CRC for
Water Sensitive Cities

Flood Damage Assessment
Literature review and recommended procedure

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Socio-technical flood resilience in water sensitive cities – quantitative spatio-temporal flood risk modelling in an urban context (Project B4.1)

Authors

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1.   Introduction

The assessment of flood risk is an essential tool in evaluating the potential consequences of a flood. The analysis of the risk can be applied as part of the flood plain management, but can also be used in a cost-benefit analysis, when comparing different adaption strategies. This analysis is therefore important when assessing flood disaster mitigation options and economical optimizations of possible measures. A common definition is that the flood risk is found with the use of a flood hazard assessment and a flood vulnerability assessment (Apel, Merz and Thieken, 2008).

The flood hazard is the quantification of amount, extent, and location of flooding expected to occur with a given return period. This means that the spatial distribution of the calculated inundation depth as a function of the return period can be used to describe the flood hazard. The vulnerability is the susceptibility of the area subjected to the flooding. A way to express the vulnerability is through a damage cost assessment. A framework to assess the flood risk has been proposed by Zhou (2012) and an adapted version of this is presented in Figure 1.
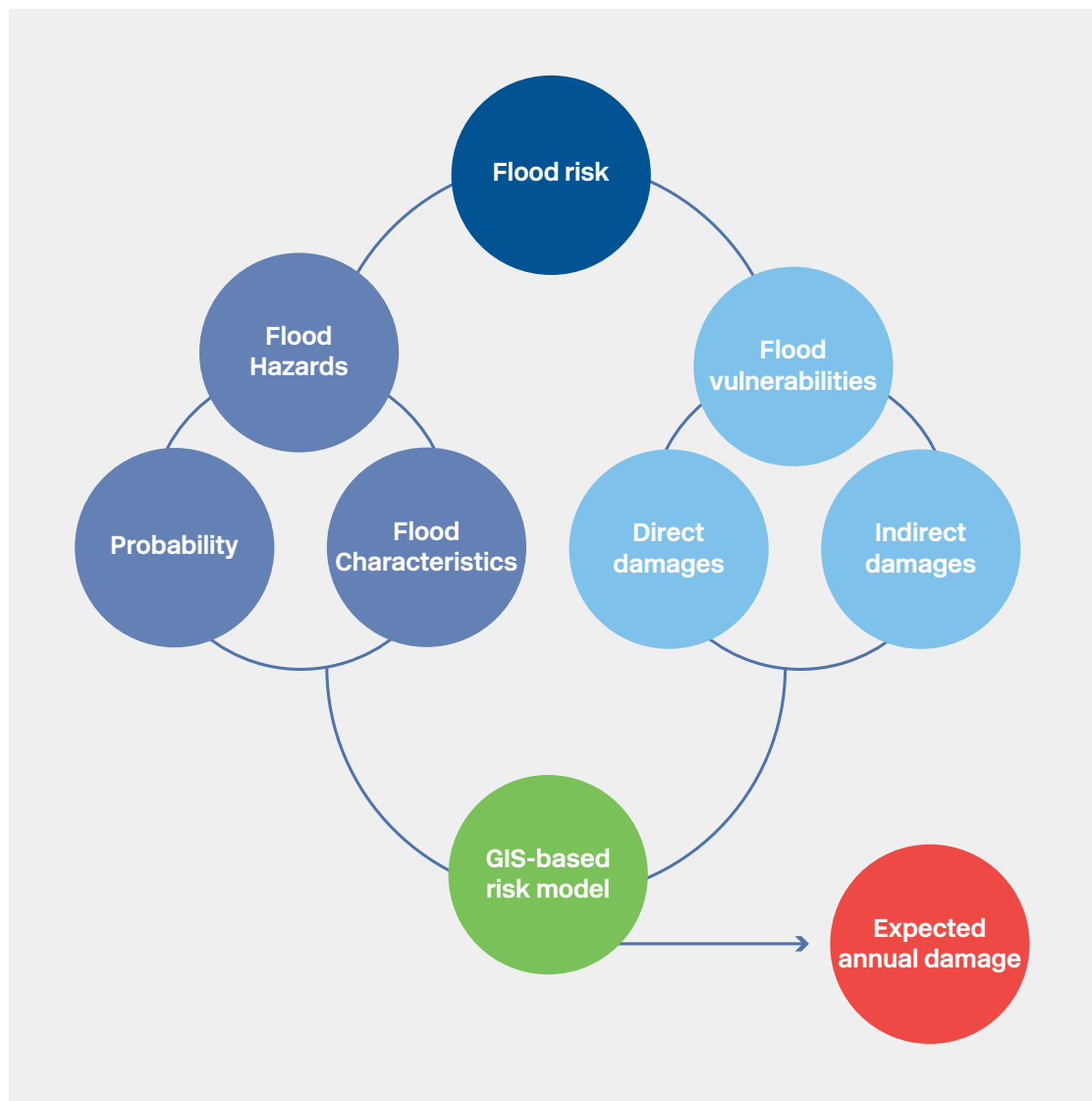
Figure 1: A framework for flood risk. Adapted from (Zhou et al., 2012).

The applied definition of flood risk is in accordance with standard risk assessment literature. However, other definitions exist. Within climate change adaptation, the other often used terminology is introduced in the IPCC report on adaptation to changes in climatic extremes (SREX, 2012). The term vulnerability in this report represents the combined impacts of vulnerability and exposure in the SREX framework and is sometimes denoted *the cost of flooding given flooding occurs* (IPCC, 2012).

As seen in Figure 1, the flood hazard assessment (based on model simulations) and the flood vulnerability assessment are combined in a GIS system to form a so-called risk model. This model can then be used to calculate the expected annual damage by defining the damage cost D as a function of the exceedance probability p. This probability is defined as the inverse of the return period of the event causing flooding. An example of such a function is shown in Figure 2. The area under the curve is equal to the Expected Annual Damage (EAD), corresponding to the average damage cost that is expected to occur each year. The EAD is defined as (Olsen et al., 2015):

To calculate the EAD in practice, several methods can be applied. We refer to Olsen et al. (2015) for a detailed discussion.

This report focuses on assessing the flood vulnerability, *D(p)* as a crucial input to a flood risk assessment. The flood hazards are evaluated with the use of expert simulation software that provides results such as spatial information on flood area and depth for a given event (rain height, sea level). It is in this report assumed characteristics of a flood that are relevant to assessing *D(p)* can be extracted from such simulation software. The flood vulnerability will be described with the use of a financial damage assessment.

$$EAD = \int_p D(p)dp$$
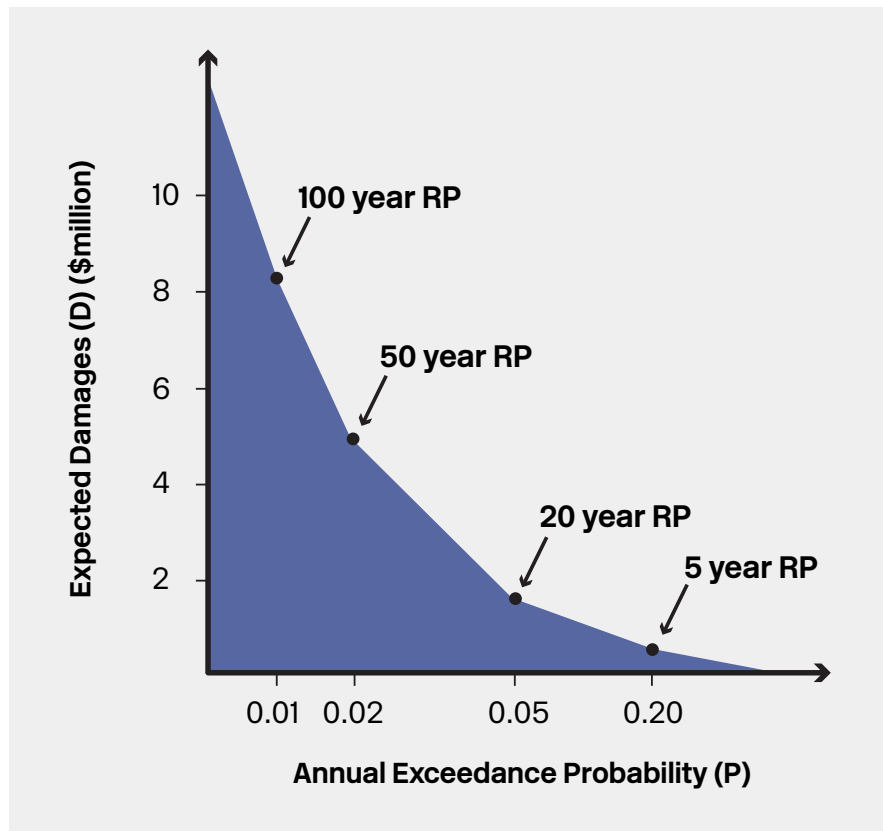
Figure 2: Expected Annual Damage (EAD) illustrated as a function of the annual exceedance probability p, the inverse of the Return Period (RP) of a given event. (Hoekstra et al., 2012).

