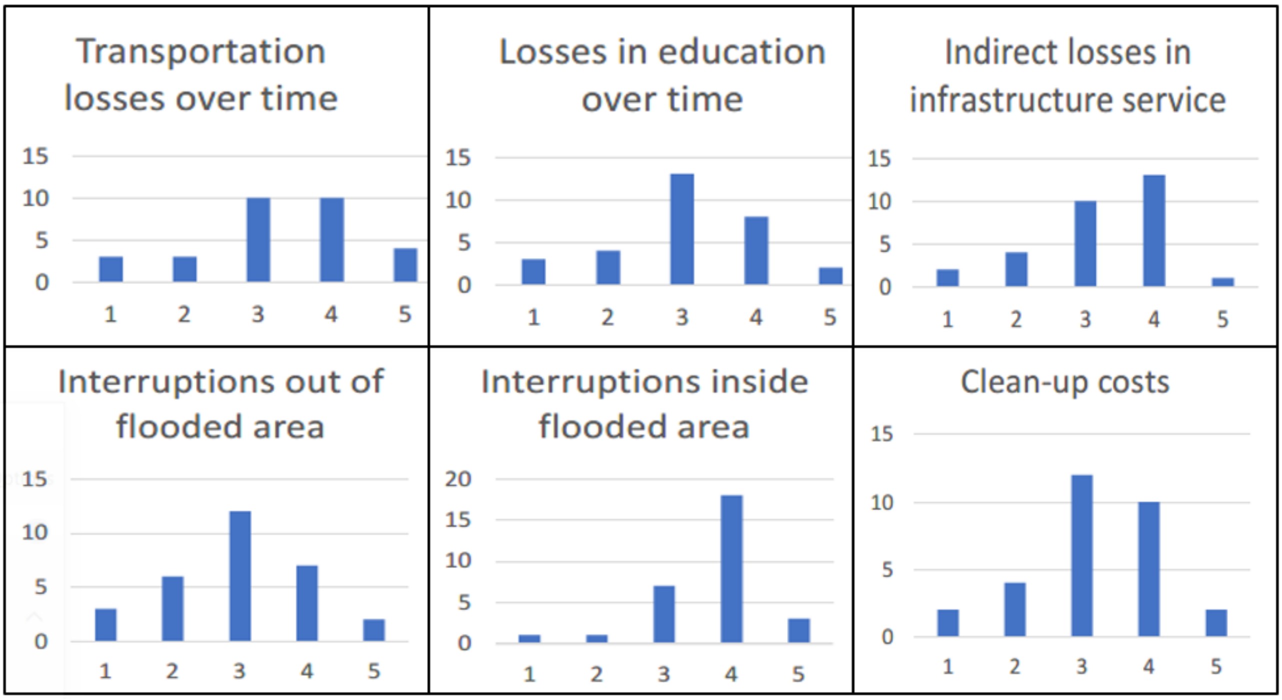


Figure 16 Expert rating of importance from 1-5 (1 is low, 5 is high) for different indirect flood damages. Y-axis shows the number of experts. The X-axis shows the importance rating

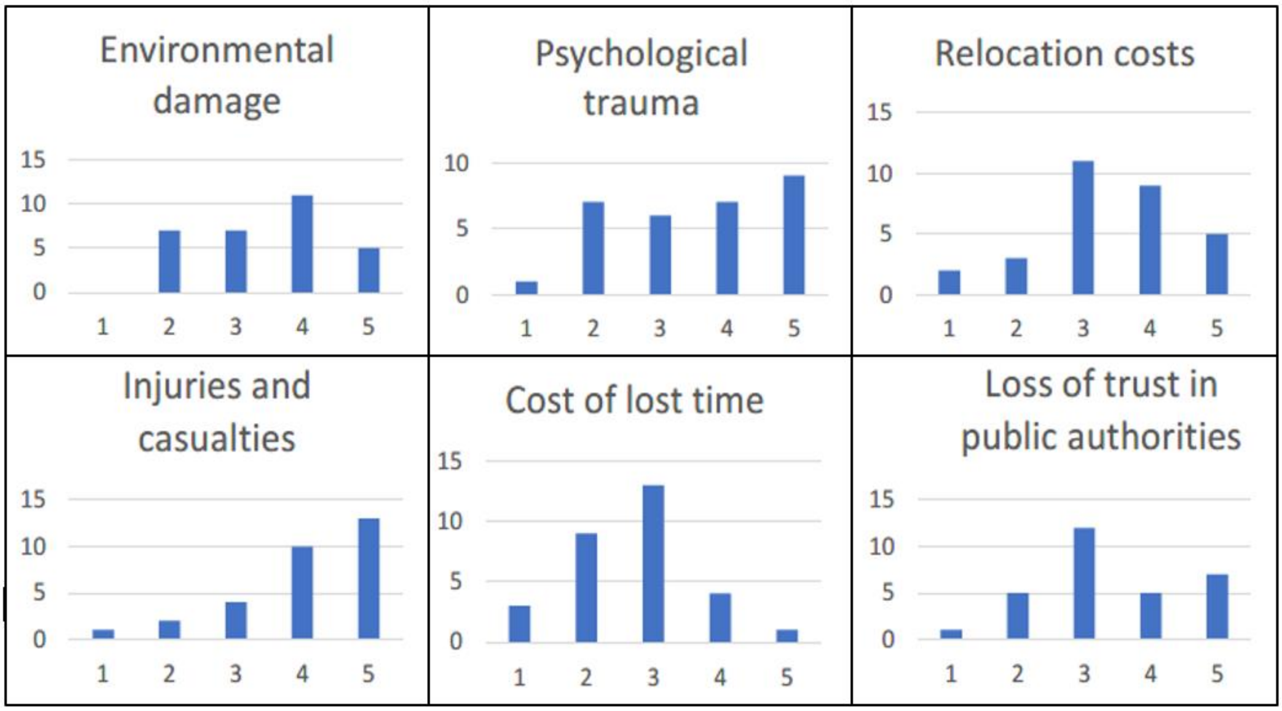


Figure 17 Expert rating of importance from 1-5 (1 is low, 5 is high) for different intangible flood damages. Y-axis shows the number of experts. The X-axis shows the importance rating

The questionnaire results match with those reported in literature. Most studies estimate that residential, commercial, and industrial damages compose at least 60% of total flood damages (Schroter et al., 2014). Direct damages to infrastructure and the transportation network can incur high repair/replacement costs, also causing major delays and disruptions as people lose access to services they require to live and work. It is acknowledged that these consequences are important, but they are complex and there is little knowledge to base damage assessments (Merz et al., 2010; Eleutério et al., 2013). The questionnaire results and literature signify that these damages should be prioritized in future research and decision-making of climate adaptation measures.

Intangible damages to the environment, psychological trauma, and injuries/casualties are stated here as more important than other intangible damages. Pluvial floods rarely lead to mortality but can cause serious injuries and the long-term effects on mental health can be considerable (Fewtrell et al., 2008). Psychological trauma is overlooked because it is harder to recognize than physical injury, but it is considered an essential element of intangible flood damage both in literature and the questionnaire results.

Table 9 Median importance ratings per damage type

Median rating	Damage type
4	Residential Commercial Industrial Infrastructure Transportation Environment Injuries/casualties Psychological trauma Business interruption inside flooded area
3	Vehicles Educational facilities Historic/recreational Cultural/religious Lost time Relocation costs Lost trust in authorities Clean-up costs Business interruption outside flooded area Lost services over time

The only indirect damage type with a median rating of 4 is business interruption inside the flooded area. Several extensive models have been developed to represent indirect flood effects rippling through the economy, but these are usually applied on national or regional scales (Hammond et al., 2015). In the case of urban pluvial flooding, flood durations are usually less than an hour, so impacts outside of the flooded area may be limited. Also, the purpose of urban pluvial FDA is usually to inform city planners who are trying to appease local stakeholders, so any damage outside the flooded area may not matter to them.

Presentation of damage: CBA or MCA

The last question asked respondents to indicate whether they prefer a CBA or MCA using multiple metrics to express damages to present FDA results. Of the 30 respondents, 13 felt they had the knowledge to answer this question. Four indicated they prefer CBA, six prefer MCA, and three commented that they would prefer a combination of both. The distribution of responses is shown in Figure 18.

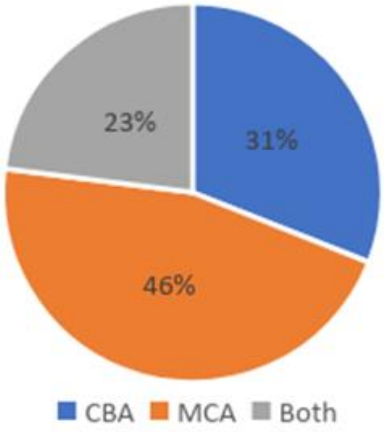


Figure 18 Preference for either a Cost Benefit Analysis (CBA) or a Multi-Criteria Analysis (MCA) obtain from expert questionnaire

As indicated with the rising tide of MCA applications in recent literature, the MCA is considered a meaningful alternative to the CBA. Most respondents note that the CBA is useful for stating flood damage in easy-to-comprehend monetary terms yet is unable to adequately include some of the important intangible damages. Overall, the MCA is the favoured approach, with general acknowledgement that not all flood damages can be monetized.

4.2 Seven-step framework for FDA

Based on the literature review, the FDA process can be split into seven steps as illustrated in Figure 19.

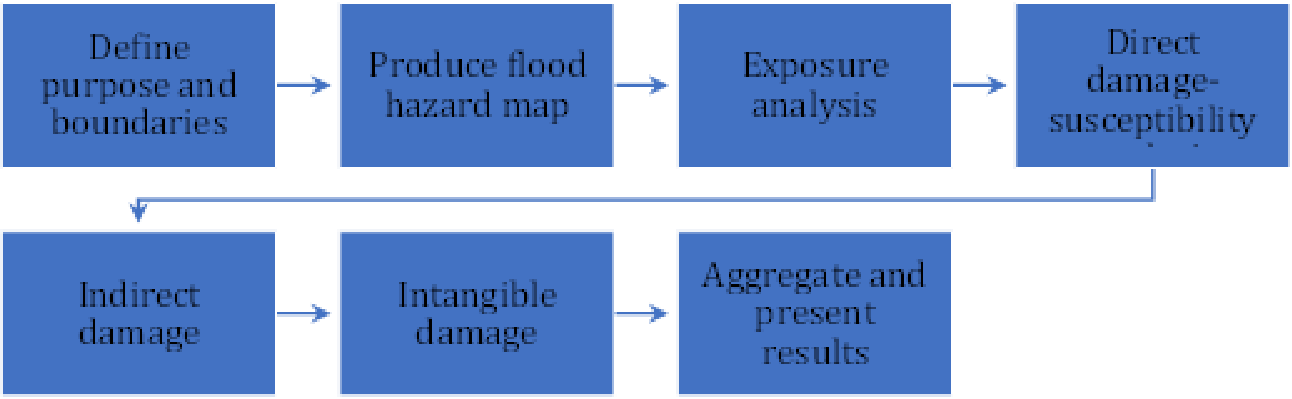


Figure 19 Seven step approach for Flood Damage Analysis

The framework for describing and distinguishing FDA methods splits the process into seven steps. First, it is crucial to define the study purpose and set boundaries of what will and will not be included in the damage assessment. Second, a map of the flood hazard is needed as input for the exposure analysis and rest of the damage assessment. Methods used to produce hazard maps are not part of this study, but the complexity should align with the complexity of the damage assessment (Olesen et al., 2017). Third, the hazard map is overlaid with land use/building register/population density maps to determine the location and type of exposed assets. Fourth, a relation between exposure and direct flood damage (susceptibility analysis) is established using damage functions. Direct damage to some assets like infrastructure or business nodes may incur indirect damages that ripple throughout the economy. Estimating these indirect impacts is the fifth step. Flooding can cause damage to the environment and human health, especially long-term effects on mental health, which are estimated in the sixth step. Finally, results of the direct, indirect, and intangible damage assessments are aggregated into an assessment of total flood damage either in monetary terms, or with multiple metrics.

4.3 Simple, refined, and comprehensive FDA

Combining the seven-step approach with results of the literature review and questionnaires, distinctions between simple, refined, and comprehensive FDA can be made. The threshold between simple, refined, and comprehensive methods is operationalized based on data, time, and financial requirements. Simple methods have minimal data, time, and financial requirements. In practice, these can provide quick, basic first estimates of potential flood damages. Refined methods may estimate flood damage per aggregated land use class, proving more fine-tuned flood risk estimates. Comprehensive methods are often applied for local (micro) scale flood risk estimates, necessitating the effort of collecting object-level data, with the benefit of generating locally-tailored damage assessments. Descriptions of simple, refined, and comprehensive FDA are shown below in Table 10, for greater detail see Appendix 7.

