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Understanding the costs of inaction -

An exploration of urban pluvial flood damage assessments

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Executive Summary

Traditionally, people have inhabited places with ready access to fresh water. Today, over 50% of the global population live 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. To properly manage flood risks, assessments are needed to determine the flood risk level and where to allocate scarce financial resources for risk reduction. Flood risk is a function of flood hazard and consequence, hazard is the flood probability and consequence is the damage caused. Methods of assessing flood hazards are more advanced than methods of assessing flood consequences and there is a lack of comparable flood damage data to build damage models. Pluvial flood damage, caused by heavy rainfall that urban drainage systems can't cope with, is less researched than river and coastal flood damage. This research contributes to knowledge of pluvial flood damage assessments (FDA) using a three-pronged approach of literature review, expert questionnaires, and case studies. A literature review is conducted to investigate the key types of FDA methods used, and approaches used to present FDA as a decision support tool. Results show that there are various FDA methods, with many studies focusing only on direct damage to buildings. Infrastructural damage, intangible damage to health and the environment, and indirect damage incurred by flooding are comparatively underrepresented. For a broader perspective, a questionnaire is distributed to flood risk experts asking them to rate the importance of various flood risk components on an ordinal 1-5 scale, and whether they prefer a cost-benefit (CBA) or multi-criteria analysis (MCA) for presenting results. Results show that experts emphasize the importance of infrastructural and intangible damages and prefer an MCA approach. Combined with literature, questionnaire results are used to develop a framework for distinguishing simple, refined, and comprehensive FDA methods. Additionally, FDA for two European cities are performed from the bottom-up, demonstrating potential pluvial flood damages of €10 million in each city from a 60mm/1hour rainfall event. Results show that there are a few limitations in the FDA process regarding data consistency and the inclusion of infrastructural and intangible damages. Flood risk assessments (FRA) are vital for spreading awareness and incubating action to reduce flood risks. So, considerable effort is needed in collecting data to further understanding of flood risks and help secure a safer future.

Glossary of terms and abbreviations

BCR (Benefit-cost ratio): Benefits of a project divided over the costs of implementation

Climate adaptation: Adjusting to the expected future climate with the goal of reducing vulnerability/building resilience

Climate mitigation: Reducing the flow of greenhouse gases into the atmosphere with the goal of reducing climate change

CBA (cost-benefit analysis): Analysis of costs of implementing a given adaptation measure relative to the benefits of adaptation, expressed solely in monetary terms (€)

COI (Cost of inaction): Future costs that arise by maintaining business-as-usual, i.e. cost of non-adaptation

Direct damage: Damage that occurs due to immediate physical contact with floodwater

Exposure: Value of assets that are subjected to the flood hazard

Flood: Temporary covering of water of area that is not usually covered with water

Flood damage: Cost that arises if flood hazard interacts with exposed objects

FDA (Flood damage assessment): Transformation of flood hazard map into an estimation of flood damage based on exposure and vulnerability analysis

Flood hazard: Probability of a flood of a given magnitude (usually depth)

Flood resilience: Ability to withstand flooding and resist damage

Flood risk: Combination of probability of a certain flood event and of the potential adverse impacts on human health, the environment, cultural heritage and economic activity

FRA (Flood risk assessment): Combination of flood hazard and flood damage assessments, portraying both the flood probability and damages that would arise if that flood hits

GIS (Geographic information system): A system designed to capture, store, manipulate, analyze, manage, and present geographical data

Indirect damage: Damage that occurs after the flood or outside the flooded area incurred by the flood event

Intangible damage: Damage that cannot readily be quantified in monetary terms, for example, due to a lack of a market price to value the damaged object

MCA (Multi-criteria analysis): Analysis of costs of implementing a given adaptation measure relative to the benefits of adaptation, expressed not only monetarily but with multiple metrics

SDC (Stage-damage curve): Function used to relate the flood hazard to monetary damage

Susceptibility: Extent to which a system is affected by a given impact (e.g. flood), interchangeable with vulnerability

VSL (Value of a statistical life): The value of a life based on the amount of money people are willing to accept for a marginal increase in the likelihood of mortality

WSS (waterschadeschatter): A Dutch web-based flood damage estimation tool

WTP (Willingness to pay): Amount of money a person would trade for a given effect or object

"There are risks and costs to action. But they are far less than the long-range risks of comfortable inaction"

-John F. Kennedy

1. Introduction

1.1 Expansion of cities

In 1960, the global urban population hovered around 1 billion (World Bank, 2018a). It's now over 3 billion and by 2050, cities are expected to shelter 2/3 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 1.1 illustrates the increase in flood occurrence since 1980 (EEA, 2016).

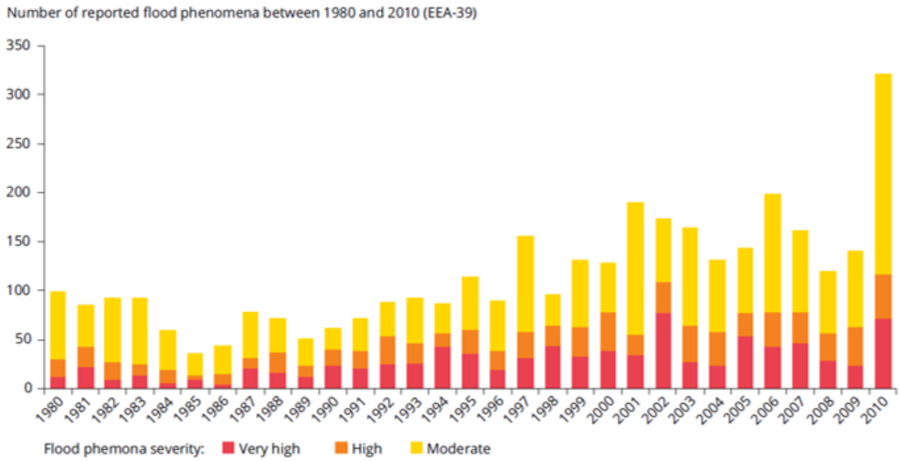

Figure 1.1: Flood occurrence in Europe 1980-2010 (EEA, 2016)

Floods are the most frequent and economically damaging natural hazard in Europe (Rojas et al., 2013). This report investigates the costs of urban flooding to expand knowledge on the ways of assessing and alleviating future flood risks.

1.2 Floods

Of the €150 billion in reported damages caused by natural hazards in Europe between 1999-2009, 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 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). To avoid repetition of these disastrous events, it's 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've 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 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.

1.3 Cost of inaction and flood risk

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 quantitively associated with IQ losses, but it wasn't 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 weren't convinced.

Years later, the COI was well-publicized when Nicholas Stern estimated the economic costs of climate change up until year 2100 if anthropogenic greenhouse 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).

Floods have been detrimental to European cities in recent years, so it's urgent to recognize the COI of flooding to minimize future costs. 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 1.2, from the work of Sayers et al. (2013).

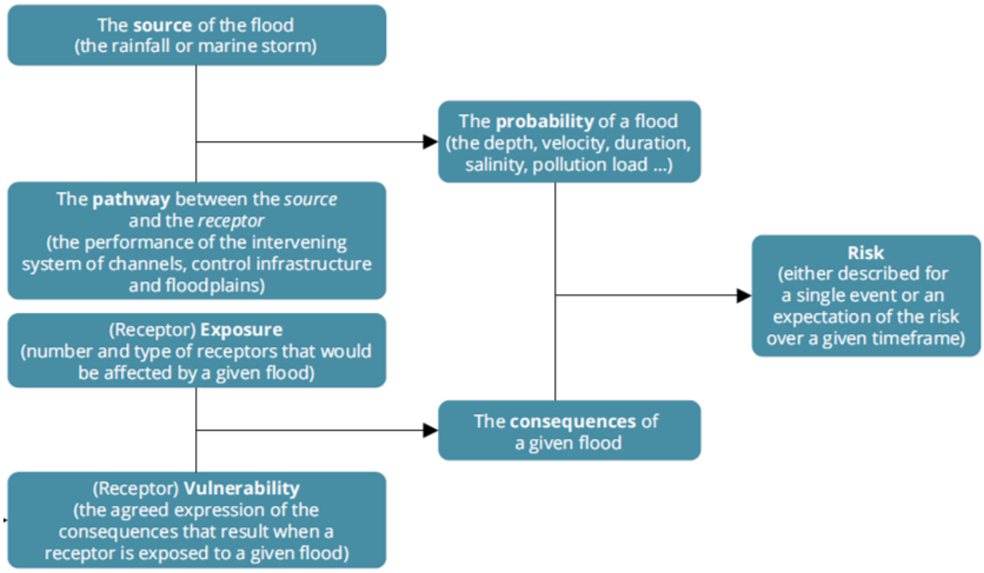

Figure 1.2: Flood risk concept (Sayers et al., 2013)

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 flood.

1.4 Flood risk assessments

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 don't really need it or 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 some reasons for assessing flood risks is shown in Table 1.1.

Table 1.1: 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

1.5 Research problem

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's 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's limited use for detailed flood hazard assessments if detailed FDA are unavailable. To undertake the effort of detailed flood hazard modelling to only assess damages crudely is like buying an expensive piece of fish and deep-frying it. There's 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's 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's 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 quantity 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 the case flood water is contaminated or a vital infrastructure network is disrupted, so it's 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 shouldn't 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.

1.6 Research aim and questions

This report addresses knowledge gaps by breaking down the existing FDA methods into core components and developing a framework to distinguish simple, refined, and comprehensive methods. FDA are also performed for two European cities to identify the practical limitations. The research question is stated below.

How can flood damage estimation methods be distinguished and what practical barriers exist for flood damage assessments in European cities?

The research question is broken down into six sub-questions, which culminate to answer the main question.