2. Vulnerability assessment

The vulnerability of an area to flooding is typically quantified using flood damage assessments. Such assessments can be applied, both, for unknown future events in the form of risk mapping and after observed events in financial appraisals for insurance and loss compensation (Merz, Thieken and Kreibich, 2011).

The focus in this chapter is to introduce damage classes that need to be considered in the vulnerability assessments and to illustrate how these can be translated into estimates for potential flood damages.

2.1 Economic vs. financial assessment of flood damages

Economists have identified two main ways of assessing the damage cost of a natural hazard; an economic loss assessment and a financial loss assessment. An economic analysis views the nation as a whole, and should therefore consider the economic impact for the country rather than focusing only on the inflicted areas. When the assessment is performed on a nation-wide scale (or other scale much larger than the potentially flooded area), it is referred to as a macro scale assessment. In the economic analysis

the real opportunity cost for a given loss is applied, and tax is excluded. A financial analysis considers the loss for the individual household, which is called a micro-scale evaluation. A financial analysis can however also be applied on meso-scale, in which case it covers a local community. A financial analysis focuses on the actual money transfer and the loss is found as the market price of a new item for replacement. In this analysis taxes are included. There are financial losses that are not economical losses; an example of this is the loss of business. Here, the individual business will suffer a loss, but most likely the nations as a whole will experience only little or no loss, due to re-allocation of activities to competing businesses (Penning-Rowsell et al., 2013). An overview of the key elements of the economic and financial loss assessments is shown in Table 1.

The scope of our work is the assessment of flood damages by local authorities on a catchment basis. In this setting, investments of the local authorities into flood protection measures need to be compared against flood damages suffered by the local community. In line with Handmer et al. (2002) , we therefore choose to apply financial analysis of flood damages. This choice is also practically motivated, as a nationwide assessment of economic efficiency is typically much less relevant for local decision makers than the area for which they are responsible.

Table 1: Overview of the difference between economic and financial damage assessment.

	Economic	Financial
Geographic restraint	Nation-wide: Macro scale	Individual catchments, municipalities and/or households: Micro/meso scale
Economic appraisal	Real opportunity cost Depreciated asset values Tax excluded	Replacement cost Replacement asset values Tax included
Indirect losses	All production and sale losses for business is excluded, unless business is being relocated outside of the nation	All business losses are included

2.2   Flood characteristic

Flood risk assessment needs to account for different types of flooding. Flooding can be divided into the following types:

- Groundwater

- Fluvial

- Pluvial

- Coastal

Different types of flooding have different characteristics that can be summarized are as follows:

- Rising groundwater will mostly lead to basements being flooded with non-polluted water.

- Fluvial flooding is caused by rivers. The degree of contamination in water from the river depends on the catchment characteristics and can, for example, be affected by the presence of industrial areas in the upstream reaches. Fluvial flooding involves a potential for high water levels and velocities. Water flowing at high velocity can also contain debris, which can pose a risk to citizens and structures.

- Pluvial flooding is flooding caused by overloading of the drainage systems during rain events. The overloading mostly happens as a consequence of cloud burst or intense long duration rain events. When assessing the impact of the pluvial flooding it is important to evaluate the citizens' risk of contracting infectious diseases, in particular if combined sewer systems are installed in the area of interest.

- Coastal flooding is caused by the rise of the seawater level, both caused by tidal surges and waves. Similar to fluvial flooding, coastal flooding involves a risk of high water levels and strong currents. The risk of infectious diseases is however not very high. There is a general risk of higher structural damage and damage to electrical components, since saltwater is more corrosive.

2.3   Valuation method

The damage cost can be holistically estimated with the use of a socioeconomic analysis. In this analysis not only material damages are considered, but also the consequential damage related to the flood, and the cost associated with the loss of welfare for the citizens is included (Hammond et al., 2015). This is a very comprehensive analysis, and when evaluating the damage costs associated with floods there are many factors to account for. Consequently, the organization of the costs and the limitations of the assessment can be hard to define. To ease the damage estimation in the socioeconomic analysis, the losses are divided into four classes, which are listed in Table 2 together with examples of loss types.

The classes are defined from the concept of direct and indirect loss, and whether the loss is tangible or not. ***Direct losses*** are defined as losses that occur as a consequence of a direct contact with the water, whereas ***indirect losses*** only occur as a consequence of the flooding. Direct losses are directly correlated with the duration of the flood, whereas indirect losses can   have effects on time scales of months and years (Merz, Thieken and Kreibich, 2011). Moreover, the losses are divided into tangible and intangible losses. In contrast to ***intangible losses***, ***tangible losses*** are losses that can be objectively quantified, i.e., the loss can be accounted for in direct monetary value, which can be determined based on whether or not a market exits for the asset in questions (Hammond et al., 2015). Each of these four damage classes will be discussed in the following. An overview is presented in Table 2.

Table 2: Overview of damage classes with examples. The table is based on Handmer et al. (2002) and Hammond et al. (2014)

		Direct loss	Indirect loss
Tangible		Structural damage	Disruption to transport
		Cars	Business interruption
		Infrastructure	Temporary housing of evacuees
		Livestock	Loss of industrial production
		Crops	
		Evacuation and rescue operations	
		Clean up costs	
Intangible		Lives and injuries	Stress and anxiety (PTSD)
		Diseases	Disruption of living
		Loss of memorabilia and pets	Loss of community
		Damage to cultural or heritage sites	Reduced land values
		Ecological damage	Undermined trust in public authorities
		Inconvenience	

2.4 Direct tangible damages

This damage class includes most of the material damage caused by direct contact with water, and contains the vast majority of insurable losses. Hence this damage class is either partly or fully always included in a damage assessment. Further, many studies find that this damage category is the most important damage category. This observation is however partly based on the fact that this class is always included in damages costs, and is mostly the only one included. Moreover, is it the best understood damage class (Hammond *et al.*, 2015).

For material damage several studies have identified the following characteristics of flood that determine the degree of damage:

- Inundation depth,
- Duration of the flood,
- Degree of contamination in the water,
- Velocity
- Level of warnings prior to the flooding.

The most important factor was evaluated to be the inundation depth, however the velocity has been found to be significant for structural damage and direct damage to road structure (Hammond *et al.*, 2015). The impacts of these flood characteristics are also related to the resilience of the material, e.g. the quality of the building, which, if possible, should also be considered (Thieken *et al.,* 2008).

In order to distinguish between different categories within

the damage class, the damages can be grouped into types. The definitions of these types are normally decided by the sector, and therefore residential buildings, business, infrastructure and agriculture are normally defined as the main types of damages. The categories can then hold a number of different subcategories, depending on the level of detail in the damage assessment, and the level of homogeneity in the dwellings. The number of subcategories can especially have a high impact on the industrial damage assessment, where experience has shown that in this damage type typically 20% of the affected objects are responsible for 80% of the loss (Merz, Thieken and Kreibich, 2011).

Method of cost estimation

Three leading methods for the quantification of direct tangible damages were recognized in the majority of previous studies are:

- Damage assessments through insurance data
- The unit cost (or average) method
- Stage-depth damage curves.

Insurance data from previous flood events has often been applied in studies where intangible and indirect damages have been neglected. The insurance pay-out is used as an indicator of the physical damage that the flooding has created. This cost represents the replacement cost. Therefore it can be necessary to depreciate the insurance pay-outs to obtain a more correct damage loss. Insurance data is also applied in ex-ante assessments, where it can

be used as empirical data and thereby help to estimate the expected loss in the future. When using insurance data in the loss assessment, the following points need to be considered.

- Not all inflicted stakeholders hold insurance, and their loss is therefore not included in the insurance data. This can concern private households as well as government owned buildings and structures.
- Not all inflicted stakeholders are economic realistically insured; some might be under or over insured.

Unit cost estimation is based on applying an average loss value to each individual damage type. The number of damage types being defined can range from a single damage type up to hundreds of damage type subcategories. By finding the number of objects being flooded within a damage type and multiplying the number with the unit cost estimation, the total damage cost within the type can be found. The average loss value can be found based on, for example, insurance pay-outs. It can also be based on expert knowledge or previous flood experiences.

The stage-depth damage curve method, does not only account for the area being flooded, but also for the magnitude of the flood. This is done by making the cost a function of the inundation depth, which has been found to be an important factor, when considering material damage. The curves are typically used for housing and other structures (Handmer, Reed and Percovich, 2002).