Money is a useful metric since it is common ground that can be used to compare investments in risk-reduction. However, different flood types should not be treated equally in monetary terms. Damage to physical assets can be monetized based on repair costs of buildings and replacement of damaged contents. However, a lost life, extinct species, or development of Post-Traumatic Stress Disorder due to flooding cannot be replaced, no matter how much money is spent. To put a monetary value on these intangible damages implies that they can be restored to pre-flood conditions. Since this is not realistically the case, methods used to value health damage like the cost-of-illness approach and contingent valuation are not always well-received. From the literature review of the common flood damage types and the expert questionnaires, it is concluded that intangible flood damages, especially long-term trauma suffered by flood victims, are too important to ignore, but at the same time cannot adequately be quantified monetarily. The usefulness of MCA is expanding into flood-risk reduction, and future research should continue this trajectory.

Table 10 Distinguishing between simple, refined, and comprehensive methods

Step	**Simple**	**Refined**	**Comprehensive**
Define purpose	Baseline risk assessment to motivate budget allocation for city	Setting building codes, prioritizing investments in risk-reduction	Insurance premium setting, local flood-risk reduction strategies
Hazard map	Flood extent	Flood depth, duration	Flood depth, duration, contamination
Exposure analysis	5 land use types (national/municipal economic data)	Sub-classes for different building types and population map	Sub-classes for precaution, recurrence, social vulnerability (age, social class, single parent) (field surveys and study data), traffic map
Direct damage-susceptibility analysis	Threshold/unit-cost method for each land use type	SDC for each flood depth/building type (FLEMO)	Bagging-tree data mining to derive factors for resistance factors
Indirect damage	Assumed %	Threshold/unit-cost for business interruption, electricity disruption, water disruption, travel disruption	Field surveys to estimate number of people affected by each disrupted infrastructure/business link
Intangible damage	Assumed %	Number of people affected	Social vulnerability index: number, descriptions of people affected
Aggregate results	CBA since all results in $$$, acknowledge limits	MCA with two metrics: monetary damage and number of people affected	MCA with several metrics: monetary damage (direct), people disrupted, businesses disrupted, people affected directly, vulnerable yes/no

4.4 Case study results

In order to test the feasibility of the quantitative flood damage assessment, the method has been applied to both the Belgrave neighbourhood in Leicester and the Lombardijen neighbourhood in Rotterdam. For a more informative MCA, it is recommended to organise several stakeholder meetings and explicitly include citizens, for example through the use of Digital Social Platforms. Only in this way, the most important intangible damages can be tailored to neighbourhood and different adaptation measures can be considered.

Belgrave

The outcome of the Flood Damage Assessment for Belgrave is shown in Figure 20. Areas depicted in red have the highest damage per m^2 (maximum 67.7€/m^2).

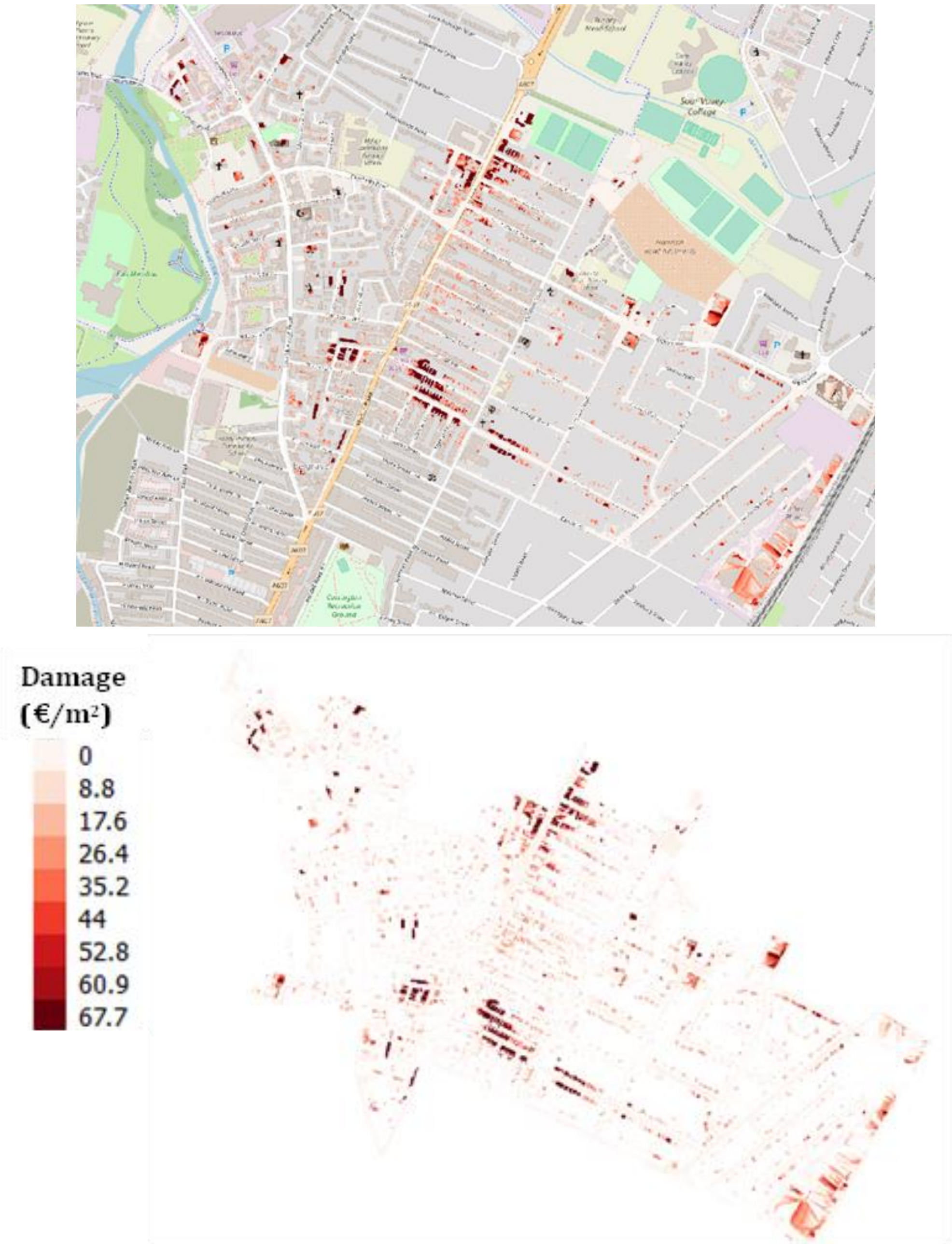
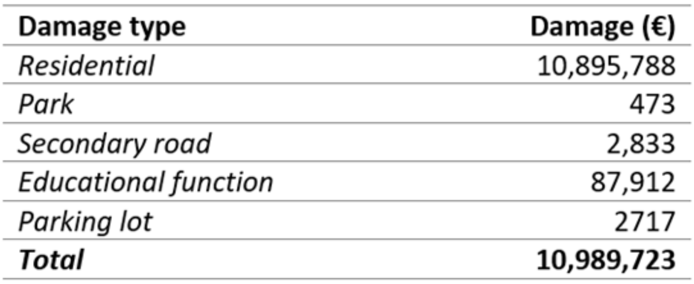


Figure 20 Damage modulation Belgrave

Figure 20 shows that there are several hotspots in the centre and north of Belgrave where flood damage is mainly concentrated. This is likely due to pooling of water at these locations as sewer drainage was not incorporated in the flood hazard model. In fact, the damage hotspots all correspond with spots of low elevation compared to surrounding areas (see Appendix 6). Table 11 displays the total damage for each land use class.

Table 11 Belgrave damage per land use class



Damage type	**Damage (€)**
Residential	10,895,788
Park	473
Secondary road	2,833
Educational function	87,912
Parking lot	2717
Total	**10,989,723**

As shown above, the total direct damage from the one-hour pluvial flood event is nearly €11 million. Over 98% of total damage comes from the residential sector. This is because a building asset register for Belgrave was not freely available, so all buildings were considered either residential or educational. Other studies show building damage of 60-95% of total direct damage (Schroter et al., 2014), but the 98% reported here is due to the rough categorisation of practically all buildings as residential, and the exclusion of damage to infrastructure nodes. However, it should be noted that there are a high concentration of businesses in Belgrave and that the main road through the area (Belgrave Road) is a major route in/out of the city. Hence, potential damages are most likely to be substantially underestimated. Hence, more effort to differentiate land uses based on satellite data is needed to provide more useful results.

Lombardijen

Results of the WSS damage assessment for Lombardijen are shown in Figure 21.

Figure 21 Lombardijen damage estimation over street map

Figure 21 shows that damage is more spread out in Lombardijen than Belgrave, but still tends to be concentrated in a few hotspots. To get a better understanding of the damage distribution, Table 12 and Figure 22 show the share of total damage composed by each damage type. Unlike Belgrave, 15 land use classes were available for Lombardijen.

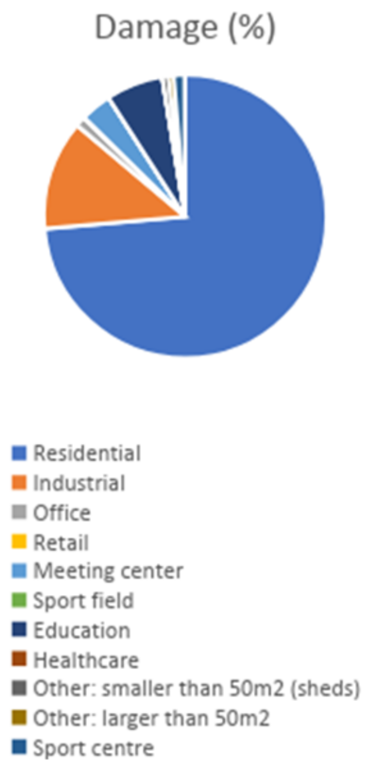


Figure 22 Distribution of estimated damage across neighbourhood functionalities Lombardijen

Table 12 Lombardijen direct damage

Function	Damage (€)
Residential	7,689,460
Industrial	1,306,684
Office	118,048
Retail	8,455
Meeting centre	369,116
Sport field	123
Education	67,7705
Healthcare	4,146
Other: smaller than 50m^2 (sheds)	70,044
Other: larger than 50m^2	63,755
Sport centre	134,132
Train track	737
Primary road	173
Secondary road	1,075.338
Park	134
Total	**10,433,787**

Table 12 shows that total flood damage from the one-hour rainfall event in Lombardijen is €10.4 million, comparable to results in Belgrave. Like Belgrave, residential damage also composes most of total flood damage in Lombardijen, although it is roughly 75% rather than 98%. Direct damage to roads was also significant, over €1 million, which hints that indirect damage could be extensive due to road closures and traffic delays.

5. Discussion

Floods have been detrimental to European countries in recent years, causing hundreds of millions of euros in damages and countless non-monetized impacts (EEA, 2016). River and coastal floods are usually studied as they are the largest floods, but high-frequency pluvial floods caused by heavy rainfall present a growing threat (Penning-Rowsell et al., 2014; Spekkers et al., 2014). Threats are amplified in densely-packed cities, which hold more economic value and impermeable surfaces than surrounding areas. In fact, the case study results show that damage from a single 60mm/one-hour rainfall event exceeds €10 million in both Lombardijen and Belgrave. However, the results were weakened by some limitations relating to the inclusion sewer drainage to calculate the flood depth, the detail of land cover maps, country specific damage functions and difficulty to account for infrastructure damage.

The damage estimates for Lombardijen and Belgrave are alike, between €39,000-50,000 per hectare in each city. They are areas of similar population and building densities, but it is surprising to see such similar results given the gap in complexity between the two studies. For Lombardijen, all relevant input data was integrated in the 3Di and WSS models, resulting in a refined damage estimate. However, data was scarce for Belgrave and the damage estimate can be described as simple, introducing three key limitations to the study.