Sub-question #1*: What components can be used to describe FDA methods?*

Sub-question#2*: How can FDA methods be distinguished between simple, refined, and comprehensive?*

Sub-question #3: *Which types of flood damage shouldn't be ignored from the simplest of assessments?*

Sub-question #4: *How can FDA results be presented to best support decisions in flood-risk reduction?*

Sub-question #5: *What are the results and limitations of an FDA for a rainfall event in Rotterdam and Leicester?*

1.7 Research approach

A diagram depicting the approach used to answer each sub-question is shown in Figure 1.3.

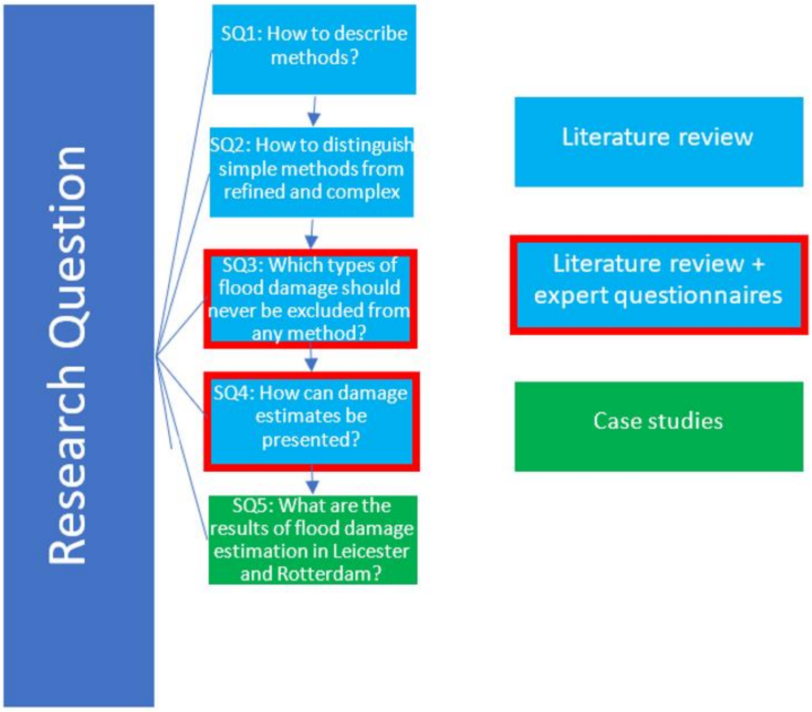

Figure 1.3: Diagram of research approach

As displayed in Figure 1.3, three methods are used to answer the research questions - literature reviews, expert questionnaires, and a case study.

Literature concerning FDA in cities is reviewed to answer the first four sub-questions. The first purpose is to form an understanding of the typical FDA methods (#1) and how to distinguish methods based on complexity (#2).

Simple FDA methods should include the most important components of flood damage (#3), which could be identified based on results reported in scientific literature. The methods of presenting FDA to decision-makers, whether strictly in monetary terms or with multiple criteria (#4), are explored to identify optimal ways of using FDA to support implementation of proactive policies. To fully answer sub-questions 3 and 4, questionnaires are distributed to experts to identify the crucial components of flood damage and ask whether results should be presented monetarily or with multiple criteria.

Questionnaire results are supplementary to the literature review, ensuring that perspectives of practitioners outside the field of scientific research are heard.

To further explore the FDA process, damages are assessed for flood events in Rotterdam and Leicester. The case study provides results that can be used to inform residents of Rotterdam and Leicester of potential flood damage (#5) and a deeper insight into the limitations of FDA methods.

Section 2 explains the main theories used for estimating flood damages, as identified in a review of recent literature. 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 thesis concludes with a synthesis and some final words in section 6.

2. FDA in theory and practice

2.1 Literature review description

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. that provided detailed descriptions of FDA were selected for review. The keywords used in the search are shown in Table 2.1.

Table 2.1: 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 2.1.

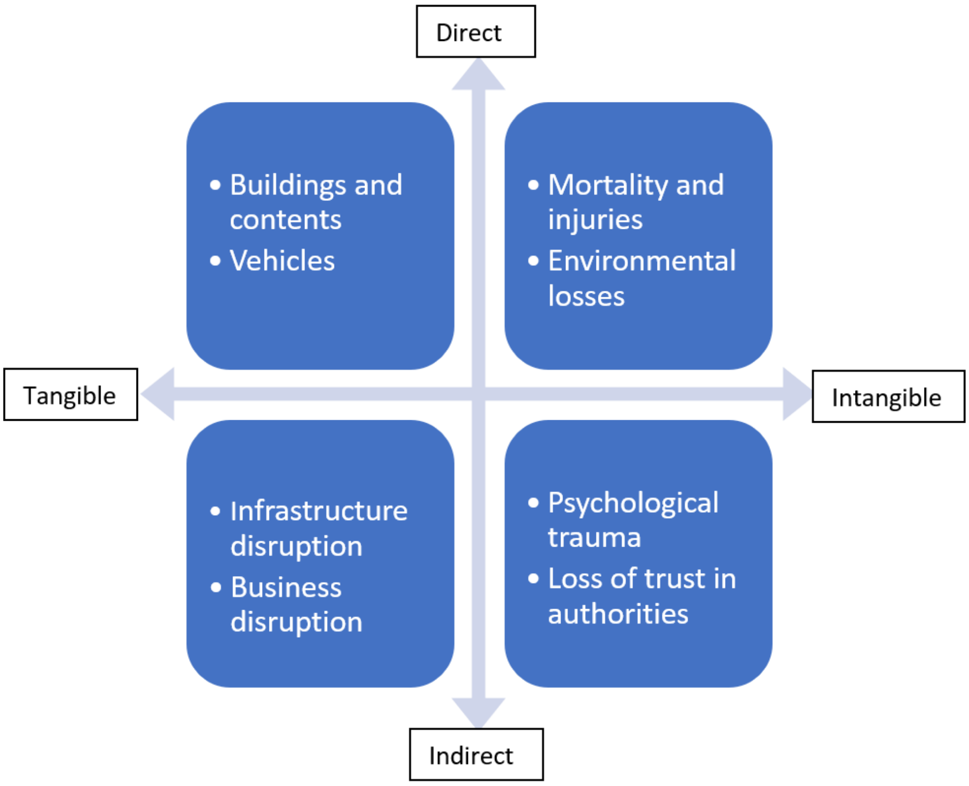

Figure 2.1: Examples of direct, indirect, and intangible flood damage

2.3 Direct damage

2.3.1 In theory

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, Figures 2.2 and 2.3 show the contribution of each land use type to total direct flood damage from recent flood events.

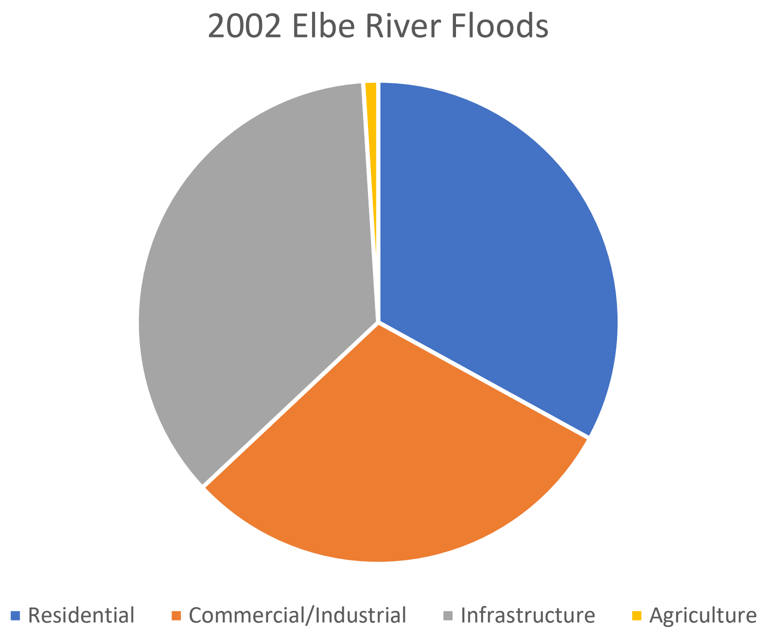

Figure 2.2: Insured losses from 2002 Elbe floods (Meyer and Messner, 2005)

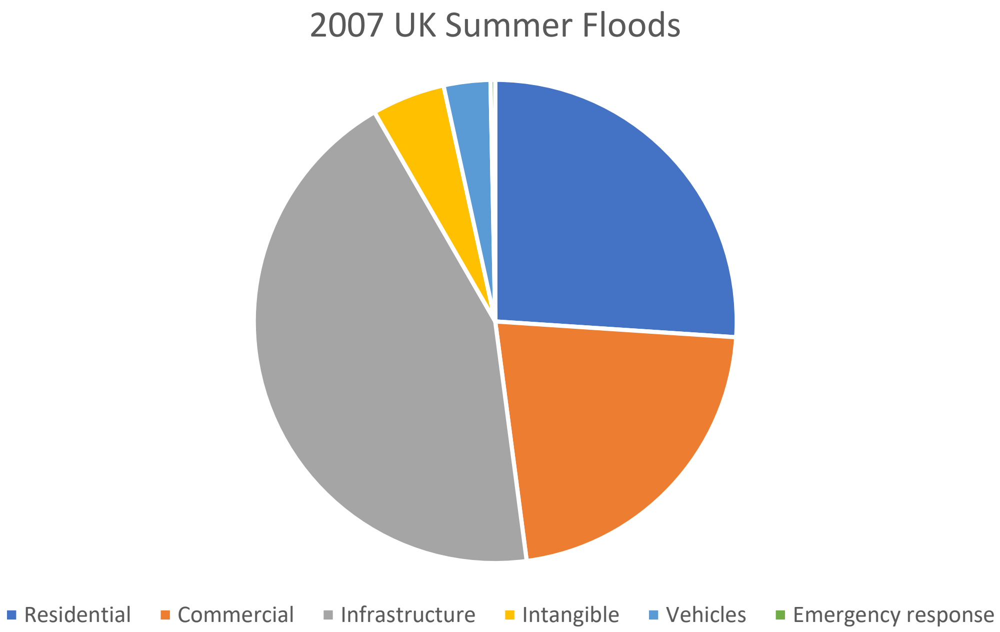

Figure 2.3: Insured losses from 2013/14 UK winter floods (Fenn et al., 2016)

As shown in Figures 2.2 and 2.3, 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 below, split between impact parameters describing the flood, and resistance parameters describing flood-prone objects (Merz et al., 2010).