Stage-depth damage curves can be defined either as absolute or relative damage costs. Absolute damage curves provide the absolute damage cost for the specific predefined damage types. This means that a specific absolute curve is required for each damage type. Relative damage curves define which portion of the potential damage for a certain object is realized for a given inundation depth. The maximum damage potential is usually defined for the specific object, for example using the sales price of a house.

Both absolute and relative damage curves can be made either empirically or synthetically. The data requirements for empirical construction of stage-depth damage curves based on observed flood damages are very high in theory, while the curves available in practice are usually based on only a small number of samples (Albano *et al.,* 2015). As extreme flood heights rarely occur, curves are often derived after shallow flooding and hereafter extrapolated to higher depth levels, which causes further uncertainties. Moreover, creating empirically based damage curves for urban areas that have not recently experienced flooding, is advised against, due to too high uncertainties (Gissing and Blong, 2004). Synthetic stage damage curves are based on synthetic data. Data generation is therefore dependent on expert knowledge, and a "what-if" principle. There is no need for damage observation, when using this method. An example for synthetic stage damage curves is the multi-coloured manual (MCM) applied in the UK (Penning-Rowsell, *et al.*, 2013).

An illustration of the different forms of the stage-depth damage curves, together with the data need, is seen in Figure 3.
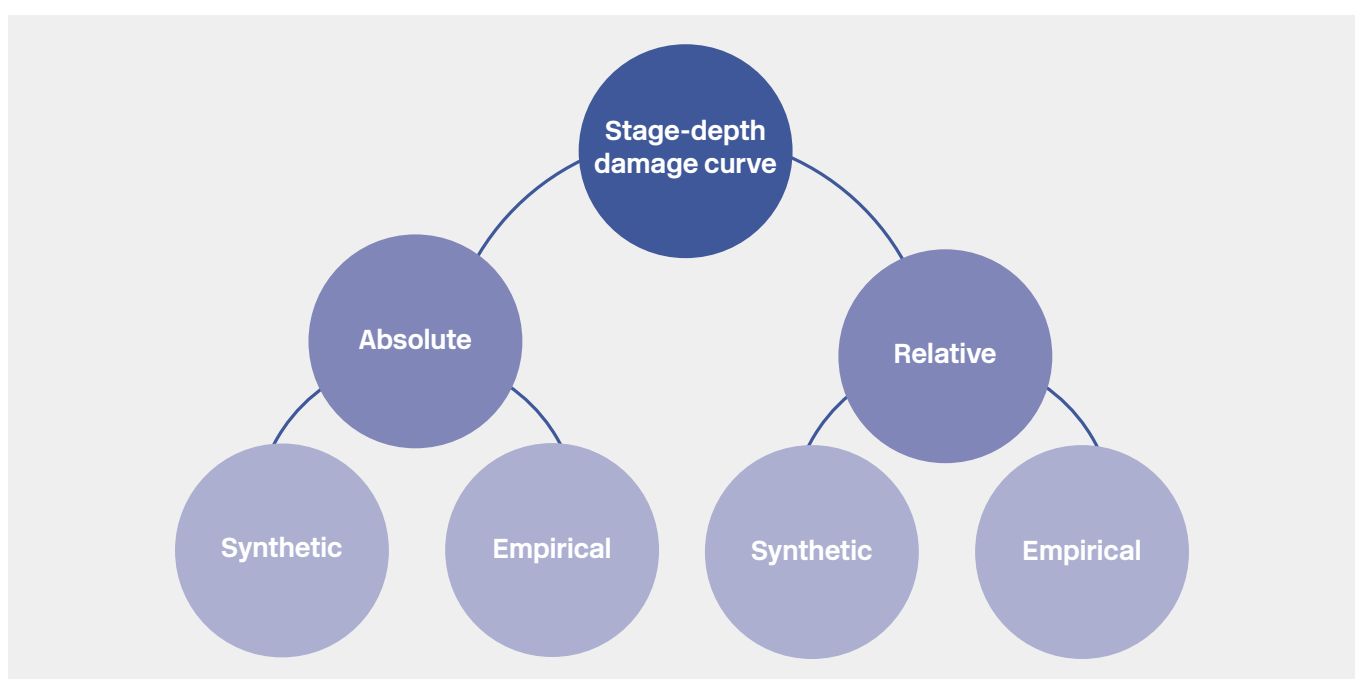

Figure 3: Overview of the different forms of stage-depth damage curves.

Extrapolation of damage curves or unit cost to other catchments is at best challenging and often not recommendable. This is especially true for the absolute stage-depth damage curves and unit costs. Here, the absolute values must be updated regularly according to the inflation and possible value changes in the inflicted area (Hammond *et al.*, 2014). Finally, the inundation depth is usually not sufficient to fully explain observed flood damages. Damage estimates based on stage damage curves or unit costs, while often being the best available guess, are therefore typically subject to significant uncertainty (Hammond *et al.*, 2015).

2.5 Indirect tangible damages

Method of cost estimation

The total estimated cost of a flood event can strongly increase if indirect damages are considered in the assessment (Djordjević, 2014). Two methods are commonly used to quantify indirect tangible damages:

- Percentage of direct tangible damage

- Unit cost method

Many case studies have applied a percentage of direct damage as representative of the indirect damage. This method therefore assumes that the indirect tangible damages are directly correlated to the direct tangible damages, which is a rather coarse assumption. Consequently, the method is primarily used as a simplification, when other data is not available.

A more precise method is the unit cost method, where a sector specific loss unit is applied. Since the indirect damages are mostly disruptions, the damage cost is given as a cost per hour or day. Hereafter it is necessary to estimate how many people and businesses will be disrupted by the different types of damages and the length of these disruptions. A method to estimate the cost of the disruptions to people, e.g. caused by traffic jams, is to set the duration of the disruption in relation to the average wage. The estimation of business loss is more difficult, but can mostly be described by interruptions of production due to flooding. For businesses previous studies have used the gross margin per day and multiplied it with the number of days the flood has caused disruption (Dutta, Herath and Musiake, 2003). The length of the disruptions can however be challenging to estimate, and is the factor that causes the highest uncertainty in this damage class.

2.6 Direct and indirect intangible damages

Intangible damages are often associated with the health and welfare of the citizens. The direct intangible losses in this damage class can include irreversible losses, like loss of human life and cultural heritage. Indirect intangible damages mostly involve an interruption in the citizens everyday lives, and can span from health issues to annoyances like power and water cut offs, to difficulties in getting to work.

Direct intangible damages are often most significant in developing countries, since high rates of loss of life as a consequence of flooding have been observed here. In developed countries, risk of life is mostly related to coastal flooding, flood defence failure and flash floods. Here, the combination of high velocity, high water depths and debris in the water causes loss of stability in the water and puts people in the risk of drowning. Moreover, high density cities with bad drainage systems can experience a high risk of infectious diseases spreading. Risks to life and health can be reduced by the implementation of warning systems that allow for an evacuation of the people at risk. The effectiveness of this is however not only based on the warning system, but also the type of flood and its lag time (Green, Viavattene and Thompson, 2011).

Indirect intangible damages are hard to quantify in general. Often, attempts are made to provide estimates based on the damage estimates for the other damage classes. However, it can be difficult to identify meaningful relations between the damage estimates for different classes. An example is the flooding of traffic infrastructure. In this case an indirect intangible damage are annoyances caused to citizens, but these are hard to set in relation to the material damage or the delay in traffic. Another example is the quantification of damages resulting from supply interruptions of water or electricity depending on the direct damages to a water treatment plant or a transformer station.

Both intangible damage classes have been neglected in the majority of previous damage cost assessments that can be found in the international literature. The most common reason for this, is that the intangible damages are hard to quantify (Meyer, Scheuer and Haase, 2009; Hammond *et al.*, 2015). In particular intangible impacts where excluded in studies, where the common metric of money has been used for e.g. risk mapping (Meyer, Scheuer and Haase, 2009; Halsnæs and Kaspersen, 2014).

Method of cost estimation

The fact that intangible damages can be irreversible makes them especially hard to quantify. Therefore, intangible losses are sometimes not monetized, but included in the damage assessment in a qualitative manner by applying, for example, multi-criteria risk assessments. A multi-criteria analysis can be performed by adding monetary values to tangible damages, but also using a scoring or weighing factor either attached to areas of specific importance or vulnerable hotspots (Halsnæs and Kaspersen, 2014).

In several case studies survey based cost estimation has been performed after major floods. Here, it is not only possible to include the tangible damages, but also the intangible costs. The primarily used methods to assess the intangible damages have been the concepts of "willingness to pay" and "willingness to accept", or the so-called contingent valuation (Meyer *et al.*, 2013). However, these concepts rely on the expressed or stated preference methods, which have been widely criticised (Handmer, Reed and Percovich, 2002). Another method for the value of recreational resources has been the so-called travel cost method. Here, the appraisal is based on valuation of the total cost the visitors have held to visit the place, which included, for example, monetizing both the actual travelling cost and the time spent on travelling (Penning-Rowsell, Priest, *et al.*, 2013).