Sewer drainage is not accounted for in Belgrave

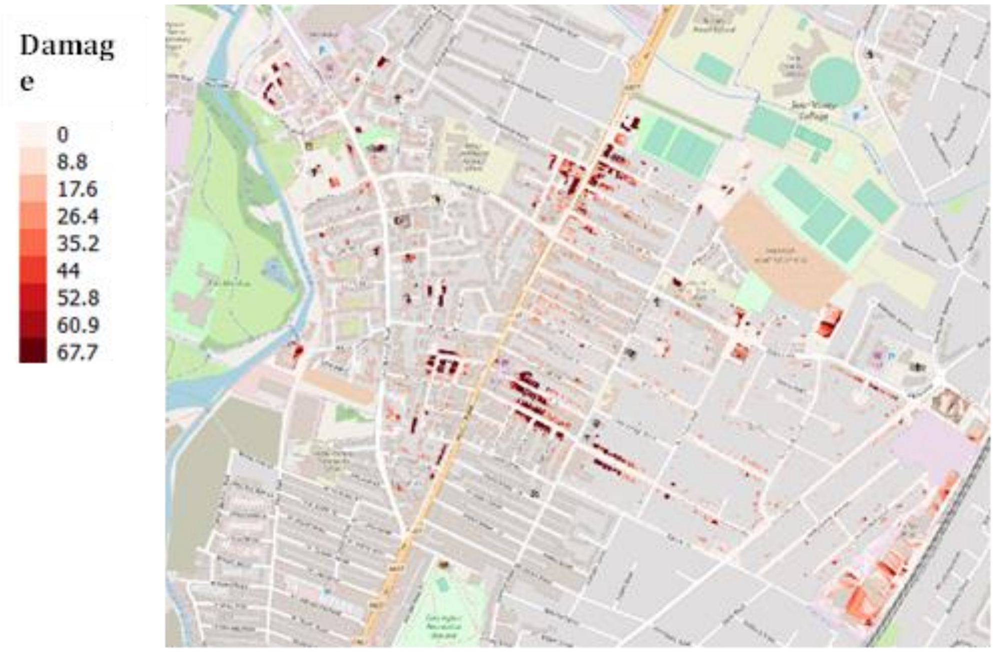
It is crucial to emphasize that the flood depth map for Belgrave was produced without consideration of the sewer network. Sewers and urban drainage systems divert excess surface water flow, which influences flow pathways in pluvial floods (Leandro et al., 2009; Maksimović et al., 2009). For an adequate representation of reality, drainage should be included in flood models, especially in impermeable urban areas where interactions between surface water and sewer systems are key to reducing flood risks. However, access to maps of sewer networks and other urban infrastructural features is often restricted due to strategic and safety concerns (Eleutério et al., 2013). This seemed to be the case in Belgrave, the sewer network map was only publicly available as a hard-copy, incompatible with computer-based 3Di flood modelling. In the absence of a sewer network map, assumptions were necessary, but not representative of local conditions in Belgrave where dynamic interactions with the sewer system are vital for controlling excess surface runoff. Because these interactions were ignored in the Belgrave study, the hazard map likely overestimated the water depth. The maximum water depth in Belgrave is double that of Lombardijen from the same rainfall event. By failing to incorporate the sewer network, the flood hazard map for Belgrave is overestimated. A silver lining is that anything more complex may have been unnecessary due to the simplicity of the subsequent damage assessment.

Undetailed land cover maps in Belgrave

Detailed land cover maps, which are vital for creating homogenous classes for the exposure analysis (Merz et al., 2010), were not freely available for Belgrave. A CORINE land cover map was available, but inadequate because it distinguished the entire Leicester area as either continuous or discontinuous urban fabric. Such broad land classification may be suitable for regional or national-scale FDA but is not detailed enough to sufficiently represent the diversity of land cover at city-scale (Jongman et al., 2012). Because of this data limitation, a land cover map for Belgrave was created manually. This was done by transposing a Google Satellite map of Belgrave over an empty layer in QGIS, and manually assigning land cover classes based on the satellite images. Figure 23 display the satellite map of Belgrave before (left) and after (right) this process.

Figure 23 Manual transposing of google satellite map an empty layer in QGIS. This was necessary to cover classes based on the satellite images

As shown above, the Google Satellite map of Belgrave was transformed into a land cover map depicting buildings in black, roads and parking lots in white, and all other areas in grey. This was a time-consuming task, as each shape had to be created manually in QGIS. So, land cover classes were designated broadly, for example, all green areas like gardens, parks, sport fields, and woodlands identified in the satellite map (Figure 23 left) were lumped into one land cover class (depicted in grey Figure 23 right). Since the Google Satellite map only shows Belgrave from a birds-eye view, it was possible to identify buildings but difficult to distinguish between building types. A building asset register would have helped with this but was not freely available. Due to these data limitations and the cumbersome process of manually assigning land cover classes, the Belgrave land cover map distinguished practically all buildings as residential. Businesses, hospitals, religious buildings, historical monuments, and all other buildings in Belgrave were not distinguished but simply accounted for as residential, which is an over-simplification of urban spatial dynamics. In fact, overlaying flood damage hotspots with a Google Street map, it is evident that more than just residences are flooded as shown in the Figure 24 and Figure 25.



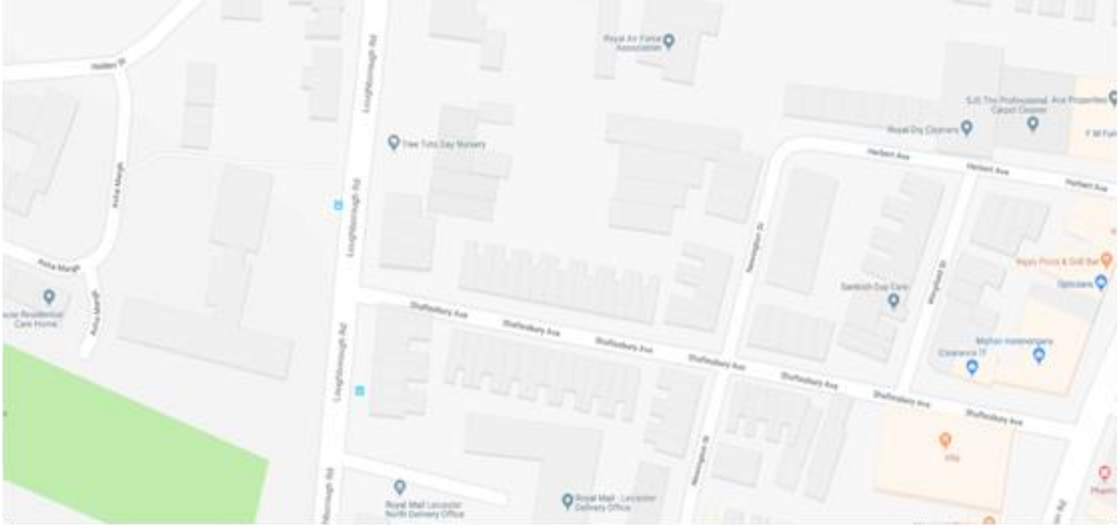


Figure 24 Zoomed in on damage hotspot, red rectangle identifies a day-care centre

Figure 25 Red rectangle shows day-care centre fully damaged

The area depicted in the red rectangle is a day-care centre that is completely damaged by the flood. Surveying the rest of the map, there are many restaurants, offices, and other commercial and industrial units damaged. Additionally, at least two churches, two temples, one mosque, two primary schools, and one police station are at least partially damaged. These different buildings will all have different values and flood susceptibility, so to apply a residential maximum asset value and SDC to all of them is a misrepresentation. It is likely that the Belgrave case study underestimated direct damage, since commercial and industrial units are worth more than residences. Social vulnerability hotspots like day-care centres, nurseries and hospitals that have heightened health risks and reduced capabilities to respond to flood warnings should also be identified for a more accurate depiction of total flood damage.

Damage functions are country specific

The extra effort needed to create detailed land cover classes can only be justified if SDC are available for each land cover class. However, for Belgrave no SDC could be found, so Dutch SDC default to the WSS were applied. Different countries use varying damage functions because they have diverse building codes, typical construction materials, and many other factors that dictate flood susceptibility (Jongman et al., 2012; Huizinga et al., 2017). For this reason, it is not recommended to transfer damage functions between countries unless it is proven that the two countries have similar characteristics (de Moel and Aerts, 2011). England and the Netherlands have some similarities in that they are both relatively wet, flat, and wealthy European countries, but the average buildings are not so similar. Many buildings in the Rotterdam area were constructed post-WW2, whereas some buildings in Leicester date to the Victorian era. Recently constructed buildings may be built to withstand floods or are equipped with some flood mitigation measures that older buildings are lacking (Spekkers et al., 2017). Additionally, England has a higher share of owner-occupied housing than the Netherlands, which has more tenant-occupied and social housing (Vijverberg and Jones, 2005). Owner-occupied houses are more likely to include flood mitigation measures than tenant-occupied, and inhabitants of social housing may not have the capability to implement these measures (Rufat et al., 2015). Considering these differences, damage functions derived for the Netherlands are not expected to realistically represent flood susceptibility in England.

Results of the Belgrave case study can only provide a first-glance, basic estimate of direct pluvial flood damages and should not be used to support any sort of spatial planning or flood-risk reduction decisions. Results between Belgrave and the less-limited Lombardijen study were only similar in magnitude, likely because the overstatement of flood hazard and understatement of flood damage in Belgrave balanced out. However, the end does not justify the means as both the hazard and damage assessments were questionable. Despite the limitations of the case studies, this research can still provide some valuable insights into how FDA can be improved and incorporated in decision-making.

Impact quantification of infrastructure damage is limited

The questionnaire revealed that infrastructural damage is among the most important damage types, with 80% of respondents rating it as either highly important or urgent. Literature tends to focus on residential flood damage, with infrastructural damage recognized but not quantified. Infrastructure damage models do exist, but they tend to underestimate damage compared to observed insurance data, citing a lack of data or insufficient understanding of the relationship between floodwater and infrastructure as key limitations (Eleutério et al., 2013).

Data availability needs to improve to support the development of more comprehensive infrastructure damage models. Without data on infrastructural damage, our understanding of total flood risks will not evolve. When assessing flood damages, it is important to include all relevant damage types, and infrastructure has been shown to be one of them. Underestimating infrastructure damage leads to underestimations of total flood risks, obstructing the case for building resilience. Opening the doors for researchers to collect infrastructure network data and further understanding of this crucial dimension of flood risk should be a priority going forward. Relationships between flood depth and infrastructural damage/disruption should be defined by expert consultation, and more emphasis is needed modelling infrastructural interdependencies at the urban scale – not only national and regional. Until these avenues are explored, infrastructural damage will continue to be inadequately depicted in FDA compared to residential damage.

The literature and questionnaire results also indicate that psychological trauma from flooding is an unspoken threat. It has been shown in some cases that 20% of flood victims develop long-term trauma (Fewtrell et al., 2008). It hardly seems adequate to express psychological damage in terms of money lost, so MCA approaches should be used in any flood studies seeking to get a complete picture of total flood risks. However, a fundamental issue with MCA is the selection of weights assigned to each dimension of flood risk. For example, imagine there is an MCA study comparing flood risk-reduction potential between mitigation options using two metrics: monetary damage and fatalities. Option A can reduce monetary damage by 1 million and saves 5 lives, while option B can reduce monetary damage by 5 million but only saves 1 life. To pick the optimal option, weights needs to be selected representing the relative importance of these two metrics. Thus, the question of how much a life is worth is implicit in the weight assigned to the fatalities metric. There is no agreed-upon method of selecting the weighting criteria, they are usually set through interactions between the researchers and stakeholders (de Brito and Evers, 2016). It is paramount that stakeholders should be involved in selecting weighing criteria in MCA because they are the ones susceptible to each risk dimension.

In this study a questionnaire was distributed to experts asking them to rate the importance of several dimensions of flood risk, showing that experts do indicate some dimensions are more important than others. There are possibilities for a similar approach to be transferred to reveal the attitude of flood-prone urban stakeholders about the types of flood damage they deem most important. This could to ensure that local stakeholders are given the opportunity to have their voices heard and represented in the weights attached to each flood risk dimension. In doing so, stakeholders may trust results more knowing they were involved in the process. Increased trust and transparency can help raise awareness of flood risks and pre-empt investments in building resilience.

6. Conclusions

In order to develop a matrix to assess the costs, benefits and societal impact of adaptation measures, the Cost of Inaction (CoI) has great potential to support decision-makers in understanding the long-term consequences of different climate adaptation options. To further develop the concept of CoI for urban climate adaptation decisions, we have focussed on a climate adaptation challenge that is both relevant and has sufficient data availability, i.e., flood risk. Accordingly, the aim of this report is to develop a simple, refined and comprehensive approach to analyse the cost of inaction that can support climate adaptation decisions in European and non-European cities. Based on an extensive literature review and expert questionnaire a seven-step approach was developed consisting of the following steps: I) define purpose and boundaries, II) produce flood hazard map, III) exposure analysis, IV) direct damage-susceptiblity, V) indirect damage, VI) intangible damage, and VII) aggregate and present results. Depending on the challenge either a simple, refined or comprehensive method can be applied. Simple methods provide quick, basic first estimates of potential damages which requires minimal data, time and expenditures. Refined methods may estimate flood damage per aggregated land use class, proving more fine-tuned flood risk estimates. Comprehensive methods are often applied for local (micro) scale flood risk estimates, necessitating the effort of collecting object-level data, with the benefit of generating locally-tailored damage assessments.

Key conclusion of this study is that not all cost-benefits can be expressed in monetary terms. In particular, indirect and intangible cost-benefits are difficult to calculate and require many assumptions. Moreover, we observe that many experts and studies argue that it is also not desirable to monetize all cost-benefits. They argue that a lost life, extinct species, or development of post-traumatic stress disorder due to flooding cannot be replaced, no matter how much money is spent. Hence, a multi-criteria analysis may be preferred in addition to the monetisation of direct flood impacts.

The raison d'être of cost-benefit analysis is to optimally support decision-making. A key lesson from institutional decision-making literature is that it is essential to strip down the deciding factors of a decision. For flood risk adaptation this can for example be the consequences of inaction in categories of direct monetary damage to I) industry and businesses and II) domestic properties. Indirect damages to III) health or quality of life (for example through for example Disability Adjusted Life Years approach), IV) mapping of major infrastructure service calamities (for example, whether a hospital is affected or major roads become inaccessible), and, if applicable, V) loss of human life. The danger of not considering these deciding factors is that decisions are highly limited to what reliably can be computed. This generally implies that quality of life aspects are largely neglected and that there is an overly focus on direct damage to buildings and business.