Table 2.2: 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 2.3: 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.

2.3.2 In practice

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 2.4 (Jonkman et al., 2008).

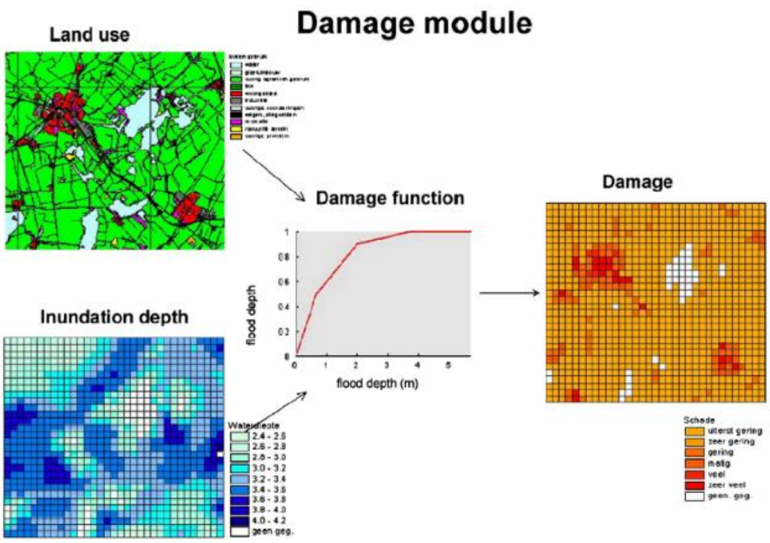

Figure 2.4: Scheme of the damage estimation process (Jonkman et al., 2008)

2.3.2.1 Flood hazard mapping

A flood hazard map (bottom-left of Figure 2.4) 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 a .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).

2.3.2.2 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, CORINE 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).

2.3.2.3 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 below in Figures 2.5 and 2.6. Note that the flood depth rises to 6 metres because these curves were developed for coastal and river floods, whereas pluvial flood depths rarely exceed 1 metre.

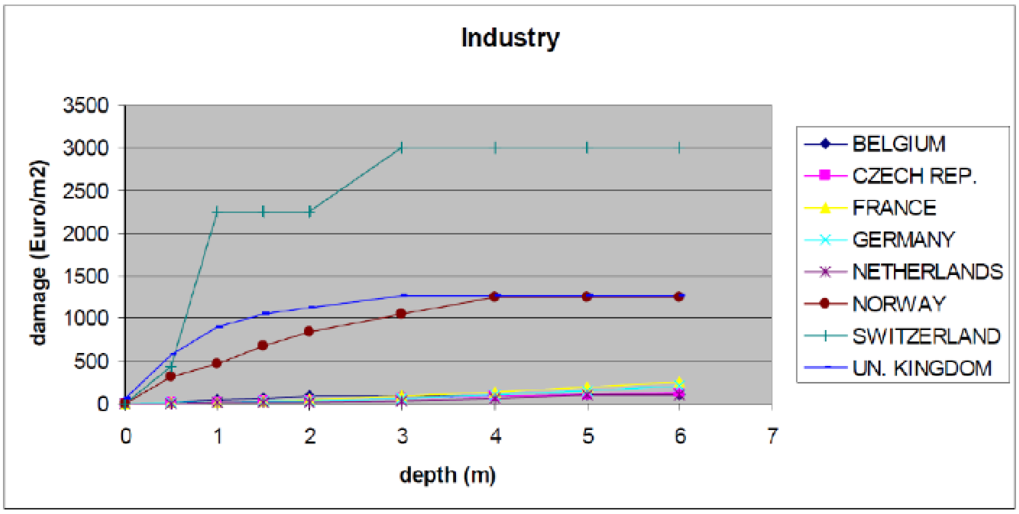

Figure 2.5: Absolute damage curves for European countries (Huizinga et al., 2017)

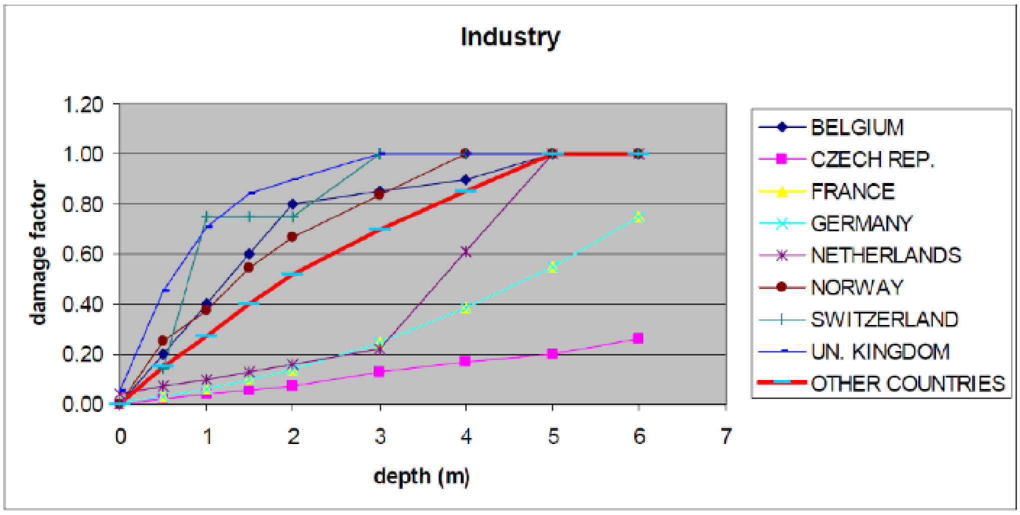

Figure 2.6: Relative damage curves for European countries (Huizinga et al., 2017)

As shown above, stage damage curves (SDC) differ widely in Europe and depth is the only flood hazard. It would be ideal to include all relevant impact and resistance parameters in direct damage assessments, but this isn't 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).

2.3.2.4 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 can't 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 FLEMO damage models 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 Multiculoured 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 below.

Table 2.4: 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 vary 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

2.3.2.5 Pluvial flood damage: recent findings

There's been extensive study 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 $WaterDepth_{building}$ < Threshold THEN $Cost_{building} = 0$

IF $WaterDepth_{building}$ >Threshold THEN $Cost_{building}$ = ContentDamage + 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 2-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 aren't 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's 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 A.

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's 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).

2.4.1 In theory

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 2.5.

Table 2.5: Indirect damage influencing parameters

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

2.4.2 In practice

2.4.2.1 Business interruption

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, IO 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 don't 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's 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's still highly simplified as it doesn't 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.

2.4.2.2 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's 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're 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's 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, wastewater) 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

2.5.1 In theory

There are numerous intangible flood impacts including fatalities, injuries, 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 PTSD (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 as shown in Figure 2.7, from the review of Rufat et al. (2016).

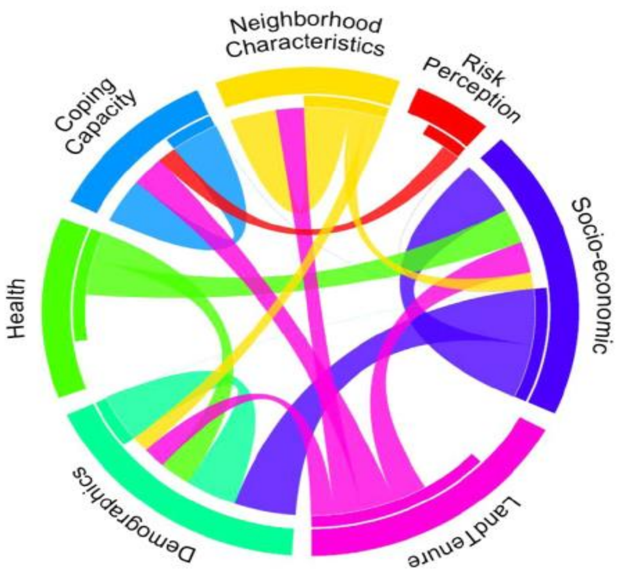

Figure 2.7: Social vulnerability characteristics (Rufat et al., 2016)

2.5.2 In practice

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.

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 (VSL) at €6.7 million (Hammond et al., 2015). Below, some common revealed and stated preference techniques are described in Figures 2.8 and 2.9, adapted from Green et al. (2011).