2.7   Spatial detail level and complexity of damage model

When choosing the complexity of the damage assessment used, the complexity of the hydraulic modelling should be taken into consideration. For example, if the inundation depth is estimated based on a topographic map and linear interpolation of measured river water levels between stations, the uncertainty associated with the flood hazard assessment might not justify a very thorough micro scale damage model. To illustrate this, the following figure depicts the suggested agreement between the complexity of the hydraulic model and the damage model. The highest agreement is shown as the darkest colour, whereas the lowest agreement is the lightest.

Vulne-rability \ Hazard	Simple	Moderate	Complex
Meso-scale averaging unit cost			
Meso-scale damage model			
Micro-scale damage model			

Figure 4: An illustration of the agreement in complexity between the vulnerability assessment and the hazard assessment. Adapted from Apel et al. (2009).

In Figure 4, the hazard assessment is illustrated as either simple, moderate or complex. A hazard evaluation is generally based on a hydraulic simulation, which can be performed with a wide range of tools, with varying complexity. An example of a simple hazard assessment would be a linear interpolation between river levels

measured at different stations. A moderate hazard model can be a so-called Blue Spot model which applies a 1D-1D hydrodynamic model of surface reservoirs and depressions (Hansson, Hellman and Larsen, 2010). The more complex hazard evaluation can be performed with the use of a 1D/2D coupled model, which can be applied in cities. Here, a spatially distributed hydrodynamic model is applied for the sewage system in 1D and on the terrain in 2D. The complexity and detail level of the hydraulic simulation also depends on the resolution of the terrain model which has been applied in the simulation.

Three different types of damage models are shown in ascending complexity in the figure. The most simple damage assessment is here presented as an average unit cost for a larger area. When applying unit cost for larger areas (meso-scale), aggregated land cover categories are used. In such a setting, the assessment is simplified to only consider the main economic sectors and the area of the flooding. A more complex damage assessment is to apply a damage model on meso-scale. In this model, characteristics of the flood are also taken into consideration. Here the inundation depth can be applied together with stage-depth damage curves and aggregated land covers to estimate the damage cost. The most complex damage model is the micro-scale damage model, where flood loss is evaluated on an object level. To use this model, detailed information about type and use of single buildings and elements is needed. The model can therefore only be applied if such data exist for the investigated area. The highly detailed model requires a great amount of data, and is therefore only recommended if the level of detail of the hydraulic simulation can match that of the damage assessment.

Based on empirical data obtained in Germany, the effect of flood damage models of different complexity was investigated. Data from five historic flood events was used to test eight different flood models with a varying number of variables, and therefore complexity. The most simple model was a stage-damage function, which only considered water depth as an input. More complex models were Bayesian network models, regression tree models and stage damage curves with multiple input variables. The study showed that increased complexity improves the predictive capability of flood damage models, but with great demands on data availability (Schröter *et al.*, 2014)

After choosing the different suggested methods and levels of complexity for the damage assessment, one more point needs to be considered. If the damage costs are used as an indicator of the vulnerability for events expected to occur in the future, the vulnerability is expected to increase. This is caused by an increase in residential and economic development, along with higher occupancy in areas that are prone to floods like coastal sites and flood plains. The damage assessment therefore needs to be adjusted to increased vulnerability in the studied area (Kreibich *et al.*, 2011).

3. International practices

Damage cost estimation of a disaster is a difficult field and no clear model or method exists on an international level. To get a better overview of the damage cost estimations used in previous studies, a literature review has been conducted. We have chosen to focus on four countries with comparable living standard that have experienced floods and where a number of studies have been performed recently: Denmark, Great Britain, Germany and Australia. For comparisons between each country it has to be taken into consideration that difference in damage costs can be observed due to differences in wages, material costs etc. Therefore, the focus of the review is primarily on the method that has been used in the damage assessments, and not the exact valuation. This is in accordance with the observations that the damage loss is area specific. Appendix 1 includes cost estimates applied in the different countries.

Several damage models were presented in the literature. An overview of the most used damage models is presented in Table 3.

3.1 Denmark

In Denmark no damage models have been created. However, a number of flood damage assessments have been conducted, starting in 2007 with rough unit cost estimates. Since not much empirical data from previous floods is available and no general synthetic data has been generated, the damage estimations have been primarily reliant on expert knowledge and literature reviews. Due to the lack of stage-depth damage curves, the primarily applied method was the unit cost method.

For easy damage estimation in Denmark, the Nature Agency has made an Excel sheet that allows for a simple and standardized analysis of the socio-economic implications of upgrading urban drainage infrastructure. The purpose is to enable local governments to do appraisals of climate change adaptation plans. The considered damage classes are damage to buildings, infrastructure and agriculture. Moreover hotspots in the form of transformer stations are included. Damage estimates are based on unit cost.

Another option that can be used for simple vulnerability estimation in Denmark is the so-called value-map. This map provides a maximum potential damage value for each cell in a grid of 100 by 100 meters. The map was created with the use of addresses, real estate valuations and building information. Each cell value was defined as the sum of the values of the houses located within the cell.

To account for the direct intangible damages, a priority scheme was created for selected case studies in Denmark. This scheme consists of weighing factors from 1-10, with 10 having the highest priority. This factor is applied to objects (so-called hotspots), where it is very important to avoid flooding, such as transformer stations, hospitals and so-called risk businesses handling, e.g. dangerous chemicals. The second highest priority (9) is given to waterworks and heat supply. Furthermore, high priority is assigned to dense urban areas, where flooding could bear a high economic cost. The lowest priority is given to nature areas, that are not especially affected by the water, and can be flooded without economic consequences (Halsnæs and Kaspersen, 2014).

Table 3: An overview of the most used damage models (Kreibich et al., 2010).

Model	Country	Data	Pricing method	Scale
RAM	Australia	Empirical/synthetic	Uniform	Micro
ANUFLOOD	Australia	Empirical	Stage-depth damage curve	Micro
MCM	U.K	Synthetic	Stage-depth damage curve and duration	Micro/meso
MURL	Germany	Empirical	Stage-depth damage curve	Meso
ICPR	Germany	Empirical/synthetic	Stage-depth damage curve	Meso
Hydrotec	Germany	Empirical	Stage-depth damage curve	Meso

Case studies

Roskilde and Aalborg

One of the first bigger case studies in Denmark was conducted in 2007 for the Danish Environmental Agency. The two studied cities were Roskilde and Aalborg. The aim was to evaluate the impact of climate change and possible adaptation measures. Damage estimates included the direct tangible damages resulting from the destruction of roads, flooding of residential buildings and damage to sewers. The indirect tangible damages identified were disruption of traffic, loss of electrical supply, loss of production for businesses and administrative cost for the municipality. Intangible costs included in this study, were the number of persons who would get in contact with the flooded water and who would therefore be at risk of health issues (Arnbjerg-Nielsen *et al.*, 2007). Part of the study was conducted as a workshop, where both experts and people with a great knowledge of the area were present. This combination made it possible to identify areas of risk, and the vulnerability of these. To estimate the cost of the damages identified, the unit cost approach was used. The prices applied were found by a literature review that covered previous studies from consulting business and governmental institutions, like the Danish Wastewater Committee, the Danish Storm Council, the agency of energy and the StatBank Denmark (Arnbjerg-Nielsen *et al.*, 2007).

Copenhagen

In 2011, a severe flooding hit Copenhagen, following a high intensity rain event. This flooding was evaluated to be the most expensive natural disaster in Europa in 2011, with a total cost around 6.2 bn DKK (COWI, 2014). This extreme event and two others in the period 2006-2012 have been used to study the damage costs for an urban flooding. It is estimated that most of the damage was caused by diluted sewage discharging from the sewage pipes during the high intensity rainfall. No clear correlation between the damage cost and the depth of the water or the contamination of the water could be identified.

This finding is somewhat contradictory to observations from other countries. It is believed that the reason for the different conclusions could be the different nature of the flooding. In Germany and England a clear coherence has been found, but the dominant type of flooding is fluvial, rather than the pluvial floods experienced in Copenhagen.

As a result of these findings, the study argues that in cases of urban pluvial flooding the damage costs can be estimated with the use of unit costs. To define representative unit costs, damages were classified into the categories: flooding of basement, flooding of the ground floor in residential buildings and flooding of businesses. Damages to businesses were subdivided into the class' structural damage, loss due to loss of production and damage to content.