In this study, we have, amongst others, scrutinised the direct impacts of flooding, however the direct impact of heat mitigation or reduction in air pollution can be monetarised in a similar fashion. For a multi-criteria analysis, it is important to involve different stakeholders and citizens in the formulation of the deciding factors with respect to specific goals such as mitigating flood damage, heat stress or reduction of water demand. In many cases, climate adaptation measures address different challenges simultaneously. For example, green roofs can reduce flood risk, enhance biodiversity, air quality and aesthetic value. In order to seize opportunities of co-benefits, it is therefore essential to formulate deciding factors that are tailored to local situations such as urban neighbourhoods which has also been the focus area of this study.

Finally, this report has shown that some key assumptions largely determine the scope of cost-benefit analyses, and in this way, also can restrict the incorporation of interests from different stakeholders. Moreover, this report has emphasized the inclusion of indirect and intangibles cost-benefits, preferably through a multi-criteria analysis. Hence, the inclusion of different interests as well as the identification of intangibles and indirect impacts, may be an important multi-stakeholder process where digital communication platforms can have an important facilitating role.

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Article

Understanding the Costs of Inaction–An Assessment of Pluvial Flood Damages in Two European Cities

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Abstract: Today, over 50% of the global population lives near water. Due to population growth, ongoing economic development, and extreme weather events, urban areas are growing more susceptible to flood risks, and the costs of inaction of failing to manage flood risks are high. Research into the benefits of pluvial flood-risk management is needed to spread awareness and motivate investments in pluvial flood-risk reduction. So far, such research is lacking. This research therefore assesses pluvial flood damage from a single 60mm/1-hour rainfall event in the cities of Rotterdam and Leicester using 3Di flood modelling and the flood damage estimation tool (waterschadeschatter; WSS). The results demonstrate that potential pluvial flood damages exceed €10 million in each city. From this research, inhabitants and authorities of Leicester and Rotterdam can learn that preparing for upcoming pluvial floods can save millions of euros resulting from future damages. The application of these tools also makes clear that data availability is a highly relevant bottleneck to the pluvial flood damage assessment process. By addressing data shortages, flood damage estimates can be strengthened, which improves decision support and enhances the chance actions are taken in reducing pluvial flood risks.

Keywords: cost of inaction; urban pluvial flooding; flood damage assessment; flood risk

1. Introduction

Throughout history, cities have sprouted in proximity to freshwater sources, as water is vital for drinking, agriculture, transportation and domestic use [1]. However, due to urban expansion and climate change, cities are growing increasingly prone to floods with serious socio-economic and environmental consequences. Flooding is the number one most frequently occurring natural disaster, causing over $20 billion in economic damage and claiming over 3300 lives worldwide in 2017 [2]. In Europe, annual flood losses are expected to increase five-fold by 2050 and as much as seventeen-fold by 2080, highlighting the need for cities to build flood resilience [3,4].

There are various types of floods, for example, river, coastal, groundwater, and pluvial floods, each requiring different techniques to prepare for. Coastal and river floods receive the most attention as they are generally the largest and longestlasting flood types, while pluvial floods-caused by heavy rainfall that urban drainage systems are unable to cope with-are relatively underrepresented in research [5]. Recent research has suggested that due to the frequent nature of pluvial floods, cumulative direct damage to property from pluvial floods equals or may even exceed damage from river and coastal floods [6]. Continued urbanization accompanied by the intensification of rainfall patterns due to climate change will likely exacerbate pluvial flood risks, so research is needed into how to manage pluvial floods to minimize damage to our economy, environment, and society [6,7].

Financial resources for managing pluvial flood risks are limited, so decision-makers need convincing that investments in flood-risk reduction are worthwhile. The occurrence of a flood disaster is often used as motivation, for example, the city of Copenhagen initiated the Cloudburst Management Plan in response to a July 2011 pluvial flood disaster that cost upwards of €800 million [8]. Such a reactive mindset does little to reduce the cost of the initial flood disaster. The concept of the cost of inaction (COI), defined as the total cost due to climate change in the absence of adaptation and mitigation measures, can be used to present the consequences of disasters that have not yet occurred [9]. By estimating and considering the COI, decision-makers may see that it is costlier to wait than act now to reduce flood risks.

To understand the COI, it is necessary to assess the amount of flood damage that occurs in the absence of any further investments in flood-risk management. Since flooding can cause a wide array of economic, environmental, and societal impacts, a distinction is often made between tangible/intangible and direct/indirect flood damage. Direct damage occurs in the flooded area due to immediate physical contact with floodwater, while indirect damages arise with a time lag or outside the flooded area [9]. For example, if a flooded business halts production, the physical damage to the building and contents within is direct damage, while induced losses to supply and demand suffered later in time outside of the flooded area are indirect. Tangible flood damage is damage to assets that can be easily monetized with a market price, whereas non-market priced damage (e.g., health loss, environmental damage) that cannot be immediately given a monetary value is intangible [10,11]. Some examples are shown below in Figure 1 [10–13].

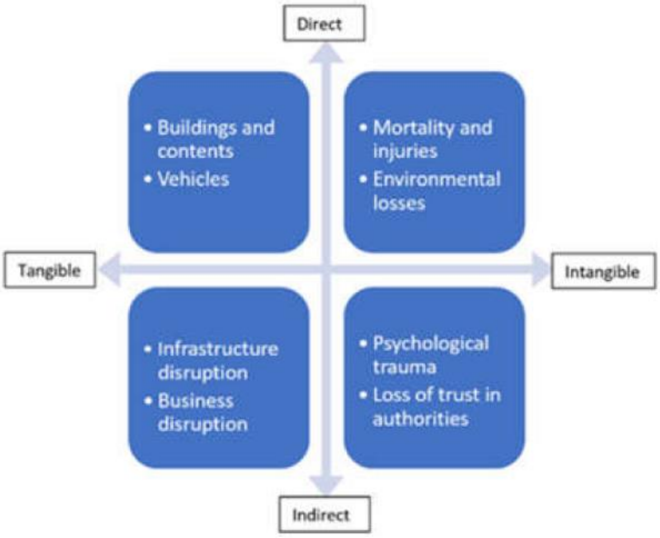


Figure 1. Distinction between tangible, intangible, direct, and indirect flood damages.

1.1. Direct Damage Assessments

Direct damage to property is considered the dominant type of pluvial flood damage and is the subject of most pluvial flood damage research [7]. This research also focuses on direct pluvial flood damage as such physical damage to structures is the most relevant damage type for densely built urban areas, and there are established assessment methods to draw upon. Potential indirect and intangible pluvial flood impacts are touched upon later in the discussion section.

The common framework for assessing direct flood damage consists of three steps: simulation of the flood hazard (hazard analysis), identification of the types of assets exposed to flooding (exposure analysis), and the translation into monetary flood damage based on the characteristics of the exposed objects (vulnerability analysis). This framework (illustrated below in Figure 2) has mainly been applied to assessments of river and coastal flood damages [14–16], but recent studies have used the same methods to assess pluvial flood damage.

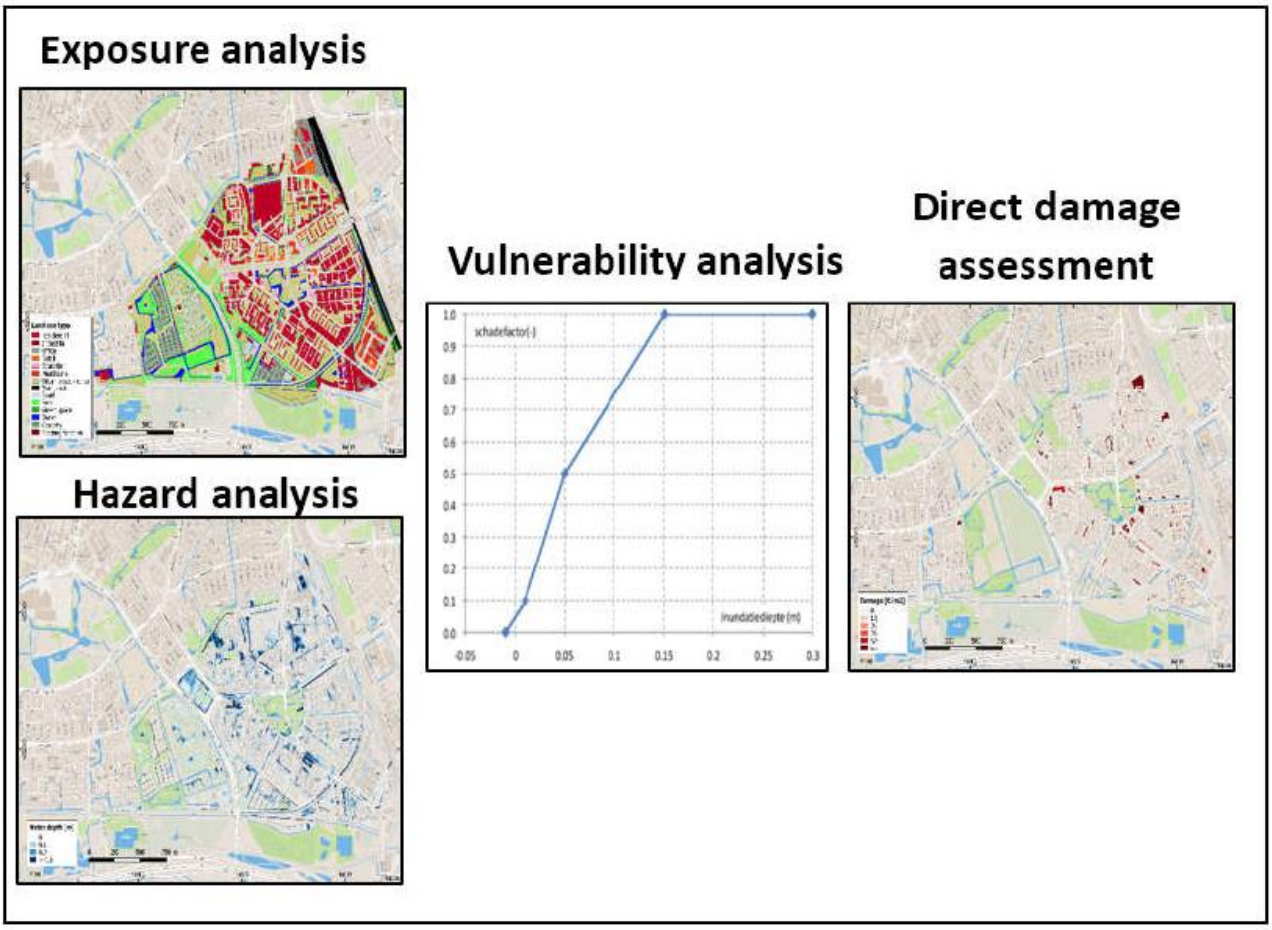


Figure 2. Standard direct flood damage assessment framework.

1.1.1. Hazard Analysis

The magnitude of direct flood damage is partly determined by the characteristics of the flood, known as impact parameters. Impact parameters such as flood depth, flood duration, flow velocity, contamination, and rise rate may determine damage to building structure and contents, but such detailed information is often not available about the flood hazard. In practice, the flood depth is the dominant and often only parameter used to represent the flood hazard. This is especially the case for pluvial floods, which usually do not occur over long durations or at high enough flow velocities to incorporate these parameters in the hazard analysis. To simulate pluvial floods, coupled 1D/2D hydrological models, which integrate both 1D sewer flow and 2D surface water flow to solve the shallow water equations, are used [17–19]. Despite representing the best option for accounting for realistic drainage processes, these models suffer from data limitations as they require hourly precipitation data and localized information on flow paths, as well as impediments to flow and interactions with drainage components [17,20]. Uncertainties in this process include extreme value statistics used, stationary and homogeneity of data series, consideration of physical properties (e.g., dikes and drainage systems) of a location, and calibration and validation of model output etc. [20,21]. As complete data are not always available, GIS-based digital elevation models (DEM) can be used to approximate pluvial flood flow [17].

1.1.2. Exposure Analysis

Flood exposure could be gauged at the object-level, but there are so many types of assets and buildings that can be exposed to flooding that assets are usually aggregated into groups based on land use classification. For city-wide flood damage assessments, land use maps displaying residential, commercial/industrial, environmental, infrastructural, and other land use/building types are used to group exposed assets. Average asset and content values for each land use type can be surmised using aggregated national or regional statistics, real estate data, or expert consultation to analyze the total value of objects exposed to flooding. However, uncertainty regarding asset types

and approximate values can be critical in many cases, especially when models developed for a specific location at a specific time are not validated and transferred across spatial or temporal boundaries [14]. The exposure analysis for pluvial floods can be carried out in the same way as has been established for river and coastal floods, as described in Merz et al. [14].