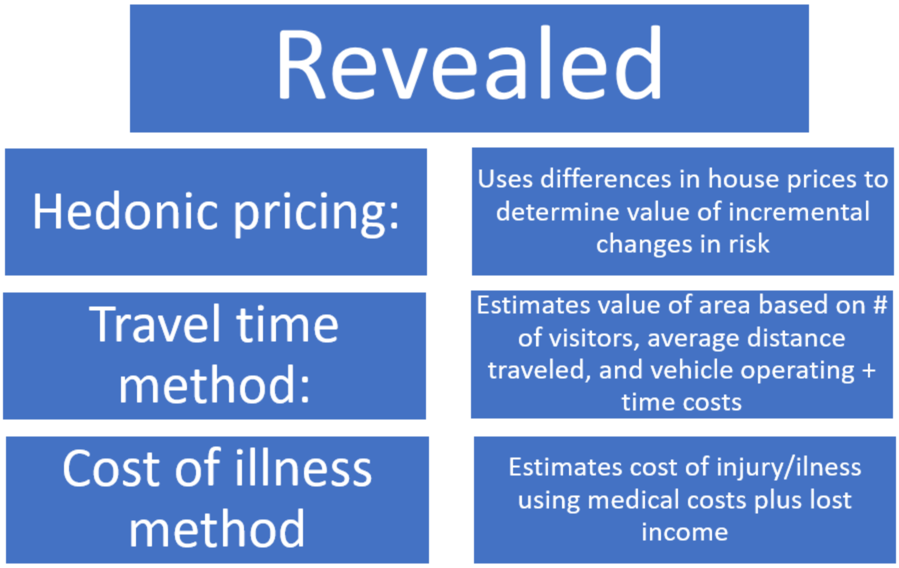

Figure 2.8: Revealed preference methods (Green et al., 2011)

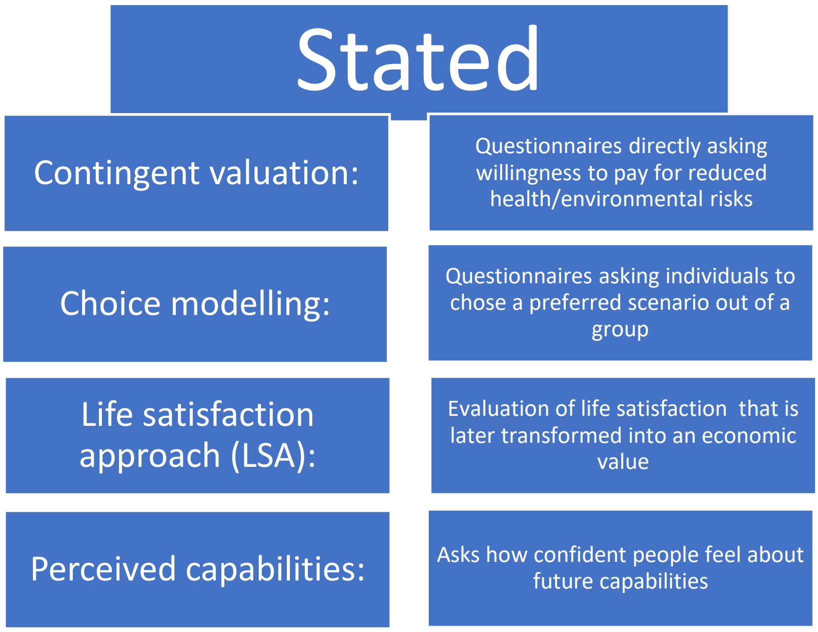

Figure 2.9: Stated preference methods (Green et al., 2011)

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 ordinally rate their level of well-being 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 CBA vs MCA

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's 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 don't paint the full picture of flood risks (Meyer et al., 2009; ten Velhuis, 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's 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's no single method of conducting an 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 below, adapted from Kubal et al. (2009).

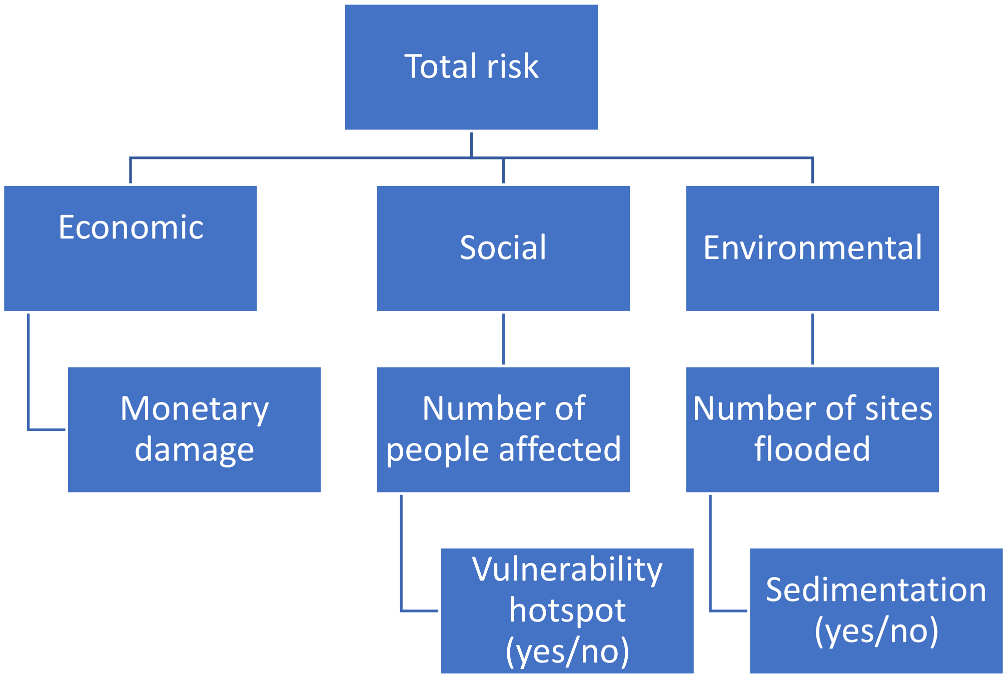

Figure 2.10: MCA criteria examples (Kubal et al., 2009)

Once damages are assessed for economic, social, and environmental dimensions (Figure 2.10), 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's 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 B.

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.

3. Materials and methods

3.1 Expert questionnaires

To get a perspective outside of scientific literature, a questionnaire was distributed to members of the Koninklijk Nederlands Waternetwerk and employees of KWR Watercycle 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.

3.1.1 Method

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 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 types questions and this last question are presented in Section 4. The full questionnaire is in Appendix C.

3.1.2 Suitability, reliability, and validity

The 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 (SQ3) and preferred method for presenting FDA results (SQ4).

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. This way, the results shouldn't be influenced by outliers. The questionnaire is meant to supplement the literature review, so results are cross-checked with existing knowledge to ensure results aren't 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.

3.2 Case study

3.2.1 Purpose

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) and Belgrave (in Leicester, UK). The purpose was to understand the nuances of the process and identify any limitations. 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.

3.2.2 Site description: Lombardijen

Lombardijen is a neighbourhood in Ijsselmonde in Rotterdam, shown in green in Figure 3.1.

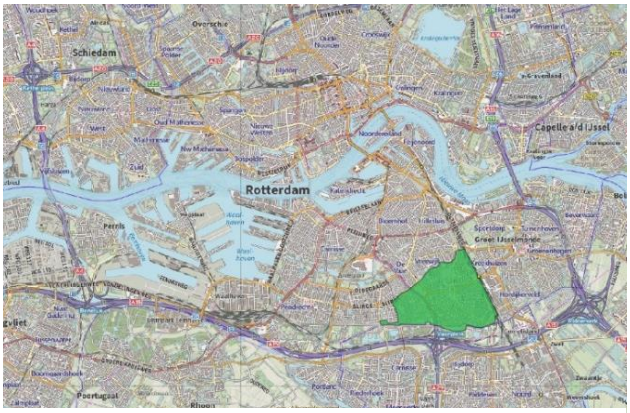

Figure 3.1: Lombardijen location

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

3.2.3 Site description: Belgrave

Belgrave is a ward of Leicester in England. The location of Belgrave within the greater Leicester area is highlighted in yellow in Figure 3.2.

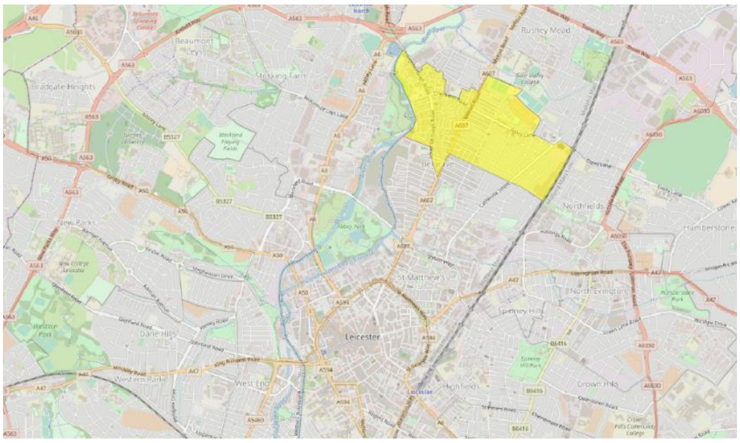

Figure 3.2: Belgrave location

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

3.2.4 3Di flood model

The 3Di flood modelling software was developed by a combination of Stelling Hydraulics, Deltares, TU Delft, and Nelen & Schuurmans. It's 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 and provides fast and accurate results (Nelen & Schuurmans, 2017). The governing equations of 3Di are given in Appendix D.

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 wasn't 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.

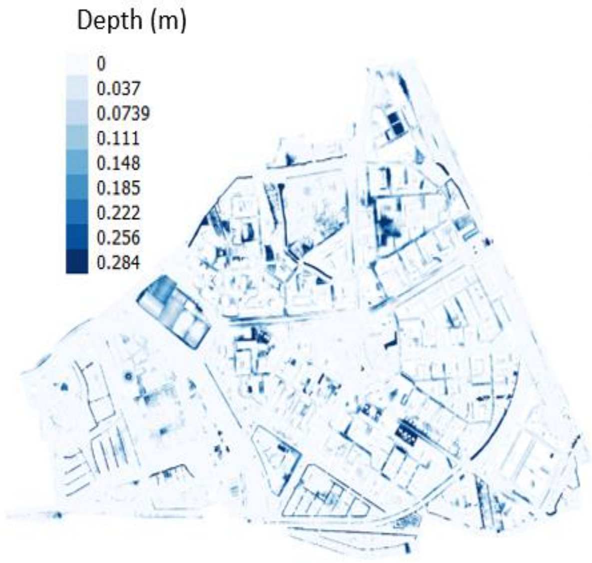

Figure 3.3: Lombardijen water depth map

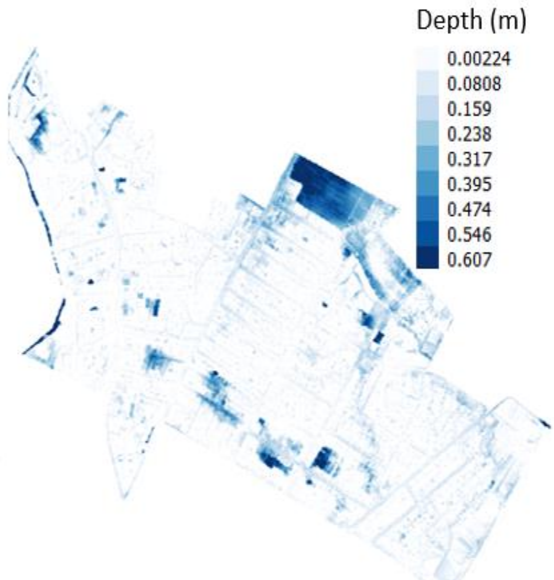

Figure 3.4: Belgrave water depth map

As shown in Figures 3.3 and 3.4, both areas have some pools of water, but the water depth in belgrave (3.4) is noticeably deeper. This is probably due to a lack of a sewer network in the Belgrave flood model.