The unit costs for each of these damage types were found from an analysis of insurance data. For residential buildings an average value per square meter of floor area was defined, while for commercial buildings a cost per business was applied (COWI, 2014).

Odense and Aarhus

Based on the experience in Copenhagen, several Danish studies have been conducted with the use of the unit cost method (Hede and Kolby, 2013). As a threshold value of the inundation depth, 10 cm is typically applied for buildings. One of these studies, is a study for Odense and Aarhus, which included the cost of residential and commercial building damage and also a valuation of public institutions, road damage and damage to sewer manholes. A direct intangible damage was considered in the form of water pollution (Olsen *et al.,* 2015).

Egedal

A recent study made for the municipality of Egedal has applied three different damage assessment methods and compared them. In the study an integrated 1D-2D hydraulic model has simulated the inundation depth for rain events with return periods of 5, 10, 20, 50 and 100 years. Considered assessment methods were (in increasing order of complexity):

- Value-map
- Unit costs
- Stage-depth damage curve

The assessments using unit costs and the value-map mostly focused on the damage to buildings. The building types considered in the unit cost assessment were industry, residential, residential with basement, public buildings, public institutions, vacation houses and protected buildings. Moreover damage to waste deposits and agricultural lands was included. The stage-depth damage curves included fewer damage types, considering only curves for buildings, buildings with basement, public buildings and public buildings with basement (DHI, 2015).

The expected annual damage cost was calculated using each method. The comparison of the three methods showed that there can be significantly differences in the damage estimates. Since the costs were determined for hypothetical events, a validation against observed damages was not possible. However, the study clearly showed that the applied method plays an important role in the damage cost estimations (DHI, 2015).

3.2 Germany

In Germany one of the best known damage models is the rule based Flood Loss Estimation Model FLEMO, which was developed by a research group from the German Research Centre for Geosciences in Potsdam. The model focuses on direct tangible damage assessments. The model uses a rule based multifactorial approach to estimate the damage loss based on inundation depths with damage intervals given as a relative damage percentage of the unit's value (Schröter *et al.*, 2014).

Within this model several sub-models exists that are used for different sectors. The two main sub models concern residential buildings and the commercial sector. These models are empirically based with the majority of the data originating from phone surveys. The main survey has been conducted after the floods of the Elbe river in 2002, but surveys from the floods of the Elbe in 2006 and the Danube in 2002 and 2005 have also been included (Kreibich *et al.*, 2010).

The FLEMOps model was developed to estimate the direct tangible damage to residential buildings, where the ps is an acronym for Private Sector (Schröter et al., 2014). The model is to be used in combination with asset stocks such as the total asset of residential buildings or insured assets. FLEMOps is based on phone surveys of 1697 private household that were affected by the flood in 2002. The degree of flood damages was identified to be subject to the following main variables: building characteristics, household structure, static flood impact and precaution and flood experience. Moreover, emergency measures, socio-economic status of the household and flow velocity of the water were found to be relevant in some sub-datasets, but not included in the function for the relative loss ratio.

The model defines the loss ratio as a function of the inundation depth in intervals, the building type and building quality. The loss ratios are depicted in Figure 5.

An extension of the FLEMOps model is the FLEMOps+ model. Here, scaling factors are used to incorporate information about the level of contamination in the water as well as the level of precautionary measures. The loss ratios are lowered if there are good preventive measures prior to the flood and no contamination, and increased if the contamination is high and no precautions are taken (Merz, Thieken and Kreibich, 2011).

The model FLEMOcs was developed for the commercial sector. It is based on the investigation of 642 loss cases, with 415 originating from 2002, and 227 from 2006 (Kreibich *et al.*, 2011).The model considers building structures, equipment and goods, products and stock of businesses. The model estimates the relative loss ratio in two stages (Kreibich *et al.*, 2010):
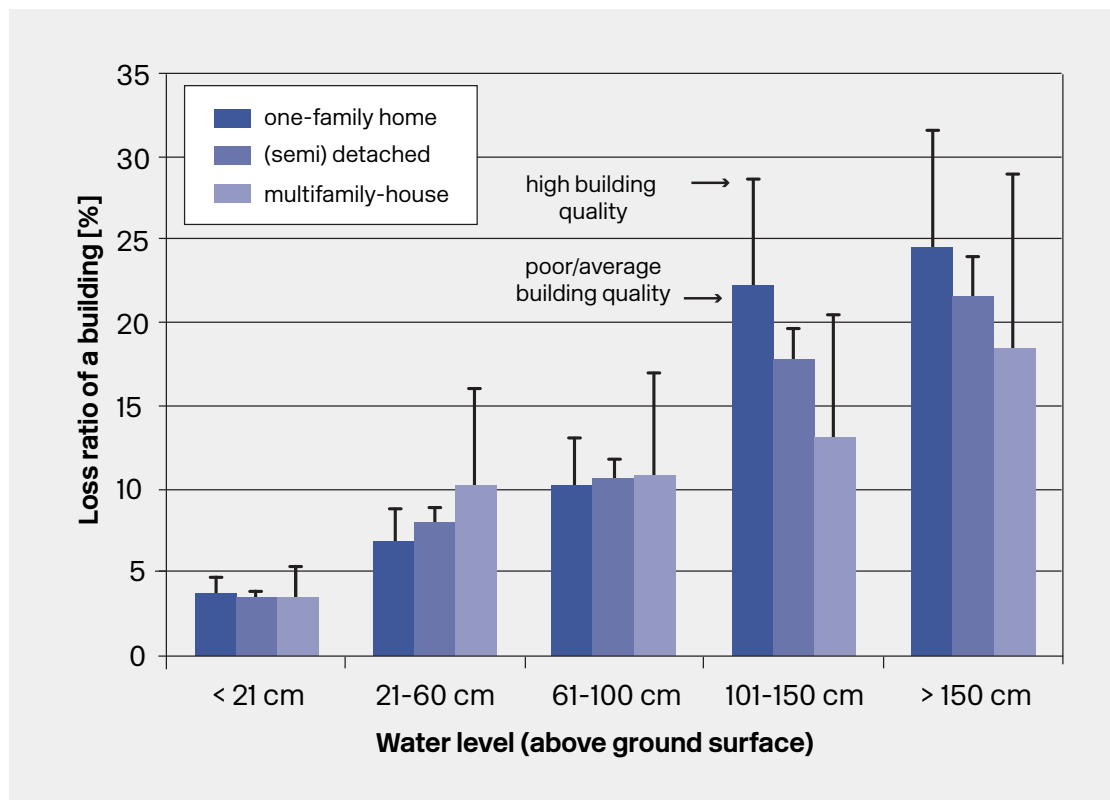
Figure 5: The FLEMOps model (Thieken et al., 2008).

- 1st stage: Water depth (4 classes), business size (3 classes) and sector (4 classes)
- 2nd stage: Precaution level and degree of contamination

The FLEMO model can be used both on a meso or micro scale, depending on the land use information available for the area (Apel *et al.,* 2009).

While many of the flood damage studies performed in Germany have been based on interviews and surveys conducted after a flood, data from insurance claims and applications for economic reimbursements of damages is also available. This data is available in the flood loss database HOWAS (Merz *et al.*, 2010), which has been a key element in developing the damage models ICPR, MURL and Hydrotec. These damage models are only made for buildings. With D being the damage ratio and h the water level in meters, the models apply the following damage functions:

MURL: $D = 0.02h$ (if h>5, D=10%)

ICPR: $D=(2h^2+2h)/100$

Hydrotec: $D=27\sqrt{(h)}/100$.