1.1.3. Vulnerability Analysis

A loss model is a central element of flood damage estimation and the most common way of estimating direct damage amount is the use of depth–damage functions, often called susceptibility or vulnerability functions [14,15]. Some loss models are multi-parameter models based on several impact parameters and resistance parameters including building function, type, age, size, presence of mitigation measures, profiles of inhabitants, etc. Prominent examples of multi-parameter flood damage assessment techniques within Europe include the UK multi-colored manual, and German FLEMOps and FLEMOcs models [16,22–25]. These models were developed specifically for fluvial (river) flood damage assessments, concentrating mainly on damage to residential and commercial buildings. The same damage functions relating fluvial flood depth to monetary damage should not be used for pluvial floods, as flooding from rainfall is dictated by different flow properties and the magnitude of flood damage to building structure and contents is likely different [26]. However, the central idea of a loss model is also applicable to pluvial flood damage assessments, for example, Zhou et al. [7] described a framework for economic pluvial flood risk assessment considering future climate change which quantifies flood risk in monetary terms as expected annual damage in different return periods of rainfall. Susnik et al. [27] used a threshold method in which pluvial flood depths above 30cm are attributed to a fixed damage amount to assess pluvial flood damages from a heavy rainfall event in Eindhoven. Efforts have also been made to relate pluvial flood damage to various parameters based on insurance data or surveys distributed to pluvial flood victims [28–33]. Such research is important for distinguishing how parameters other than flood depth, such as preparation, prior flood experience, and presence of mitigation measures, can determine pluvial flood losses. Outcomes of these studies illustrate how non-structural measures, for example, increasing the flood warning times or spreading awareness on how to adequately respond to a flood event, can significantly reduce pluvial flood risks [30–33]. However, the flood damage assessment models to date contain a number of uncertainties in both the hazard and damage models. The largest sources of uncertainties in damage modelling are associated with prescribed depth–damage functions [11,13,14]. A reason for uncertainty in many loss models is the crude assumption of the relationship between damage and flood depth only. Optimally, other parameters that impact flood damage like building age, presence of basements, and preparedness to respond to flooding would be included in the damage assessment, yet data on these factors are often incomplete [28,34]. There is still a need to develop a stronger understanding of different parameters impacting pluvial flood damage to develop stronger and more rigorous flood damage assessment methods [9,10,30]. Equally important is for decision-makers to recognize the simplifications and uncertainties present in flood damage assessment models, so the results of imperfect damage assessments do not misguide pivotal policy choices in flood-risk management.

1.2. Objective of This Research

In this paper, the process of estimating the COI of urban pluvial flooding is illustrated through pluvial flood damage assessments in two selected European cities. Using a combination of a state-of-the-art flood simulation model and a flood damage estimation tool developed by a consortium of Dutch water companies, flood damages are estimated for a single rainfall event in the cities of Rotterdam (NL) and Leicester (UK). The purpose of this research is two-fold: to illustrate potential flood costs that could arise if these cities fail to prepare for a pluvial flood event, and to shine a light on the key limitations of the flood damage assessment process so decision-makers are better prepared to translate results into tangible policy action towards reducing pluvial flood risks. If estimates of the COI are transparent and trustworthy enough, they can be used to convince urban flood-risk managers to reduce flood risks proactively rather than responsively, thus saving the cost of the initial flood disaster [13].

In the next section, the flood damage assessments carried out for neighborhoods in the cities of Leicester (United Kingdom) and Rotterdam (the Netherlands) are described. In Section 3, the results of the flood damage assessments for both study areas are presented, followed by a discussion of the values and limitations of the research in Section 4. This paper finishes with a short summary of the research and concluding remarks in Section 5.

2. Materials and Methods

A flood damage assessment is conducted for a 60 mm/h rainfall event (constant rainfall) in Belgrave (Figure 3), a part of Leicester (UK) and Lombardijen (Figure 4), a part of Rotterdam (NL) using 3Di flood modelling software and the Dutch 'Waterschadeschatter' (WSS) flood damage assessment tool.

Figure 3. Belgrave location.

Figure 4. Lombardijen location.

2.1. Study Areas

These areas were both selected for analysis, firstly because they are both low-lying areas that are identified as flood prone [35–38]. Through consultation with members of the Leicester City Council, Belgrave was identified as a neighborhood especially at risk to pluvial flooding. Belgrave is also of a comparable size, population and climate to Lombardijen, so it is included as a point of comparison for Lombardijen. The Netherlands contains many low-lying, flood-prone areas, but Lombardijen was chosen in particular because of the availability of a pre-calibrated and validated high-quality 3Di model for the area. The use of a high-quality 3Di increases the trust in the results of the 3Di modelling conducted in this research.

2.2. Flood Modelling with 3Di

The 3Di flood modelling software was developed by a combination of Stelling Hydraulics, Deltares, TU Delft, and Nelen & Schuurmans. It is a physically-based model designed to simulate the passage of water through urban areas during flood events. According to Van Dijk [17], the sewer and surface water systems should be coupled in dual drainage models for realistic flood simulations. The governing equations of 3Di can be accessed on the 3Di Water Management website (https://3diwatermanagement.com/3di-start). 3Di flood modeling is used because it represents state-of-the art hydrodynamic modelling. It uses a sub-grid method for 2D surface water flow, 3Di provides fast and accurate results [39]. This is one of the best currently available ways to link 2D surface flow to 1D drainage flow to simulate the process of flooding in urban areas. In the UK, 3Di software is also regarded as one of the best currently available methods for dual drainage modeling based on a benchmark developed last year.

For the Lombardijen study area, data accessed were from AHN2 digital elevation map (DEM) (2008, 25 m^2), BAG (building register), TOP10 (topography), OSM (open streetmap), and CBS land use datasets. A map of the urban drainage network was provided by the municipality of Rotterdam. For Belgrave, a soil type map was accessed on the Cranfield Soil and Agriculture Institute website

[40], a DEM (2015, 25 m^2) was obtained from the UK governmental environmental data online portal
[41], and a land use map was created in a GIS environment based on CDRC Open Map Survey data (https://data.cdrc.ac.uk/dataset/cdrc-2015-os-geodata-pack-leicester-e06000016). The parking lots were manually added based on Open Street Map data. In the figures below, the water depth maps developed for Belgrave (Figure 5) and Lombardijen (Figure 6) are displayed. It is important to note that a digital map of the urban drainage system was unavailable for Belgrave because of the privatization of the water supply industry in the UK and concerns regarding confidentiality. Therefore, the interactions between surface water flow and the sewer systems are left out of the Belgrave flood model.

From the figures above, it is visible that the rainfall event causes pooling of water in the fields to the North of Belgrave and in residential areas in the Center/South (Figure 5). In Lombardijen (Figure 6) the water pooling appears more spread out, but there are still significant flood depths over 0.5m in the Northwest, and just Southeast of the center. To assess flood damage, the water level map (maps above show water depth, water level = water depth + elevation) for each study area is combined with land use information and damage functions in the online WSS damage estimation tool. Below, the land use maps developed for Belgrave (Figure 7) and Lombardijen (Figure 8) are displayed. It should be mentioned that due to difficulties accessing land use and building register information in the UK, the land use classification is less detailed (7 land use classes) in Belgrave than Lombardijen (14 classes).

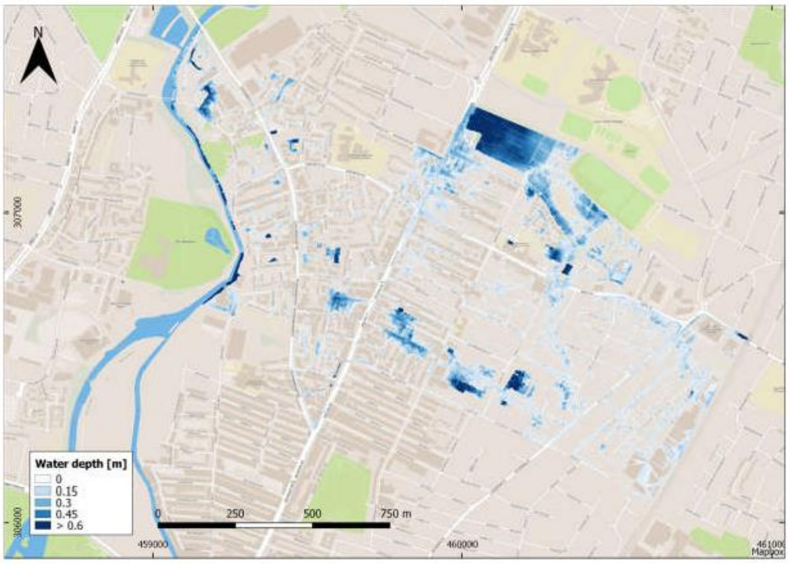


Figure 5. Belgrave water depth map.

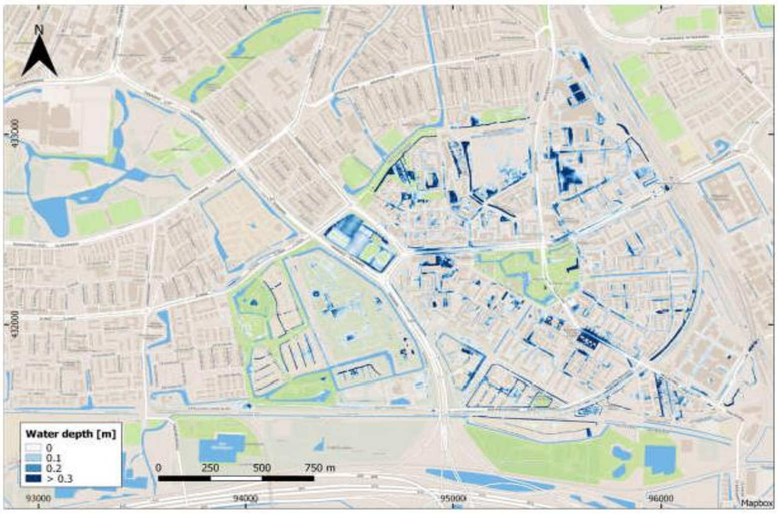


Figure 6. Lombardijen water depth map.

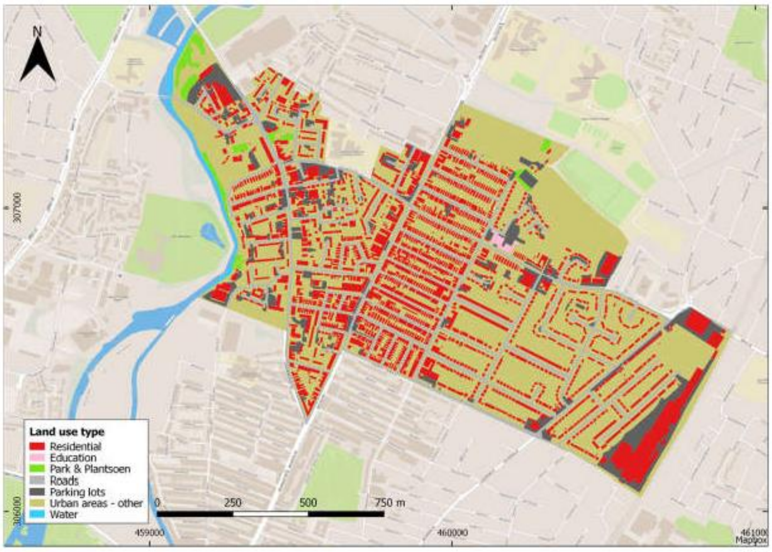


Figure 7. Belgrave land use map.

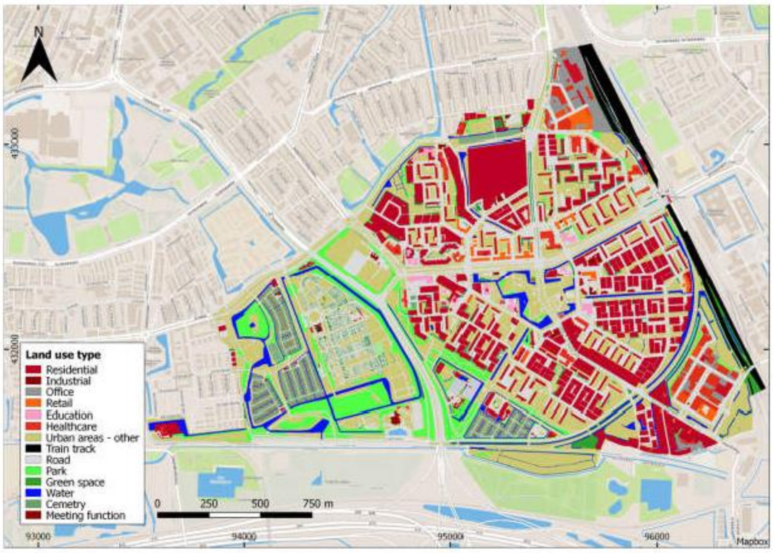


Figure 8. Lombardijen land use map.