3.2.5 WSS

The resulting maps are inputted into the waterschadeschatter (WSS) online FDA tool. It's 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 AHN2 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 wasn't 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. Due to time requirements, this had to be done broadly, and 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 E. 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 (D_{dd}), factor for flood depth (Y_d), factor for flood duration (Y_t), and factor for the month (Y_s). 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 isn't part of this FDA. The equation used for damage calculations in the WSS is shown below, with examples for the six land use classes included in the Belgrave damage assessment.

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

Table 3.1: WSS damage equation

Land use class	Max damage/m^2 (D_{dd})	Flood depth (Y_d) (0cm, 1cm, 5cm, 15cm, 30cm	Flood duration (Y_t)	Month (Y_s)
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 (D_d) = 271*0.1*1*1 = 2.71€/m^2. If water depth reaches 5cm, the damage factor (Y_d) increases to 0.5, and if water depth reaches 15cm, then Y_d becomes 1 and direct flood damage is equal to the maximum damage value. The SDC implementing these equations are shown below, Figures 3.1 shows the SDC used for all buildings and Figure 3.2 shows the SDC applied to parks, roads, and parking lots.

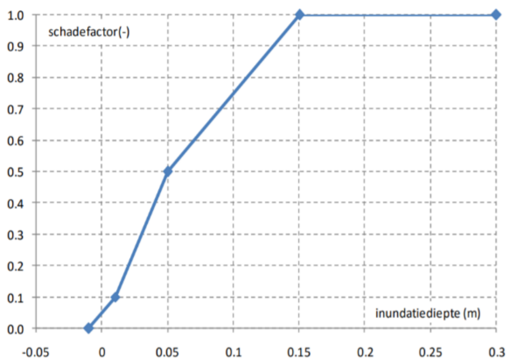

Figure 3.1: SDC buildings

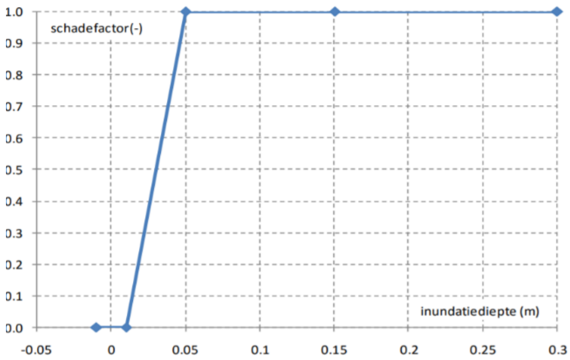

Figure 3.2: SDC park/road/parking lot

The SDC shown above were developed for Dutch land uses, but were applied to Belgrave. It's 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. However, it was done due to troubles finding suitable SDC for the UK.

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

4.1 Questionnaire results

Questionnaire responses are shown in the graphs below. 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.