An illustration of depth damage curves based on the HOWAS database and the two FLEMO models, is shown in Figure 6.
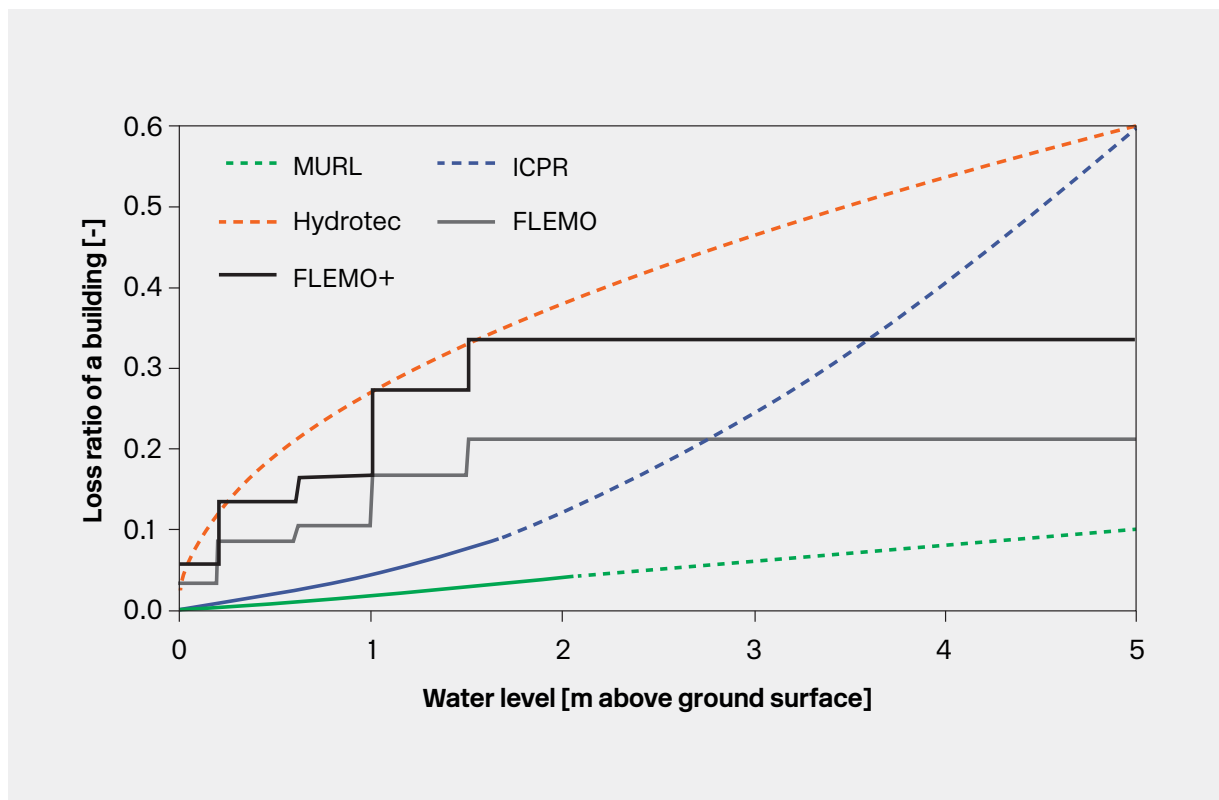
Figure 6: Illustration of the depth-damage curves for buildings applied in the German models (Thieken et al., 2008).

Case studies

Damage estimation in Germany is usually performed by the federal states. The motivation to do these damage assessments is mostly to determine compensation levels, and the costs are estimated based on the costs the different stakeholders have held. Therefore, only tangible damages are included in these assessments.

Nationwide

A case study for the whole of Germany evaluated the consequence of climate change. Damage functions provided by the German Insurance Association (GDV) were used. The functions were made for three categories, residential buildings, small enterprises and interiors. The damage assessment was limited to direct tangible economic flood losses. The functions exist for the whole of Germany, and depend on the zip code of the area. The functions were made an integral part of the flood loss model HQ Kumul, which was used in this study. The hazard assessment was based on observed river runoff and data from rain gauges in the period 1961–2000 and considered 100 historic rain events. As a result, HQ Kumul solely describes flood damages as a function of return periods (Hattermann *et al.*, 2014).

Saxony

The FLEMOps+ model was evaluated based on floods in Saxony. A micro scale model evaluation was applied using of flood data from 3 municipalities for the extreme event in August 2002. The repair cost from the SAB database (database for repairs) were used for validation. The damage assessment considered the building type, the mean asset value per building type and the level of contamination and precaution. The level of contamination and precaution was estimated based on telephone interviews. Hazard assessment was performed using three different methods; observed water levels, simulated water levels using a 1-D model and simulated water levels using a 2-D hydraulic model. The results showed that the FLEMOps+ model on a micro scale was validated with the data from SAB within an acceptable uncertainty of 20% (Thieken *et al.*, 2008).

Saxony and Baden-Wuerttemberg

FLEMOps+ was tested on meso-scale for 5 municipalities in Saxony considering the event in 2002 and five municipalities in Baden-Wuerttemberg that experienced flooding in 1993. Damage models were validated with flood damage data from the SAB database for the 2002 event, and from loss data from the municipality from the 1993 event. FLEMOps and FLEMOps+ were compared with the other German damage models Hydrotec, MURL and ICPR. The evaluation showed that out of the five models, the losses were estimated best by the FLEMOps and the FLEMOps+ model. The study moreover showed that while the MURL and ICPR model tended to underestimate the loss, while the Hydrotec model overestimated it (Thieken *et al.*, 2008).

3.3 United Kingdom

The most used damage estimation model in the UK is described in the so-called color manuals dating back to 1977. They are continuously developed by the Flood Hazard Research Centre in Middlesex University, and the newest version is the Multi-Coloured-Manual (MCM) that was published in 2013. In the UK it is standard practice to base damage assessments on the MCM. The manual provides absolute stage-depth damage curves that allow for quantification of many damage categories in monetary terms (Penning-Rowsell *et al.,* 2013).

The MCM model is based on synthetic data that is generated with the use of "what if" questions and expert knowledge. A large database of synthetically generated data was created and hereafter used to define absolute loss functions in monetary units (Penning-Rowsell, Priest, *et al.*, 2013). Damage functions are provided for direct tangible damages, where many types of damages have been identified. For example, for residential buildings a classification based on type, age and social status of the inhabitants has led to 100 different damage functions. The required input data is available in the national property dataset, which contain data about the age of the property, the social class of the residents, and the type of the building (Hammond *et al.*, 2015).

For non-residential buildings, information from the Focus database, a national property database has been used. Moreover, interviews have been conducted in order to assess the risk in the different sectors. Hereafter the susceptibility of the different sectors has been evaluated and damage functions were created based on this information. The non-residential damage functions give the cost per square meter, unlike those for residential buildings which are given per property. To account for the damage to inventory, curves were created for flooding of both long and short duration.

In this manual it is argued that the indirect non-residential losses are financial rather than economic. Therefore there is no loss for the national economy, if the production/sale is transferred to other businesses. It is recommended to only include the indirect loss in special circumstances, e.g., if the produced wares are exported.

Even though intangible losses are not included in the MCM damage model, they were still considered in the manual. As part of the work, a conducted survey showed that the citizens of the UK are willing to pay 200£ per year per household to avoid the risk of flooding, which is likely due to the fact that the country frequently experiences flooded and the public is thus aware of the issue.

The MCM also discusses the matter of social equity. Damage assessments that solely focus on the quantification of flood damages in monetary terms risk to give a higher priority of flood adaptation to wealthier areas, because these present higher values at risk. To address this issue, the MCM proposes that weighing factors could be included in order to obtain better socio-economic equity. Factors should be applied as the last step of a damage assessment. The factors could, for example, be determined from the so-called social vulnerability index. This index prioritizes areas with people above the age 75 years, the residence of single parents and/or people with long term sicknesses (Penning-Rowsell *et al.,* 2013).

Case studies

Summer 2007 floods

A case study was performed to estimate the impacts of the large floods in 2007 based on survey and insurance data (Chatterton *et al.*, 2010). The total cost of the flood was estimated to range between £2.5 bn to £3.8 bn, with a best guess of be £3.2 bn. The study grouped damages into the following sectors:

- Households
- Business
- Power and water utilities
- Communications (including roads)
- Emergency services
- Agriculture
- Public health and school education

The quantification of the damage costs in the sectors was performed without considering separate damages classes. Therefore, the total amount of loss within the sectors includes the tangible, intangible, direct and indirect damages. The damages to business and households were based on aggregated insurance data and were assessed to hold moderate uncertainties. These two sectors were estimated to be responsible for two thirds of the total damage cost. For the power and water sector, the damage to the plants and additional operating cost were found with the use of data provided by the plants. The disruption to the provision of water and electricity was estimated by applying standard rates provided by the Department for Energy and Climate Change and OFWAT, which is the economic regulator of the water sector in the UK. However, the assessment of damages resulting from disruptions to these services was subject to considerable uncertainties.

Data from audited accounts of local authorities was used to find the costs held by the local authorities, which included the emergency services, and some of the infrastructure damages, most of which were roads. These data were deemed very reliable. Damage to railways was estimated based on information from railway company records and personal communication. Passenger delays were included with the use of standard rates for the value of traveller's time. The magnitude of road traffic disruptions was estimated with the use of information from the Highway Agency and flood maps. To assess the damage cost to agriculture, surveys and visits were conducted for 78 farms, which had been flooded.

To assess health impacts, the willingness to avoid method was applied. Here, the willingness to avoid exposure to the distress caused by flooding was appraised. Moreover 13 fatalities were recorded after the flood. These were considered with a unit cost of £1.15 million per fatality defined by the Treasury for the appraisal of public investments in health and safety.

The loss of the school education was estimated to be equal to the cost of a school day and parental work days lost (Chatterton *et al.*, 2010).