2.3. Damage Assessment with WSS

The WSS is a freely accessible cloud-based flood damage estimation tool. It is owned by the STOWA consortium of Dutch water companies and was designed to estimate damages from flood depths up to 2.5 m. The flood damage estimation tool can be accessed at the website: https://www.waterschadeschatter.nl/damage/. WSS software was used for this damage estimation because it is a free, entirely web-based tool that does not require heavy computing power which has been developed to estimate pluvial flood damage in the Netherlands. It is simple enough that the functions used to estimate damage can be understood and used to calculate flood damage for areas outside the Netherlands.

Within the Netherlands, the only required input for the WSS is a water level map because land use and DEM data are already included in the WSS tool. With the water level map, the WSS subtracts the DEM to calculate water depth in each grid cell. Land use information is then used to identify the flooded land use classes, and damage functions are applied to relate the flood depth to monetary direct flood damage values for each land use class. Since the WSS is a tool developed for Dutch flood damage assessments, the water level and land use raster with a UK projection cannot be processed by the WSS cloud. Therefore, the damage estimation for Belgrave was conducted using a raster calculator in Python with the default damage functions used in the WSS tool and Lombardijen case study.

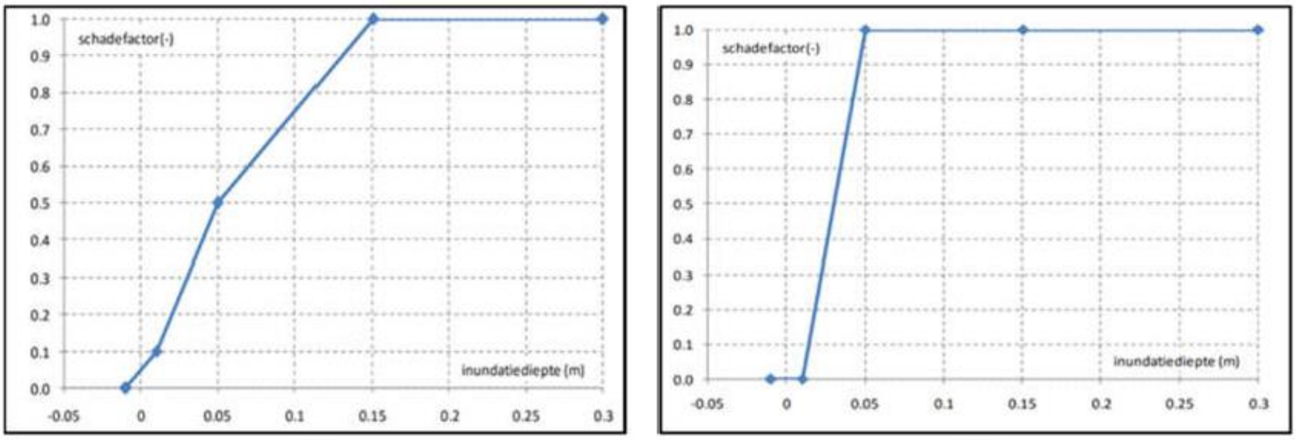
After uploading a water level map to the WSS web site, the user is asked to select the flood duration (h), recovery time for buildings and roads (h), month of flood event, and whether to use minimum, average, or maximum damage values. In this research of direct damage from a one- hour rainfall event of 60 millimeters, the flood duration was set to one hour, recovery times for buildings and roads were set to zero (direct damage only), the month was set to September, and average damage values were selected. Below, Tables 1 and 2 display the average damage values for all land use classes considered in the Belgrave and Lombardijen case studies. Figure 9a,b shows the damage functions that were applied for the different land use classes.

Table 1. Average damage values for each land use class, Belgrave.

Land Use Type	Average Damage (€/m^2)
Residential	271
Educational	271
Parks & greens	0.1086
Roads	0.076
Parking lots	0.076
Urban areas-other	0
Water	0

Table 2. Average damage values for each land use class, Lombardijen.

Land Use Type	Average Damage (€/m^2)
Residential	271
Industrial	271
Office	271
Retail	271
Educational	271
Healthcare	271
Meeting	271
Sport	54
Parks & greens	0.1086
Train track	0.076
Roads	0.076
Urban areas–other	0
Cemetery	0
Water	0



(a) (b)

Figure 9. Damage function for residential, educational, industrial, retail, office, healthcare, meeting, urban area – other, and sport land use classes (**a**); Damage function for train tracks, roads, parks and greens, parking lots, water, and cemetery land use classes (**b**). On the *X*-axis, the flood (inundation) depth is displayed (up to 30 cm) and on the *Y*-axis, the damage factor, total share of the asset value that is damaged, (0–1) is shown.

Tables 1 and 2 display the average maximum value that is susceptible to flood damage per m$_2$ of each land use type. Figure 9a,b shows the relative damage curves used to translate water depth to a share of the average maximum value that can be damaged in each land use class. This results in a monetary estimate of direct flood damage for each land use type, as presented in the next section.

3. Results

Below, the results of the flood damage assessments for a one-hour 60 mm rainfall event in Belgrave and Lombardijen are shown.

3.1. Direct Flood Damage in Belgrave

Figure 10 shows that flood damage in Belgrave is concentrated in a couple of hotspots in the North and South. Comparing this with the water depth map of Belgrave (Figure 5), it is noticeable that flood damage is not always highest in areas with the greatest flood depths and is highly dependent on land use. For example, the field to the North of Belgrave that experiences heavy pooling in Figure 5 does not show flood damage in Figure 10. On the other hand, the less-flooded residential area surrounding the field in Figure 5 does show heavy flood damage. Direct flood damage can only be as high as the value of the asset that is damaged, so it is important that areas identified as flood- prone on flood hazard maps do not become overdeveloped. As more areas in the Netherlands and UK are expected to become flood-prone in the future, it is crucial that anticipated future rainfall patterns be incorporated in present-day decisions regarding development and urban spatial planning. Below, Table 3 breaks down the flood damage in Belgrave per land use type.

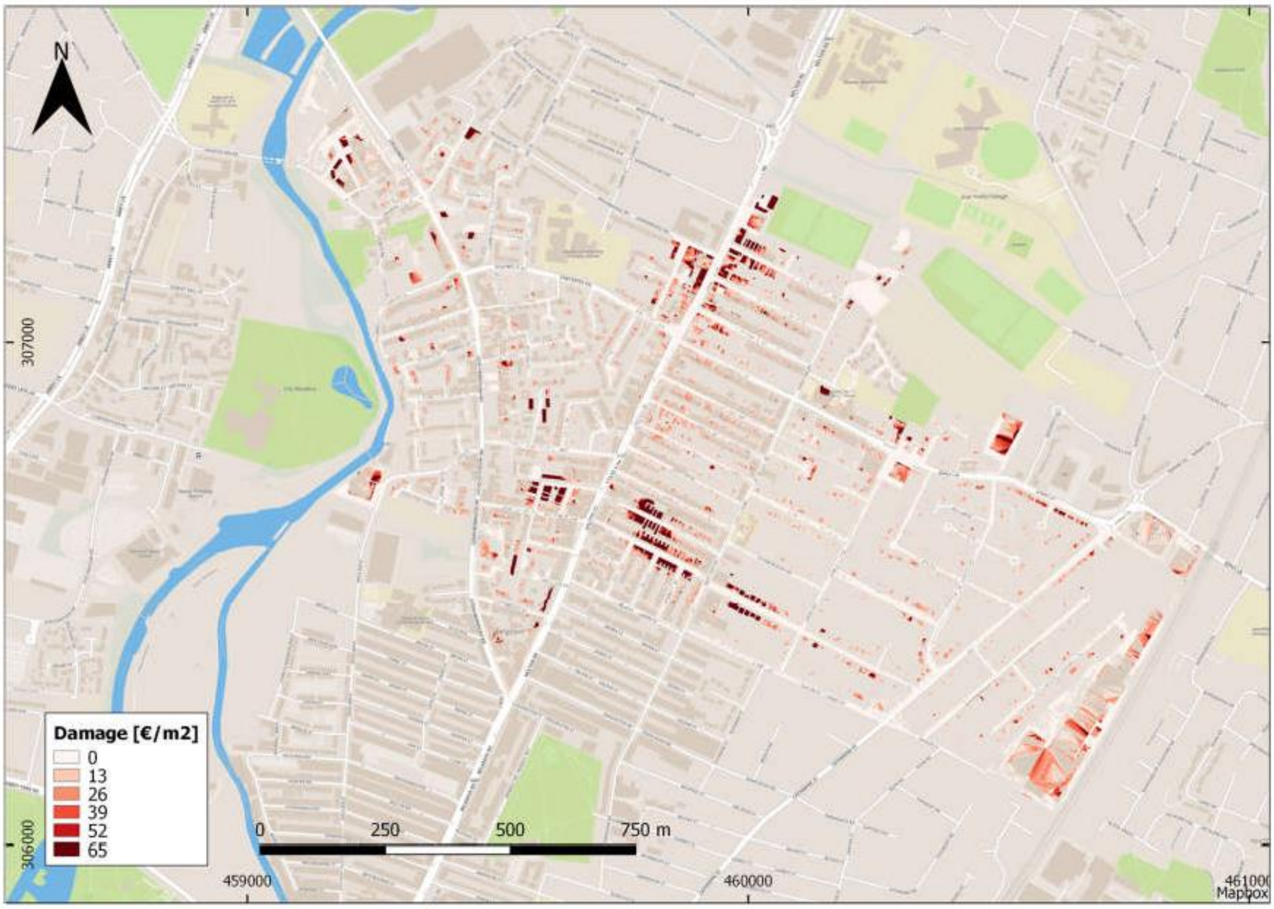


Figure 10. Belgrave flood damage map (dark red signifies high flood damage).

As shown in Table 3, the total direct damage from the one-hour pluvial flood event is nearly €11 million. Over 98% of total damage comes from the residential sector, which is likely because all buildings were considered residential except for one school. Other studies show building damage of 60–95% of total direct damage [42], whereas in this research the total share of building damage is over 99%. This could be because other damage types (e.g., infrastructure damage) were neglected and the average damage values for water and urban areas–other were set to zero. Thus, the >99% of total damage associated with property damage yielded in this study is likely an overestimation. However, the total damage estimate of €10.99 million could be an underestimation as flooding of urban areas– other and water land use classes would realistically cause some monetary damage.

Table 3. Belgrave damage estimate per land use type.

Damage Type	Damage (€)
Residential	10,895,788
Educational	87,912
Roads	2833
Parking lot	2717
Parks & greens	473
Water	0
Urban areas-other	0
Total	10,989,723

3.2. Direct Flood Damage in Lombardijen

Figure 11 displays the distribution of flood damage throughout the Lombardijen neighborhood. There are several areas of concentrated high damage to the east and southeast of Spinozapark (note the dark red blotches).

Comparing this with the water depth map (Figure 6), it is clear that water pooling does not always correlate with high flood damage. More important is the land use class of the area that is flooded. In the case of Lombardijen, the damage hotspots exist in the densely packed residential/industrial areas where there are more buildings exposed to flooding.

Figure 11. Lombardijen flood damage map (dark red signifies high flood damage).

As shown in Table 4, residential damage makes up most of the pluvial flood damage, followed by damage to industrial and meeting function buildings. The total share of building damage (99%) is on the high end of what is reported in literature [12,42,43]. This is likely because damage to water utilities, power stations, and other infrastructural components was not part of this assessment, resulting in an overstatement of the total share of building damage. It is important to also mention that although direct damages to roads and train tracks were minimal in this simulation, traffic delays and diversions would be expected to cause high indirect and intangible damages like inconvenience and lost time. Although the urban drainage system was accounted for in the Lombardijen damage estimation, the results still show greater flood damages in Lombardijen than Belgrave. This could be due to the inclusion of a more detailed land use map for Lombardijen (Figure 8). Much of the Belgrave area was classified as urban area – other, which had a maximum damage value of zero, whereas the more detailed land use classification for Lombardijen considered comparatively much less area as urban area - other. Damage estimates are sensitive to the level of detail in the land use classification, so it is difficult to compare the damage estimates between the two areas due to the difference in the land use maps used.

Table 4. Lombardijen damage estimate per land use type.

Damage Type	Damage (€)
Residential	7,558,742
Industrial	2,283,720
Meeting	1,224,713
Educational	672,239
Office	487,369
Sport	137,291
Retail	13,025
Roads	645
Train track	220
Parks & greens	135
Healthcare	0
Urban areas-other	0
Total	12,378,099

4. Discussion

4.1. Data Limitations

The two case studies are contrasting since all Lombardijen information was readily accessible, while the Belgrave damage estimation was hampered by data availability issues. Consequently, critical elements for the flood damage assessment like a sewer network map displaying locations of drains, sewers, pipes, and manholes, and average asset values specific for buildings in Belgrave were not available. Because of this, the damage assessment for Belgrave was conducted with the best available data to the knowledge of the authors and the damage estimate of €10.9 million should only be considered a ballpark estimate. It has been noted that even with state-of-the-art 1D/2D hydrodynamic flood models, there is still a poor understanding of the mechanisms of urban flooding and high uncertainties in flood depth simulations [13,17–20]. Data on real flood events are needed, not just to validate the results of flood level maps, but also to better our understanding of the relationship between flood depth and flood damage among different land use classes and to develop damage functions tailored to each class.