Direct damage

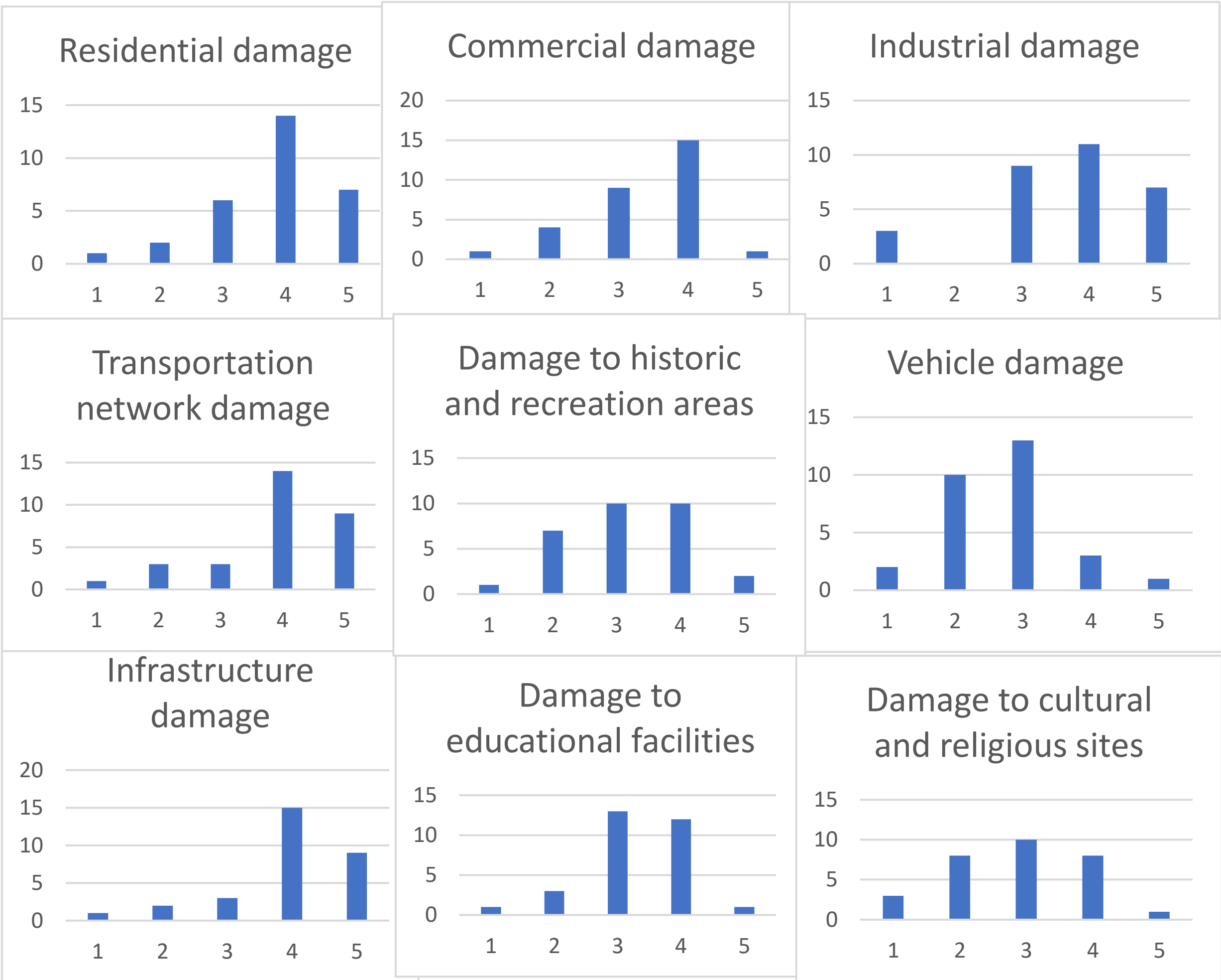

Figure 4.1: Direct damage importance ratings

Indirect damage

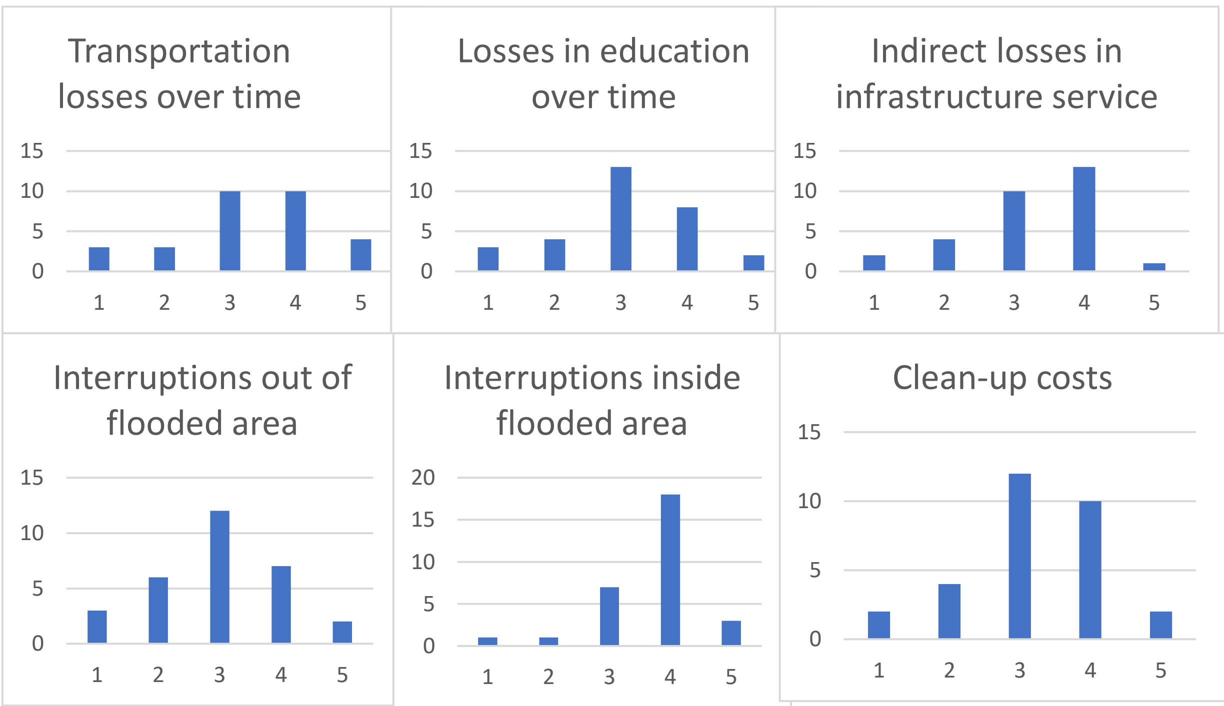

Figure 4.2: Indirect damage importance ratings

Intangible damage

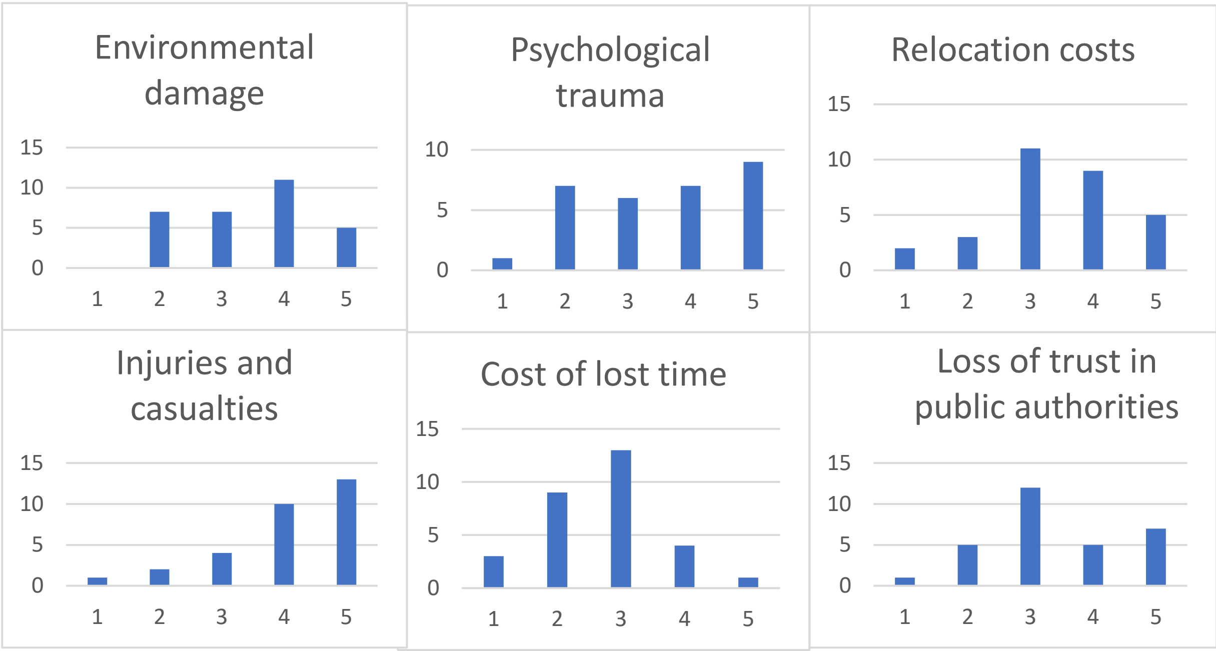

Figure 4.3: Intangible damage importance ratings

In Figures 4.1-4.3, it's 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 median response was either 3 (somewhat important) or 4 (very important), as shown in Table 4.1.

Table 4.1: Median 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 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’s acknowledged 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.

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’s harder to recognize than physical injury, but it’s considered an essential element of intangible flood damage both in literature and the questionnaire results.

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.

4.1.2 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 4.4.

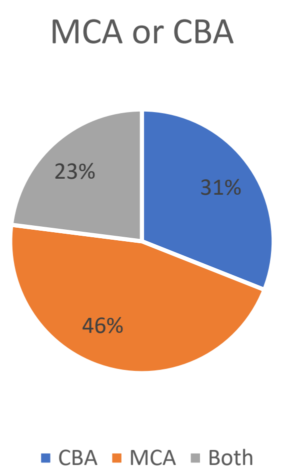

Figure 4.4: CBA or MCA questionnaire results

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 4.5.

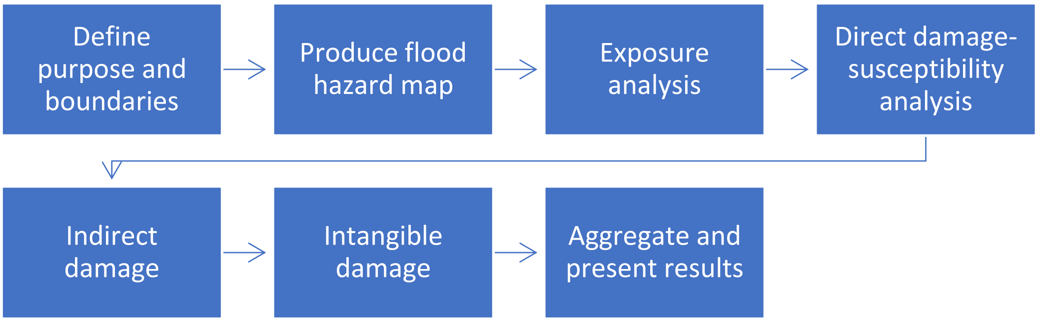

Figure 4.5: Framework describing the FDA process

The framework for describing and distinguishing FDA methods splits the process into seven steps. First, it's 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 framework 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 4.2, for greater detail see Appendix F.

Table 4.2: Distinguishing between simple, refined, and comprehensive FDA

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 CBA or MCA

Money is a useful metric since it is common ground that can be used to compare investments in risk-reduction. However, different flood types shouldn't 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 PTSD 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 isn't 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's 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.

4.5 Case study results

4.5.1 Belgrave

The outcome of the WSS FDA for Belgrave is shown in Figures 4.6 and 4.7. Areas depicted in red have the highest damage per m^2 (maximum 67.7€/m^2).

Figure 4.6: Belgrave damage estimation (€/m2)

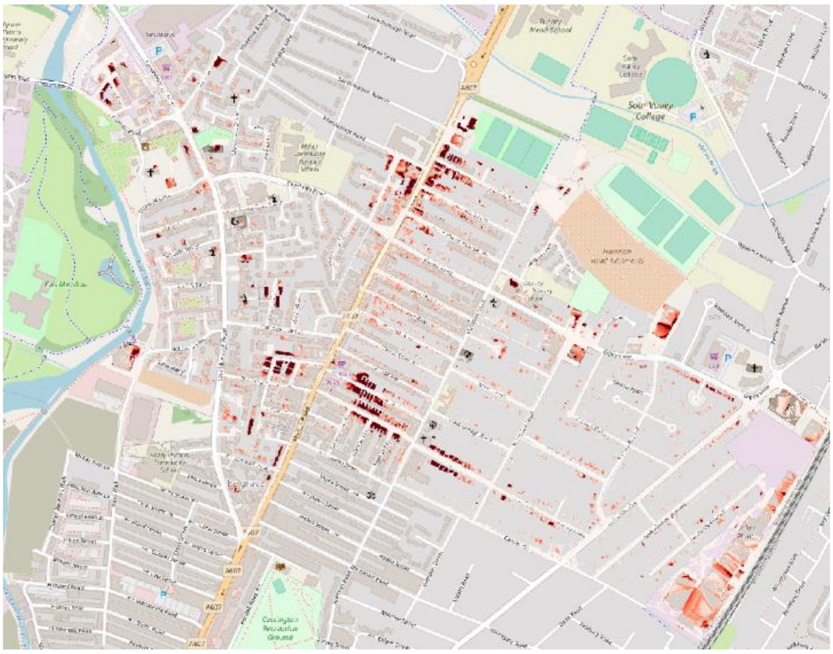

Figure 4.7: Belgrave damage estimation over street map

Figure 4.7 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 E). Table 4.3 displays the total damage for each land use class.

Table 4.3: 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 wasn't freely available, so all buildings were considered either residential and 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. More effort to differentiate land uses based on satellite data is needed to provide more useful results.

4.5.2 Lombardijen

Results of the WSS damage assessment for Lombardijen are shown in the figures below.

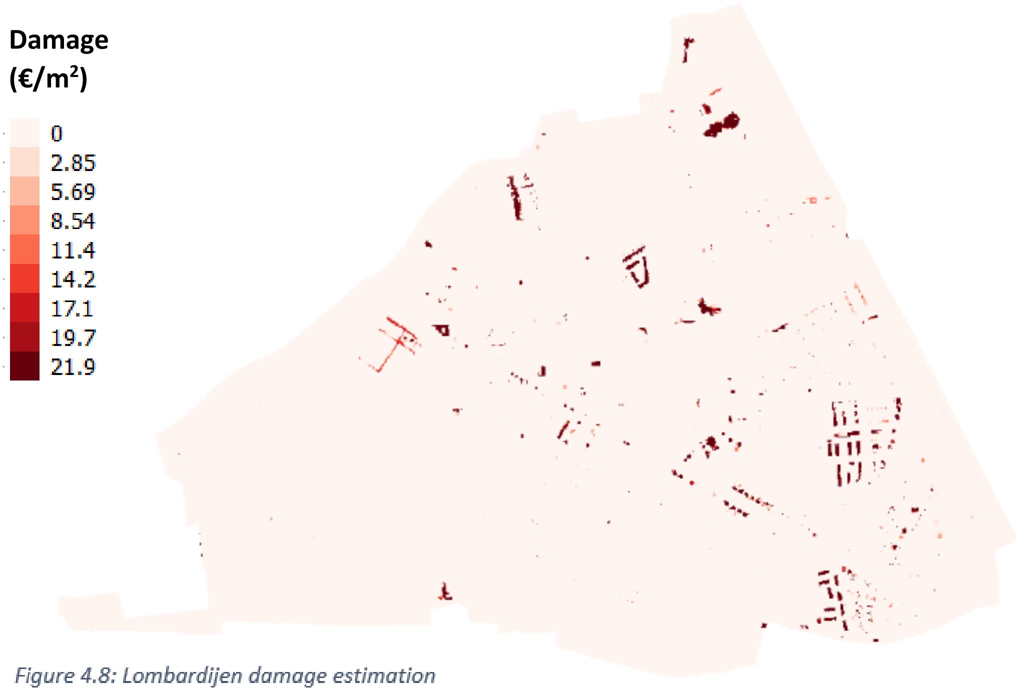

Figure 4.8: Lombardijen damage estimation

Figure 4.9: Lombardijen damage estimation over street map

Figures 4.8 and 4.9 show 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 4.5 and Figure 4.10 show the share of total damage composed by each damage type. Unlike Belgrave, 15 land use classes were available for Lombardijen.