Humber Region

A recent study of the Humber region, on the east coast of England was conducted to assess the potential damage costs for future events. The estimation was primarily based on prior floods, and the area of risk was identified. The damage assessment included:

- Residential buildings
- Businesses
- Agricultural land
- Roads
- Hotspots: schools, hospitals, water and wastewater assets, electricity sub-stations, emergency service assets and national grid substation
- Loss of income and disruptions to business
- Disruptions of the supply chain

All the direct tangible damage costs were estimated based on the MCM stage-depth curves and recommended prices (Raynor and Chatterton, 2014). The case study also included indirect tangible damages. While this is not recommended by the MCM, the authors argue that these damages can have a large impact on the local and regional scale and should therefore be included in this particular study.

A particular point of interest was the local port, which is the largest port in the UK, and could cause high losses if flooded. Businesses and hotspots in the area, including oil refineries and several sensitive chemical and pharmaceutical manufacturing sites, were also considered in the assessment of indirect damages. The cost of the indirect damage was estimated as a percentage of the direct damage. A percentage of 76% was applied based on a downscaling of the factor found in another case study for the Thames Estuary. A cost-benefit analysis based on the described damage assessment could clearly demonstrate the economic benefit of investments into flood adaptation measures (Raynor and Chatterton, 2014).

Thames

A study for the river Thames was performed with use of a hydraulic model, and property damage data, derived from the Multi-Coloured manual. The study included a formal estimation of risk to life and the appraisal of this as a monetary value. It was taken into consideration that the damages in London might vary from the general damages across the UK applied in the MCM. Therefore the damage assessment was supplemented with the appraisal of damage to some key non-residential properties. A multi-criteria analysis was performed to include the intangible damages, which included the impact on the environment, such as lowered water quality and social effects, such as loss of community. Here, scoring and weighing were used instead of monetary values. The studied showed that the "Do minimum (maintain)" scenario would yield the lowest benefit, while the implementation of a barrier would be the preferred option (Penning-Rowsell, Haigh, *et al.*, 2013).

3.4 Australia

The two main damage models used in Australia are ANUFLOOD and RAM. ANUFLOOD was developed by the Center for Resource and Environmental Studies at the Australian National University for the Queensland government in 1983 (Middelmann-Fernandes, 2010). This model applies synthetic stage-depth damage curves for residential and commercial properties, where there are 5 value classes for residential buildings and 15 nonresidential damage curves. In ANUFLOOD indirect damage is estimated as 15% of the direct residential damage and 55% of the direct commercial damage (Gissing and Blong, 2004).

The Rapid Appraisal Method (RAM) was developed for the Victorian State Government in 2000 (Gissing and Blong, 2004). RAM is described as an empirical-synthetic model, with an absolute unit loss for micro scale damage assessment. It includes the losses to building structures and contents, where the only distinction is whether the buildings are smaller or larger than 1000 m2 (Handmer, Reed and Percovich, 2002). It is recommended to estimate the indirect damage as 30% of the direct damage. 20% can be applied for rural regions and 45% for urban centres with a substantial tourism sector. The RAM documentation suggests that ANUFLOOD stage damage curves underestimate the cost, and should therefore be increased with 60%.

In 2002 a Disaster Loss Assessment guideline was published as part 3 of the Emergency Management Practice. The guidelines were developed by the Queensland Department of Emergency Services and Emergency Management Australia. These guidelines draw on the work of the UK Flood Hazard Research Centre, work at the Centre for Resource and Environmental Studies at the Australian National University and the Victorian rapid appraisal method (RAM). The approach is moreover compatible with HAZUS developed by the US federal Emergency Management Agency. The guideline does not develop a particular flood loss model, but focus on ensuring a standardized method, and a full and auditable analysis, thus allowing construction of a decision making tool (Handmer, Reed and Percovich,

2002). For this purpose, the guideline presents a step-by-step loss assessment process. The guidelines recommends a financial damage cost assessment and favours a unit-cost approach, thus recommending to apply the unit cost model RAM (Handmer *et al.,* 2005).

Case studies

North Queensland

This study was conducted after the flooding in North Queensland Region in January 1998. It considered the following damage classes:

- Residential buildings
- Commercial buildings
- Emergency response relief
- Disruption to the transport network
- Public health

Direct residential losses and direct commercial losses were priced with the use of insurance payments and surveys. The magnitude of traffic disruptions was found with the help of average daily traffic figures for the blocked road sections and a cost for each hour of disruption. Emergency costs were estimated based on pay-outs to the Queensland Department of Emergency Services.

Business disruptions were neglected in the study, although they locally were reported to be as high as $15 M AUD. However, it is argued that these losses are mostly a gain for competing businesses and that the real damages were in the vicinity of $1-2 M AUD. With a similar argument, costs for housing of evacuees were neglected in the study.

The following intangible damages were considered in the study:

- Fatalities, serious injuries and minor injuries,
- Other health effects,
- Loss of the citizens' memorabilia,
- Short-term quality of life losses such as difficulties in getting to work, disruption to routines, disruptions of police work, and discomfort and/or inconveniences like loss of utilities (power, water and telephone) and stench caused by sewage water,
- Long-term quality of life losses associated with lowered socioeconomic status and long-term psychological problems, and
- Environmental degradation including seagrass bed loss, coral bleaching and heavy metals entering the environment from mine site.

However, due to the absence of a clear market, only the cost of death or injury was included in the damage assessment. This valuation was based on a report from the Australian Bureau of Transport Economics (BTE), where fatalities were given a value of $1.3 M AUD, serious injuries $317,000 AUD and minor injuries $10,600 AUD. The intangible damages

resulting from the flood where thus estimated to $4.68 M AUD (Handmer, Reed and Percovich, 2002).

The study of the floods in North Queensland also compared the differences between the RAM model, insurance data and loss data obtained from surveys for the direct residential and commercial losses (Handmer, Reed and Percovich, 2002). A summary of the results is shown in Table 4.

Table 4: Difference between unit cost for residential and commercial buildings derived after the flood of North Queensland in 1998 using different methods (Handmer, Reed and Percovich, 2002).

	Insurance	Survey	RAM
Residential [AUD/ building]	3,735	24,491	20,500
Commercial [AUD/ building]	46,000	15,998	20,500

It is seen that the RAM model clearly deviates from the average residential damage cost obtained from insurance data. This is believed to be because many of the 7454 damaged houses only suffered slight damages and thereby lowered the average damage cost significantly (Handmer, Reed and Percovich, 2002). Further, the RAM model underestimates the damage to businesses when compared to insurance data. This may be caused by the fact that the businesses in this area held a high level of good flood insurance. The indirect damages were also compared with the RAM model. The cost for emergency response relief and disruption of the transport network amounted to $1.5 M AUD and $2.5 M AUD, respectively. If the RAM proposal to consider indirect damages as 30% of the direct damages was applied, the cost would however be estimated to $37 M AUD. This great difference between the RAM model and the observed cost of the indirect damages, is believed to be a result of excluding most of the indirect business losses in the damage assessment (Handmer, Reed and Percovich, 2002).

Kingston

A study of the adaption to climate change and the increased risk of urban flooding was conducted for the Kingston City council, as part of the Port Phillip Bay coastal Adaptation Pathways Project. Only damage to residential, commercial and public assets was included together with clean-up costs and indirect damages in the form of disruptions. The methodology of the study limits the damage assessment to tangible damages, and applies the RAM model. It is however discussed that there are benefits in avoiding the indirect and intangible costs, and therefore the benefits are underestimated. The damage cost assessment has used a shapefile of the area, together with an asset property database, with information about construction type and number of stories. The cost-benefit analysis of the area

indicated that there was no economically beneficial adaption option for this case study, with the highest benefit cost ratio of an adaption strategy being 0.73 (Hoekstra *et al.*, 2012).

Duck river catchment

A study of the Duck River catchment was conducted as a corporation between Parramatta, Auburn and Bankstown city councils. Based on experience from previous flooding together with simulation results from a 2-D hydraulic model, estimations of the magnitude of floods caused by events with different return periods were made. As part of the damage cost estimation the tangible and intangible damages were split into direct and indirect and further split into the sector specific subgroups, residential, commercial and public. Within these subgroups it was also listed if the direct damage was internal, structural or external and if the indirect damage was clean-up, financial or opportunity. By using this approach a large matrix with a wide range of damage classes was identified.

For the direct damages, internal refers to the content in the building, structural to the damage of the material, and external damages cover damages to outside items like cars. In order to estimate when the inundation depth would have an impact on residential structures, a floor level database was created. Industrial and commercial flood damages were not included, since a floor area survey would be required. The authors argue that this is an acceptable exclusion, since these damages are subjected to government assisted flood mitigation measures.