Due to input data shortages for model validation and damage function development, the damage estimates presented here have not been tested, thus caution should be taken if the outcomes are used to inform decisions in urban flood-risk management. It is also important to note that this damage estimate focuses only on direct damages to physical property, neglecting indirect and intangible damage to health and the environment that is also likely to occur. By omitting these damage types, the full spectrum of flood damage is not included in the damage assessment, resulting in an estimate of direct damage only. It is pivotal to include all damage types in flood damage assessments to build a complete understanding of flood risks and ensure the benefits of flood-risk reduction are not underestimated [44]. In fact, some studies comparing the benefits of coastal flood-risk reduction measures to implementation costs have shown that investments in flood-risk reduction are only net-beneficial if intangible damages like loss of life are included in the damage assessment [45,46]. Without the inclusion of the diverse types of potential flood damage, the estimated benefits of flood-risk reduction are understated, thus the case for implementation is weakened. Even though pluvial floods are likely to be smaller and cause less significant intangible and indirect damage than coastal floods, all damage types should still be considered to ensure nothing is left out and the assessment of flood risk is complete. It could also be unethical to base decisions in flood risk reduction only on direct damage estimates as it may lead to the prioritization of reducing flood risks in areas with the most economically valuable building assets, in other words, the richest areas. Although the WSS attributes constant average damage values to all buildings regardless of building quality, the use of these damage estimates could result in the prioritization of flood damage mitigation for the largest buildings, not necessarily the most vulnerable. Recent research has highlighted that the less fortunate and socially vulnerable encounter greater flood damage due to information and resource shortages, yet this is ignored by damage assessments based only on asset damage [47,48]. Although there may be less chance of heavy intangible or indirect damage compared to river or coastal floods, pluvial floods can result in casualties, injuries, long-term trauma, and significant environmental damage [9,49]. As climate change is expected to bring about more frequent and intense pluvial flood hazards, it is prudent to continue to dedicate research to the assessment of not only direct, but all types of pluvial flood risks.

4.2. Looking Towards the Future

Despite the simplicity and imperfections of the damage assessments conducted here, the results are still valuable for raising awareness of the absolute minimum potential flood damage that communities can expect to face, as well as pinpointing where future research is urgently required. This can be helpful for inspiring people to start a (very necessary) conversation about what flood risks we are willing to face, and how to be prepared to reduce flood risks in the future. Many cities are either sitting atop outdated drainage systems that do not have the capacity for future rainfall patterns or are developing rapidly without a centralized drainage system in place [50,51]. In any case, decisions need to be made on how to decrease pluvial flood risks to avoid future disasters. Options for reducing pluvial flood risks exist, from conventional 'grey' options like increasing the capacity of existing sewer systems to 'green' and 'blue' innovations such as green roofs, sustainable urban drainage systems, and designated floodwater reservoirs in cities, which serve to delay or divert rainfall from over-stressed sewers [8,50,51]. Since each approach comes at a cost, it is necessary to estimate pluvial flood damage in cities to determine whether investments in flood risk reduction are economically justifiable. Flood damage estimates also provide valuable information for insurance firms, local businesses, spatial planning authorities, emergency planners, and households.

Data collection and accessibility need to be improved for water depth and damage model validation, so results of flood damage assessments can be trusted to better represent reality. Flood depth and flood damage data are collected for a variety of purposes, but methods and standards for data collection are rarely aligned. This is problematic since consistent and accurate data are needed to validate the outcomes of both water level and flood damage estimates. Without a consistent and reliable source of flood data, it becomes more difficult to reinforce and improve flood damage estimates. It is understandable that drainage network and infrastructure maps are difficult to attain due to safety, security, and strategic concerns, but there are tangible benefits to increasing accessibility of this information for dedicated research purposes. Not only would this allow for more accurate simulation of the flood routing and urban drainage process, but maps of other infrastructural components like utility stations and power networks can identify further components at risk to flood exposure. Severe pluvial floods can incapacitate infrastructure networks, and the interdependencies and knock-on effects should be further investigated [52–54]. Without drainage and infrastructural network maps in the hands of researchers, it is difficult to trust that the simulated flood depths or estimated value of assets exposed to flooding match with reality.

The assumption of this research that all building types have the same damage characteristics and average values can be called into question, for example, industrial buildings often include heavy machinery and equipment that is more valuable, thus susceptible to greater flood damage than residential buildings. By associating the same damage functions and average asset values to all buildings in Lombardijen and Belgrave, the damage estimates of €10.9–12.2 million to buildings in the two cities merely reflect the fact that they are comparably sized with similar building densities. It is imperative to dedicate continued research to addressing data deficiencies so the role of flood damage assessments as decision-support mechanisms is strengthened. Flood damage assessments are also key for raising awareness of flood risks and closing the gap between perceived and actual risks [55]. Flood damage assessment therefore plays the important role of increasing awareness of flood risks prior to disasters so societies can be better prepared to reduce future flood risks. Flood defense via structural or technical means is regarded as the cornerstone of European flood risk management, but risks can also be addressed with other paradigms in flood risk management such as flood prevention via spatial planning, risk mitigation, preparation, and recovery [55,56]. Research has shown that non-structural means like installation of early warning systems or adaptation of water sensitive cities master plans can repay setup costs within a matter of years, especially when cleverly combined with structural options [46,57]. Key to raising awareness and hastening action flood risk reduction is for people to understand, as well as believe, the results of flood damage assessments [44,58]. Thus, it is important to continue to research and dissect existing flood damage assessment methods to increase our understanding of the methods used as well as the limitations. By studying urban pluvial flooding, the risks appear more real and awareness can be raised on potential flood impacts. Raising awareness is a crucial pre-cursor for inspiring action to reduce flood risks and cope with the challenges of climate change in cities.

5. Conclusion

The significance of expanding knowledge about pluvial flood risks and the costs of inaction cannot be understated. Climate change is steering society into unchartered territory, and urban conglomerations only serve to aggregate flood risks. People are becoming increasingly aware of flood risks after catastrophic events that have plagued society in recent decades. This backward-looking attitude is not well-suited for a future where we face uncertain conditions yet near-certain intensifications of flood risk. Instead, it is urgent to act now to reduce risks before disasters occur. Awareness precludes action, and to raise awareness, flood risks need to be assessed.

This research used a combination of 3Di flood modelling and the WSS flood damage estimation tool to assess direct flood damage from a 60 mm/1-h pluvial flood event in two urban areas: Belgrave (Leicester, United Kingdom) and Lombardijen (Rotterdam, the Netherlands). For Belgrave, direct damage was estimated at roughly €11 million, while for Lombardijen direct damage was €12.4 million. Due to a lack of pluvial flood damage data, identical average asset values and damage functions were applied for both neighborhoods. Thus, the comparable damage estimates yielded in this research merely reflect the fact that the areas are of similar size and building densities. This research could be improved by using locally-tailored asset values, land use maps, and damage functions to account for differences between building types as well as study areas. Furthermore, the Belgrave damage assessment was hampered by the failure to include a map of the urban drainage infrastructure, resulting in an overly-simplified portrayal of the flood propagation. Urgent research is needed to address data bottlenecks, especially for validating flood depth simulations and developing damage values and functions for the wide variety of land use classes that exist in modern cities [59]. With more complete data of past flood events, work can be put into improving pluvial flood damage assessments that can play a stronger role supporting decisions in flood-risk reduction. This can be vital for reducing future flood risks, as most studies demonstrate investments in flood- risk reduction at least break even with implementation costs [46,60].

Pluvial flood damage assessments are essential for supporting arguments for building flood resilience, raising awareness of flood risks, and determining how flood-risk management could best be implemented. Ideally, such damage assessments are based on sound data. Decisions should not be based on damage assessments alone without recognizing input data limitations, which result in some significant uncertainties underpinning the damage assessment process. A way forward is to keep studying flood damages and developing solid databases to validate and improve models for assessing potential future flood damages. Stronger flood damage assessments will be essential for building the case that the costs of inaction are too great to ignore flood risks any longer. To borrow a quote from John F. Kennedy, “There are risks and costs to action. But they are far less than the long-range risks of comfortable inaction”

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Appendix 2 Overview of recent pluvial flood damage studies

Model	Data Source	Impact Parameters	Resistance Parameters	Key Conclusions	Source
Residential (Belgium)	Survey	Depth	-Building type -Building size -Basement (Yes/No) -Recurrence -Risk awareness -Emergency action	-Damage 65% lower for terraced flats than detached houses -Risk awareness and recurrence can reduce damage -Prior flooding history influences ability to take emergency action	Van Ootegem et al. (2015)
Residential (Sweden)	Insurance	Rainfall	-Precipitation previous day -Day/night -Population density -In/out city center	-Rainfall at night, in city center slightly increased damage -0.2% damage per mm of rain the previous day, flood experience reduces damage	Grahn and Nyberg (2017)
Residential (Germany)	Survey	-Depth -Duration -Velocity -Contamination	-Preparedness -Early warning -Emergency measures	-Preparedness and implementation of emergency measures reduces content damage -More preparedness (from past floods) increases ability to respond	Rozer et al. (2016)
Residential (Netherlands)	Model (threshold method)	Depth	Adaptation options: separate sewer system, opening a river	-Taking only direct damage into account, adaptation options do not yield significant net benefits	Susnik et al. (2014; 2015)

Residential (Netherlands)	Insurance	-Rainfall intensity -Volume -Duration	-Building age -Building area -% low-rise -Value	-Insurance claim frequency associated with rainfall intensity, value, age, % of low-rise buildings -Tree mining method more predictive than standard regression	Spekkers et al. (2014)
Residential (France)	Survey	Depth	House/apartment -Basement (yes/no) -Mitigation measures: -Adapt furniture -Raise floor -Raise power outlets -Water resistant floor -Sandbags -Strengthen foundations -Elevated boiler -Anti-backflow valves	-Depth, proximity to flood source are main damage determinants -Mitigation measures: adapt furniture, raise electrical appliances, sandbags are most cost-effective	Poussin et al. (2015)
Residential, infrastructure, intangible (Denmark)	Model (threshold method)	Depth	Building type (basement/no basement)		Zhou et al. (2012)

Appendix 3 Discount rate equation

A discount rate is used to determine the net present value (NPV) of the future net benefits of a project after a given amount of years (n), as shown in the equation below.

$NPV = NetBenefitsn / (1+r)^n$

Assume an investment in flood-risk reduction will yield net benefits of 100,000 per year for a time span of 3 years, and a discount rate of 10%. The NPV of benefits accrued in year 1 = 90,000 ($100,000/1.10^1$). In year 2, the NPV = 82,645 ($100,000/1.10^2$), and in year 3, the NPV = 75,131 ($100,000/1.10^3$). The total NPV, representing the present value of all benefits generated by the investment = 247,776. Alternatively, if the discount rate is set to 0%, then the value of money does not depreciate over time, so the NPV would be 300,000. If the investment in flood-risk reduction costs an initial 250,000, then the investment would be a net loss if the discount rate is 10%, but a net gain if it is 0%.

Appendix 4 Questionnaire

1. Your Role in the Water Sector

Description (optional)

Name

Short answer text

Job Description

Long answer text

Organisation

Short answer text

Location

Short answer text

2. Flood Risks

Please indicate the level of importance you place on the topics presented below.

A scoring of 1 indicates that the subject is not important at all.
A scoring of 2 indicates that the subject is of minor importance
A scoring of 3 indicates that the subject is somewhat important
A scoring of 4 indicates that the subject is significantly important
A scoring of 5 indicates that the subject is of urgent importance

A. Flood Consequences

How important would you rate the following flood consequences in terms of magnitude and likelihood?

Direct Damages

Description (optional)

Physical damage to residential buildings

1 2 3 4 5

Physical damage to commercial buildings

1 2 3 4 5

Physical damage to industrial facilities

1 2 3 4 5

Physical damage to infrastructure

1 2 3 4 5

Physical damage to transportation network

1 2 3 4 5

Physical damage to mobile assets (vehicles)

1 2 3 4 5

Physical damage to the environment

1 2 3 4 5

Physical damage to educational facilities

1 2 3 4 5

Physical damage to historic and recreational areas

1 2 3 4 5

Physical damage to cultural arid religious areas

1 2 3 4 5

Clean-up costs

1 2 3 4 5

Indirect Damages

Business losses inside flooded area

2 3 4 5

Business losses outside flooded area

2 3 4 5

Losses in infrastructure services (over time)

2 3 4 5

Losses in educational services (over lime)

2 3 4 5

Losses in transportation services (over time)

2 3 4 5

Intangible (non-market priced) Damages

Lost time
1 2 3 4 5

Injuries and casualties

1 **2** 3 4 5

Psychological trauma

1 **2** 3 4 5

Effort required to relocate

1 2 3 4 5

Loss of trust in flood management authority

1 **2** 3 4 5

B. Uncertainties in Flood Risk Management

How would you rate the following aspects of flood risk management in terms of the uncertainties they introduce?
(1 = full certainty 2 = mostly certain, 3 = 50-50, 4 = uncertain, 5 = no certainty)

Knowledge of flood characteristics

2 3 4 5

Translation between flood characteristic and damage (stage-damage curves)

2 3 4 5

Estimation of direct, tangible flood damages

1 2 3 4 5

Estimation of indirect flood damages

2 3 4 5

Estimation of intangible flood damages

2 3 4 5

C. Flood Risk Estimation as a Policy Tool

Please rate the usefulness of flood risk estimation methods for the following policy objectives (1 = not useful at all, 5 = absolutely useful)

Spreading awareness of flood risks to the public

2 3 4 5

Motivating urban spatial planning policy

2 3 4 5

Prioritizing physical flood protection investments

2 3 4 5

Assessing the impact of non-physical flood risk management strategies

2 3 ***4***

Improving understanding of flood risks to policy makers

2 3 4 5

D. Flood Risk Management

in your opinion, how effective are the following mechanisms for managing flood risk?