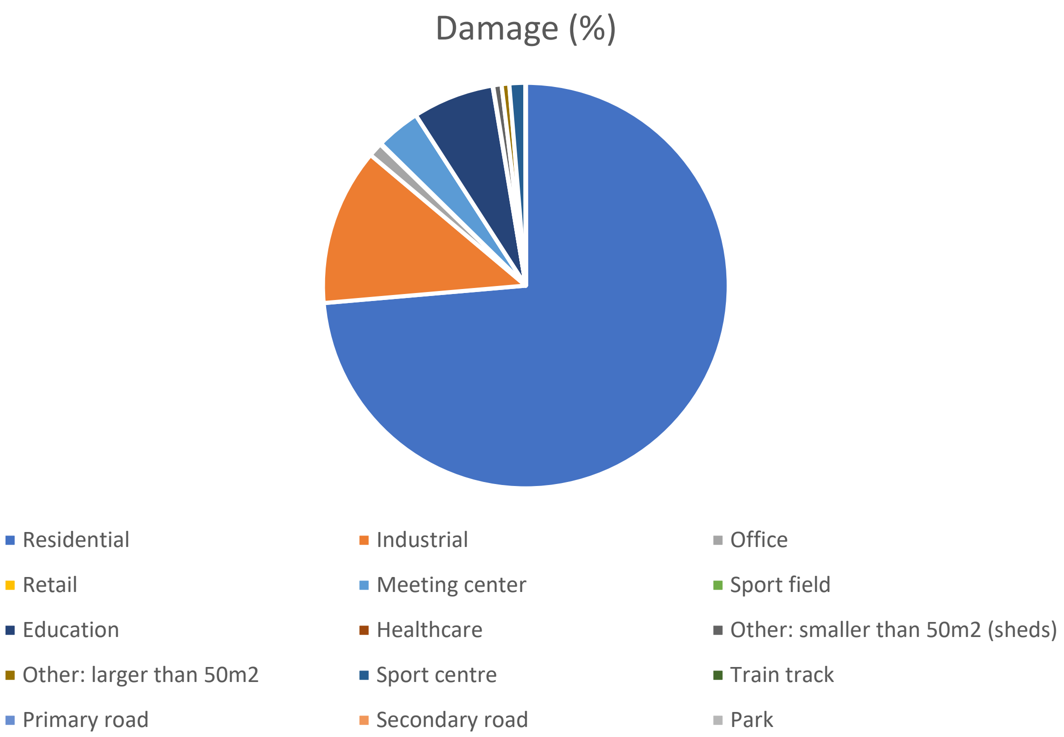

Figure 4.10: Lombardijen damage distribution pie-chart

Table 4.4: 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 50m² (sheds)	70,044
Other: larger than 50m²	63,755
Sport centre	134,132
Train track	737
Primary road	173
Secondary road	1,075.338
Park	134
Total	**10,433,787**

The table and figure above show that total flood damage 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're 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 as discussed below.

5.1 Limitations

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's surprising to see such similar results given the gap in complexity between the two studies. For Lombardijen, all relevant input data for 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. Note that limitations also exist regarding the omission of some subscription-only articles in the literature review and the use of a subjective 1-5 rating scale in the questionnaire, but these are not as profound as limitations encountered in the case study.

5.1.1 Sewer network map

It's 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 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. As shown in Figures 3.3 and 3.4, 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 can be described as simple at-best. A silver lining is that anything more complex may have been unnecessary due to the simplicity of the subsequent damage assessment.

5.1.2 Land cover map

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 isn't 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. The figures below display the satellite map of Belgrave before (5.1) and after (5.2) this process.

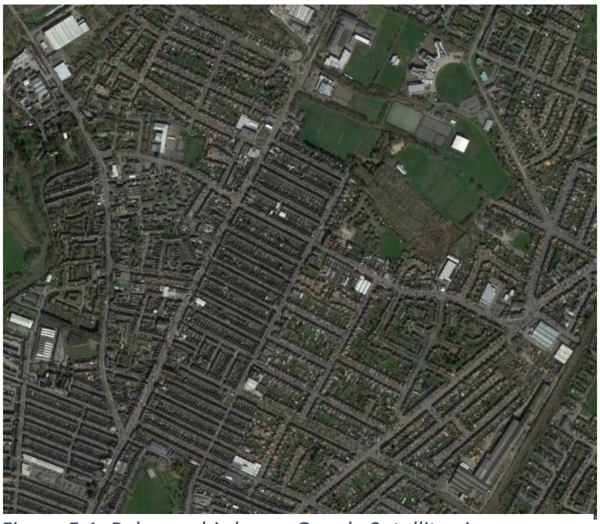

Figure 5.1: Belgrave birds-eye Google Satellite view

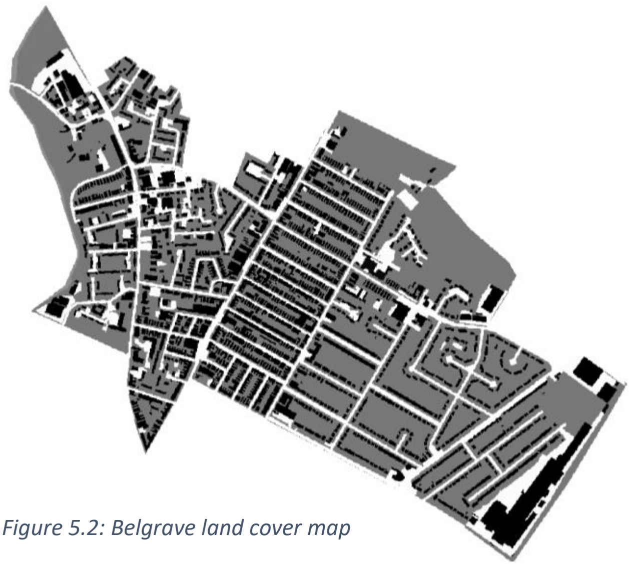

Figure 5.2: Belgrave land cover map

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 mundane and time-consuming task, as each shape displayed in Figure 5.2 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 5.1) were lumped into one land cover class (depicted in grey, Figure 5.2).

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 wasn’t 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 wrongly classed as residential, which is an over-simplification of urban spatial dynamics. In fact, overlaying flood damage hotspots with a Google Street map, it’s evident that more than just residences are flooded as shown in the figures below.

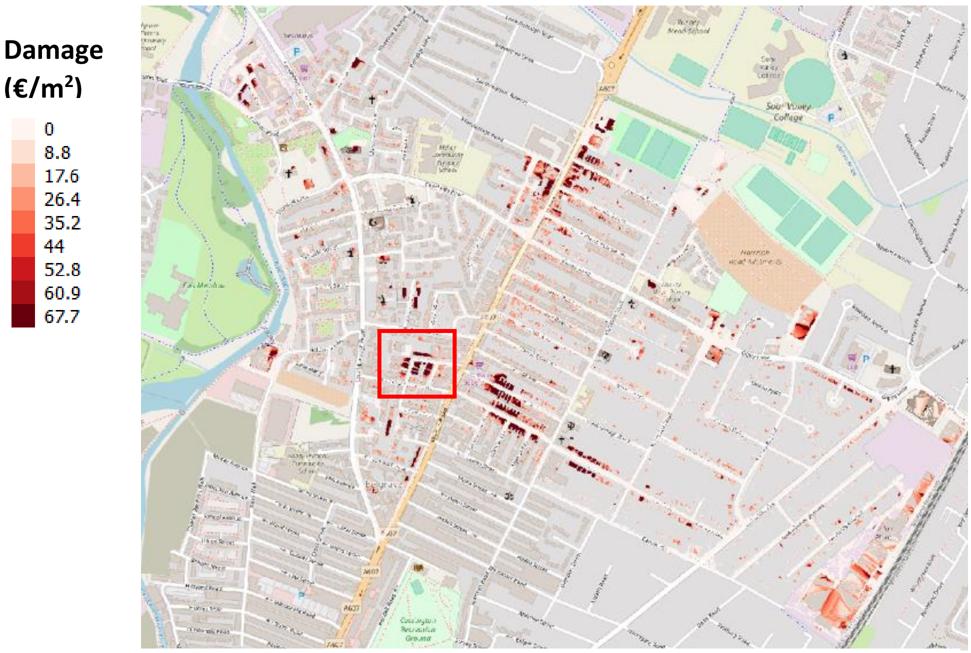

Figure 5.3: Belgrave damage estimate, zooming in on boxed area

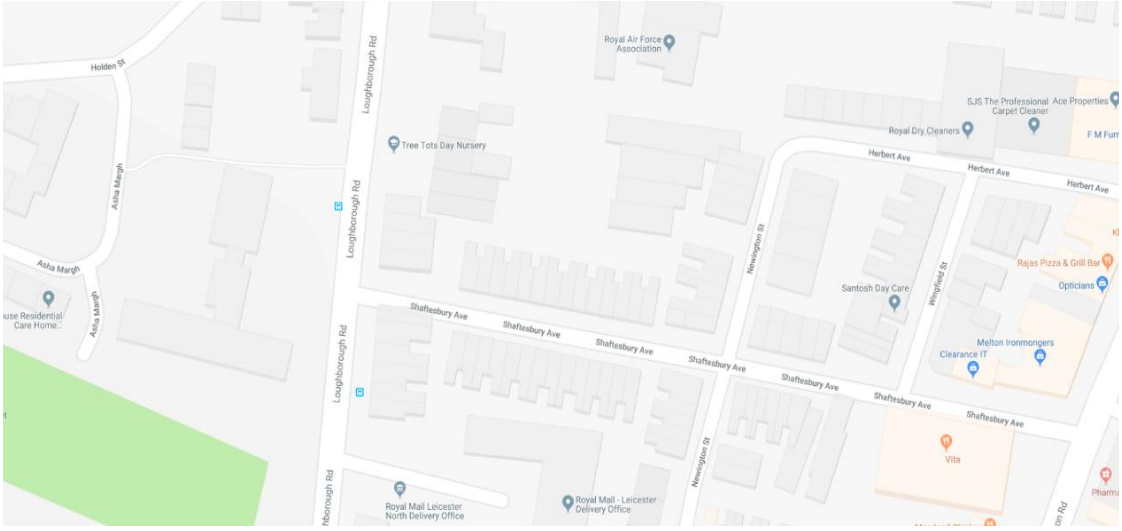

Figure 5.4: Zoomed in on damage hotspot, red rectangle identifies a day-care centre

Figure 5.5: Red rectangle shows day-care centre fully damaged

The area depicted in the red rectangle is a day-care centre that's 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's 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.

5.1.3 Damage functions

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's not recommended to transfer damage functions between countries unless it's 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 aren't 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 shouldn't 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.

5.2 Words for the future

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's 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's been shown in some cases that 20% of flood victims develop long-term trauma (Fewtrell et al., 2008). This was a surprising discovery - before going into this research, psychological trauma wouldn't have come to mind as a major type of flood damage.

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's 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. When more metrics are included like

There's 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's paramount that stakeholders 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're 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. Conclusion

The significance of expanding knowledge about flood risks and the COI 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's 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 investigated FRA, focusing on the methods used to assess flood damage. There are glaring inconsistencies and limitations of the methods applied between different areas, and a failure to incorporate all dimensions of flood damage. So, this study sought to answer the question.

How can FDA methods be distinguished and what practical barriers exist for flood damage assessments in European cities?

The question was split into five sub-questions that were answered with three objectives: a literature review, a questionnaire distributed to 30 experts, and a bottom-up FDA for two European cities using the Dutch WSS method. The research approach is restated in Figure 6.1, followed by the solution to each sub-question.

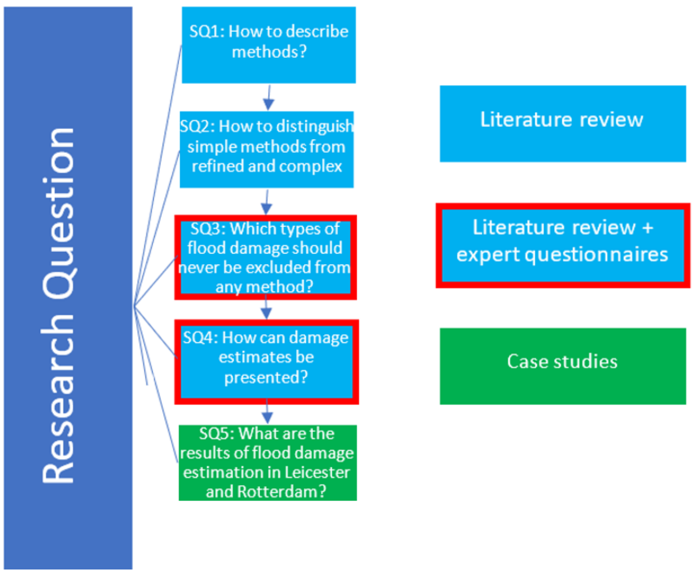

Figure 6.1: Research approach restated

SQ1: It was revealed that FDA can be distinguished based on seven factors: study purpose, flood hazard maps, exposure analysis, direct damage susceptibility analysis, indirect damage analysis, intangible damage analysis, and method of presenting FDA results.

SQ2: The components described above can reveal the distinction between simple, refined, and comprehensive methods based on input data requirement. Availability of standardized data is a bottleneck for FDA, so this distinction helps to identify a suitable method based on what's available.

SQ3: Literature and questionnaire responses indicate that physical damage to buildings, infrastructure, the transportation network, indirect damage within the flooded area, and intangible damage to human health and the environment are the key types of flood damage that should be included in all FDA if possible.

SQ4: The assessment of health-related flood damage is hampered by methodological constraints concerning the transfer of health impacts into monetary values. These damages need to be included to maximize impact of the flood damage assessment, so MCA approaches should be used rather than a rigid CBA approach.

SQ5: FDA revealed damages upwards of €10 million in both Lombardijen and Belgrave from a single rainfall event. All data for Belgrave had to be gathered manually, which proved troublesome and resulted in sub-optimal damage assessment, signifying the importance of considering data limitations before undertaking a FDA.

The overall results show that FDA can be distinguished with seven components, but data inconsistency and a lack of a standardized method severely constrain the assessment of pluvial flood damage.

FDA are vital for raising flood risk awareness and supporting arguments for building flood resilience, but decisions should not be based on FDA alone without recognizing the uncertainties underpinning the damage assessment process. A way forward is to keep studying flood damages and developing solid databases to construct reliable models for assessing potential future flood damages. This could be essential in convincing decision-makers to look towards the future to prepare for floods lying ahead. To borrow another quote from John F. Kennedy, "Those who look only to the past or the present are certain to miss the future".

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Appendix A

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 models	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 B

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.

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

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 C

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 and religious areas

1	2	3	4	5
○	○	○	○	○

Clean-up costs

1	2	3	4	5
○	○	○	○	○

Indirect Damages

Description (optional)

Business losses inside flooded area

1	2	3	4	5
○	○	○	○	○

Business losses outside flooded area

1	2	3	4	5
○	○	○	○	○

Losses in infrastructure services (over time)

1	2	3	4	5
○	○	○	○	○

Losses in educational services (over time)

1	2	3	4	5
○	○	○	○	○

Losses in transportation services (over time)

1	2	3	4	5
○	○	○	○	○

Intangible (non market-priced) Damages

Description (optional)

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

1	2	3	4	5
○	○	○	○	○

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

1	2	3	4	5
○	○	○	○	○

Estimation of direct, tangible flood damages

1	2	3	4	5
○	○	○	○	○

Estimation of indirect flood damages

1	2	3	4	5
○	○	○	○	○

Estimation of intangible flood damages

1	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

1	2	3	4	5
○	○	○	○	○

Motivating urban spatial planning policy

1	2	3	4	5
○	○	○	○	○

Prioritizing physical flood protection investments

1	2	3	4	5
○	○	○	○	○

Assessing the impact of non-physical flood risk management strategies

1	2	3	4	5
○	○	○	○	○

Improving understanding of flood risks to policy makers

1	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?

Long answer text

APPENDIX D

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

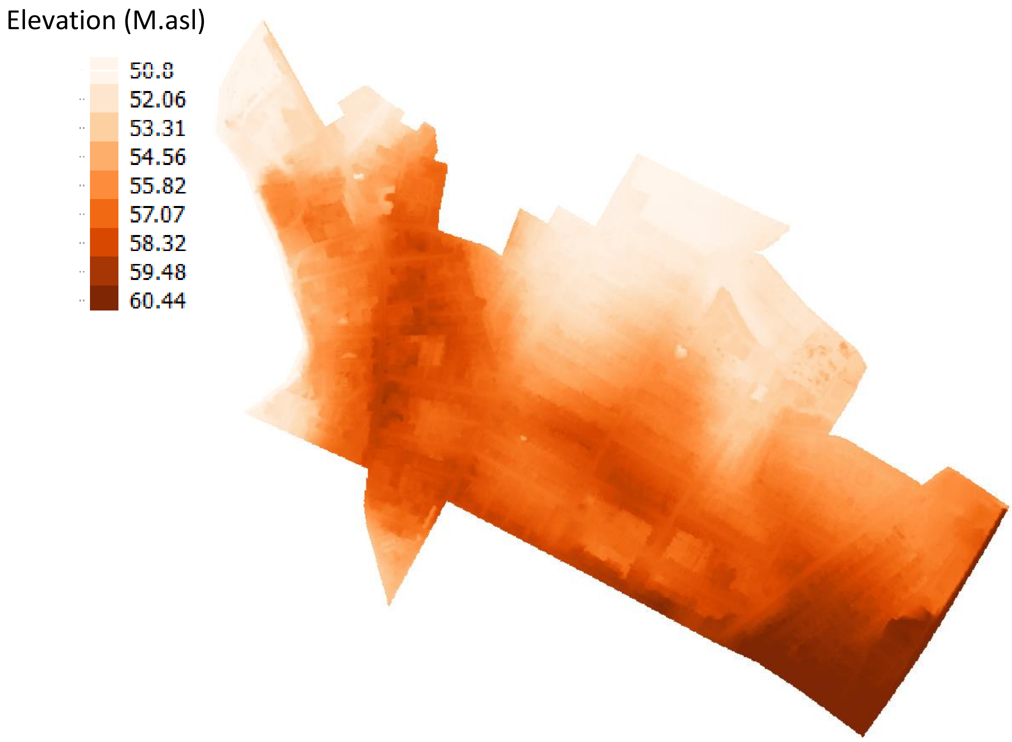
A = cross-sectional area of pipe

g = constant for gravitational acceleration

γ = the friction coefficient

APPENDIX E – ELEVATION AND LAND COVER MAPS

Belgrave - Elevation



Belgrave – Land cover

APPENDIX F

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 forced 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.