Grey structural protection (dikes)

1 2 3 4 5

Increasing infiltration capacity (green areas)

1 2 3 4 5

Surface water storage (reservoirs)

1 2 3 4 5

Flood warning systems

1 2 3 4 5

Flood insurance

1 2 3 4 5

Spatial planning (develop less in flood-prone areas)

1 2 3 4 5

E. Cost-Benefit or Multi-Criteria Analysis?

Flood risks are often conveyed to decision-makers in the form of cost-benefit analyses (CBA) and multi-criteria analyses (MCA). The core difference is that CBA expresses all flood impacts (including intangibles) in monetary terms, whereas MCA tends to express these impacts in terms of the number of people affected, using criteria other than monetary costs to justify policy recommendations.

In your experience, is there a difference between the persuasiveness of these two ways of expressing flood impacts? If so, do you have a preference in which method should be used to express flood impacts to decision-makers?

Appendix 5 Sub-grid method, 3Di simulates equations

Surface (2D) flow equations

In the 3Di computational engine, surface water flow (2D) is computed by solving the Saint-Venant shallow water equations, consisting of the continuity and conservation of momentum equations in one or two directions.

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} = 0 \qquad \textit{continuity equation}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + \frac{c_f}{h}u\|u\| = 0 \qquad \textit{momentum equation in } x - \textit{direction}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} + \frac{c_f}{h}v\|u\| = 0 \qquad \textit{momentum equation in } y - \textit{direction}$$

h = water depth

ζ = water level above the plane of reference (m.ASL)

u = the flow velocity in the x-direction

v = the flow velocity in the y-direction,

g = constant for gravitational acceleration

||u|| = velocity magnitude

cf = dimensionless Manning friction coefficient

Sewer (1D) flow equations

To represent water flow within the sewer system (1D) the continuity and momentum equations are utilized.

$$\frac{\partial A}{\partial t} + \frac{\partial Au}{\partial x} = 0 \qquad \textit{continuity equation}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial \eta}{\partial x} - \gamma u \qquad \textit{momentum equation in } x - \textit{direction}$$

t **=** time

x = the position in a local coordinate system

u = the water velocity

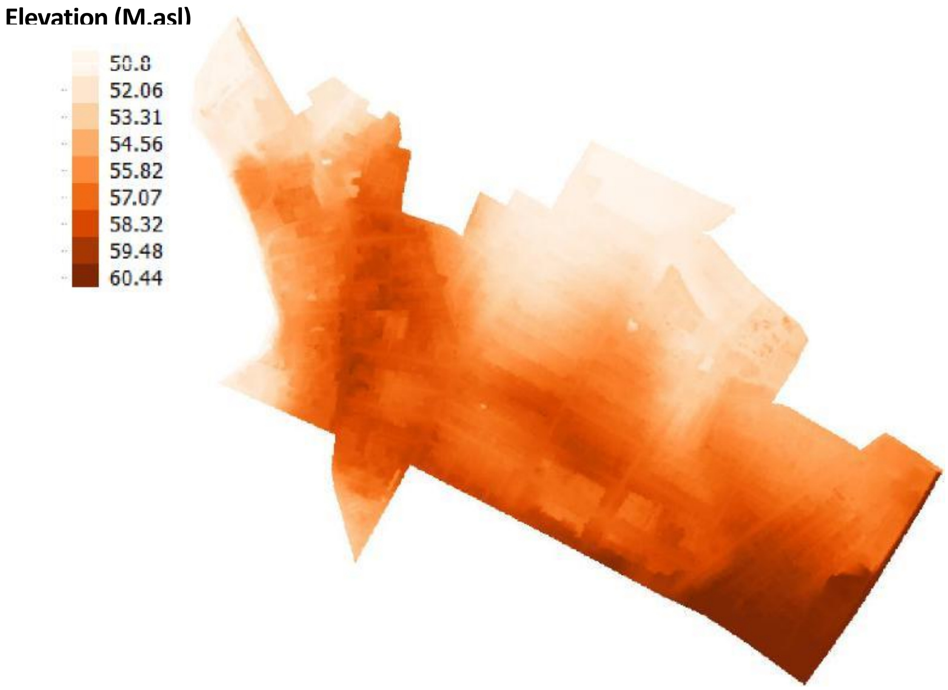
η = pressure of the free surface or piezometric head

A = cross-sectional area of pipe

g = constant for gravitational acceleration γ

= the friction coefficient

Appendix 6 Belgrave Elevation map and land cover map




= buildings
= parks and gardens
= roads and parking lots

Appendix 7 Descriptions simple, refined & comprehensive Flood Damage Assessment

Simple FDA

A simple FDA may be performed to yield a baseline assessment of the extent of flood risk, perhaps to motivate flood-risk reduction in the allocation of budgets. A suitable flood hazard map could display the flood extent to simple identify the flooded/not flooded areas. For all flooded areas the exposure analysis should at least distinguish between residential, commercial, industrial, environmental, and infrastructural (including transportation network) land uses. This can be based on CORINE level 2 or 3 land cover data, which depict 4-11 urban land use classes throughout Europe.

A simple susceptibility analysis can use a threshold/unit-cost approach in which each land use type is assigned a constant damage value per m^2 of flooded area. The damage value can be derived from insurance data or expert estimation if empirical data is unavailable. Indirect damage can then be simply estimated as a percentage of direct damage. Hallegate et al. (2008) estimated the share of indirect damage to be around 40% of direct damage for Hurricane Katrina, while the Australian RAM guidelines suggest it is around 35% (SOURCES). Since pluvial flood events tend to be short-lived with relatively low flood depths, it's recommended here that indirect damage is unlikely to exceed 30% of direct damage.

Similar to indirect damage, the estimation of intangible damage can also be performed as an assumed percentage of direct damage in simple assessments. This percentage cannot be expected to approximate actual intangible damage, which is time-consuming and controversial to monetize (e.g. Green et al., 2011), however it can be used to simply acknowledge that the total damage will exceed the physical damage to assets and buildings. Penning-Rowsell et al. (2014) establish intangible damage as 10% of direct damage as a minimum for river and coastal floods. Pluvial floods have been shown to cause extensive psychological damages (Fewtrell et al., 2008), so a minimum of 10% for pluvial floods is also suggested here. All values are expressed in monetary terms and a CBA can be used to present the results. However, the potential underestimation of indirect and intangible damage using this approach should be acknowledged, especially if social (schools, hospitals, elderly homes) or physical (infrastructure nodes, crucial production input suppliers) vulnerability hotspots are flooded.

Refined FDA

A refined approach may be needed by, for example, developers of building codes that need to assess flood risks for assorted building types, or city-planners seeking to optimize investments in flood-risk reduction. A flood hazard map for this could show the flood depth and duration of inundation across the study area. For the exposure analysis of buildings, each CORINE land use class can be split into sub-classes, for example, residential buildings can be distinguished based on building type (single vs multi-storey), presence of a basement, and building age. Commercial and industrial buildings can be sub-divided based on the type of economic activity (retail, trade, manufacturing, mining, etc.), and the infrastructure class can be split between railways, major roads, secondary roads, bridges, wastewater plants, telecommunications, power plants, airports, and ports. In the Netherlands, this can be done with data from the CBS land use, Top10 topography, BRP and BAG building register datasets (see de Moel et al., 2015). CBS socio-demographic data can be used to display population per six-digit zip code that are exposed to intangible flood damages (see Koks et al., 2015).

A refined susceptibility analysis should use relative SDC to depict the share of the asset value damaged by flooding. For each sub-class a separate SDC is needed, which could be developed synthetically with expert knowledge since empirical data for pluvial flood damage to each building type is lacking (Olesen et al., 2017). For indirect and infrastructural damage, a unit-cost approach can be used whereby each flooded asset is assumed to cause a specified amount of indirect damage per hour, multiplied by the flood duration to get total indirect damage (see Stone et al., 2013).

For intangible damage, the population map can be overlaid with the hazard map to show the number of people affected by flooding. The UK used contingent valuation surveys to estimate that £200 per household is the annual WTP to avoid flood-related health injuries, but many people exposed to pluvial floods (20% in some studies) escape short-term damage but experience long-term psychological trauma. It's difficult to measure how many flood victims suffer long-term trauma, and to put a value on long-term trauma is too controversial to be recommended here. So, intangible damage can be expressed by the number of people affected, to be used in a MCA damage assessment. A refined MCA could consider two metrics: total monetary damage (representing direct and indirect damages), and number of people affected (intangible damage).

Comprehensive FDA

If data and time permit, a comprehensive FDA could be used, for example, to help insurance companies decide premium rates that fully incorporate physical and social risks from flooding, or by an agency with rich resources at their disposal seeking to get an in-depth picture of local flood risk.

To map the flood hazard, a 1D/2D dual-drainage model may be used, assuming the sewer network map is available. For the exposure analysis, object-level data about building value, floor area, number of floors, presence of basement, etc. can be gathered through field surveys, searches through real estate databases, or aerial imagery. Transportation network maps should also be obtained to represent possibilities for indirect damages and disruptions. Telephone surveys and demographic data can be used to gather socio-economic data of households, for example age of inhabitants, number of parents in household, presence of mitigation measures, location of electrical appliances, etc. These factors can be important in determining damage from small-scale high frequency pluvial floods, but information can generally only be gathered by conducting telephone or mail surveys. For a comprehensive analysis, this effort can be focused on understanding the social vulnerability of exposed households, so resources can be dedicated towards protecting the most vulnerable.

A comprehensive susceptibility analysis could go further than the standard SDC. Bayesian network and tree data-mining techniques have recently been applied to the field of flood risk management (Merz et al., 2013; Schroter et al., 2014). These techniques have been used to correlate past flood damages with a variety of variables, with all data gathered from post-flood telephone surveys to victims (Merz et al., 2013; Schroter, 2014). They have been shown to improve the predictive capacity of models because they can better deal with non-linearity and account for relationships between variables. However, data is often unavailable for each variable for pluvial flood events, so effort is needed to collect object-level building, socio-demographic, and flood damage data, so more comprehensive damage modelling techniques can be applied. Until then, a comprehensive susceptibility analysis could apply a standard SDC for direct damage based on flood depth, then apply damage factors that increase the damage estimates if the household is in a low socio-economic class, or is an old building, or if floodwater is contaminated, like those used in the German FLEMO and UK MCM models (Penning-Rowsell, 2014; Gerl et al., 2016). Despite being derived for river and coastal floods, these damage factors can help to incorporate some of these unknown parameters until pluvial flood data improves.

To model indirect flood damage comprehensively, surveys can also be sent to businesses, infrastructure providers, and households, to gauge the type and amount of infrastructure and business disruptions associated with flooding. Traffic disruptions can be simulated with a threshold of 30cm of flooding to represent road closures (Pregnolato et al., 2017). Since the expense of each traffic, infrastructure, and business disruption is not known, a comprehensive approach could express these impacts in terms of estimated hours of delay, number of businesses disrupted, number of infrastructure nodes disrupted, rather than in uncertain monetary terms.

The intangible impacts of flooding can be better assessed if social vulnerability is part of the exposure analysis. To estimate the intangible damage, the flood hazard map could be overlaid with a map of the social vulnerability index, allowing the identification of not only the number of people affected, but also whether they are socially vulnerable (Rufat et al., 2015). This adds an extra dimension, since not all people are expected to share the same flood vulnerability and it's crucial to recognize the vulnerable.

FDA may comprehensively estimate direct, indirect, and intangible damages, but to combine them all in one monetary damage estimate is too simple. Detailed methods of modelling social vulnerabilities to determine intangible flood risks are wasted if these health risks are crudely force into a monetary value with current techniques. Instead, MCA should be used to express damage to buildings, intangible damage to non-vulnerable people, damage to vulnerable people, infrastructure, traffic, and business disruptions each in their own natural metric. A problem is the setting of weights to assign to each respective risk dimension to form an assessment of total flood damage. With time and resources, this could be resolved by sending surveys to local stakeholders to reveal the most important risk dimensions according to them. The results could be used to improve public participation and justify the selection of weighing criteria in MCA approaches. In responding to the surveys, stakeholders will gain automatic awareness of flood risks, and in participating in the process, there will be greater trust in the MCA outcome.