Stage-depth damage curves were developed and each component was allocated a maximum value and maximum inundation depth. The damage to motor vehicles was included by defining the inundation threshold as 0.3 m and assuming 1.3 vehicles per household. Indirect damages were included as a percentage of the direct damages. For residential properties 20% of the direct damage was applied and for infrastructure 15% of the total direct damage was used. Lastly, social damages were considered as 25% of the total direct damages (Molino Stewart, 2012).

Newcomb-Whittington catchment

A flood study was conducted for Newcomb-Whittington catchment in Geelong in 2011. To estimate the damages costs of these events, the stage-damage curves from ANUFLOOD were applied. The recommendation from RAM of an increase of the costs by 60% was implemented in the study. Moreover the indirect damages were accounted for as 30% of direct damages, in accordance with the RAM costing principles. To include the damage reduction caused by warnings, a factor of 0.9 was applied, assuming that a minimum of two hours warning time will always be applicable (WBM BMT, 2011).

3.5 Comparison of the approaches

The conducted literature review identified 13 case studies. An overview of the damage assessments and the methods applied in these studies is given in Table 5. A variety of methods was applied in the different countries, with some studies applying standardized assessment methodologies, while others developed catchment specific approaches. Four studies only included the direct tangible damages, five also included the indirect tangible damages and the last four also included the intangible damages. Despite of the relative small sample size, this review does not confirm the general perception that the majority of the studies only include the direct tangible damages.

For the damage classes that cannot be quantified directly, many studies considered only specific elements of a class that was deemed important. An example would be the health of citizens in the intangible damage class. This approach is reasonable, because it is close to impossible to consider any damages a flood potentially may cause and cost estimates for many intangible damage classes can only be provided a very rough guesses.

Table 5: Overview of damage assessments performed in Denmark, Germany, the UK and Australia.

	Study	Ex-ante or ex-post	Cost function	Damage classes considered	Damage Model	Data Sources
Denmark	Roskilde and Ålborg 2007	Ex-ante	Uniform costs	Direct tangible Indirect tangible Direct intangible		Insurance Expert knowledge
	Copenhagen	Ex-post	Uniform costs	Direct tangible		Insurance
	Odense and Aarhus	Ex-ante	Uniform costs	Direct tangible Direct intangible		Litterature review
	Egedal	Ex-ante	Uniform costs Synthetic damage curves	Direct tangible		Value-map
Germany	Climate change in Germany	Ex-ante	Empirical damage curves	Direct tangible	HQ Kumul	Insurance
	FLEMO evaluation	Ex-post	Empirical damage curves	Direct tangible	FLEMOps	
United Kingdom	Floods in 2007	Ex-post	Uniform costs	Direct tangible Indirect tangible Direct intangible Indirect intangible		Insurance Willingness to avoid Data from local authorities Appraisal of Fatalities Surveys
	Humber region	Ex-ante	Synthetic damage curves Uniform costs	Direct tangible Indirect tangible	MCM	Indirect damage included from experience
	Thames	Ex-ante	Uniform costs Synthetic damage curves	Direct tangible Indirect tangible Direct intangible Indirect intangible	MCM	Weighing factors for hotspots
Australia	North Queensland Region in January 1998	Ex-post	Uniform costs	Direct tangible Indirect tangible Direct intangible Indirect intangible	RAM	Insurance Surveys Governmental data Cost of damage to health
	Kingston City council	Ex-ante	Synthetic damage curves	Direct tangible Indirect tangible		
	Duck River catchment	Ex-ante	Uniform costs Synthetic damage curves	Direct tangible Indirect tangible		Indirect and social damage as percentage
	Newcomb-Whittington catchment	Ex-ante	Empirical damage curves	Direct tangible Indirect tangible	ANUFLOOD RAM	Indirect damage 30% Warning factor of 0.9

4. Recommended procedure

To initiate a damage estimation it is important to follow a clear and transparent procedure, in order to make it clear what costs are included, and how they are included. The procedure suggested is outlined in Figure 7. In this framework the method is based on making a thorough scoping of the assessment followed by adding the damage classes in the order outlined in the figure. Not all damage classes need to be included, but it is important to highlight which ones are. Typically, including more damage classes in the assessment leads to higher damage estimates as well as higher uncertainty of the estimates. The reason is that the intangible damage classes are more difficult to monetize and in general not much data exists for these classes. On the other hand, exclusion of these classes will lead to a systematic underestimation of the overall costs of flooding.

4.1 Initial step: Defining the damage assessment

Firstly a definition of the purpose of the damage estimation should be presented, in order to scope the analysis. This should include the limitations, where it is made clear what should be included, and what should be neglected. In many studies involving damage estimations, the main limiting factor is the availability of data. Another limiting factor is the resources available to make the assessment. For example, creating new damage functions for the specific study poses significant challenges in terms of required resources as well as expert knowledge.
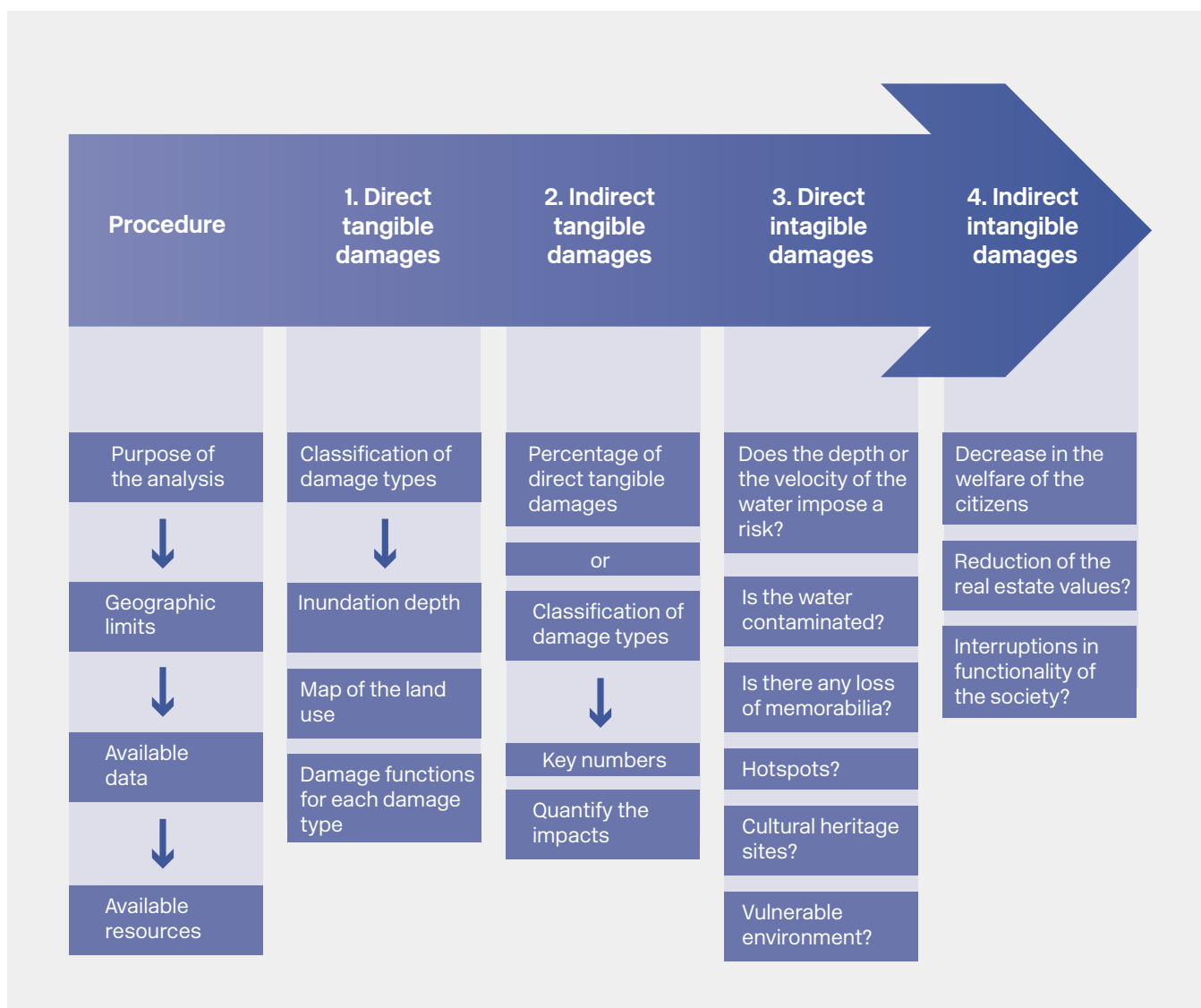

Figure 7: Procedure for damage assessment.

A damage cost assessment has a high demand for data, which in some case can be hard to acquire. Consequently, it is important to state the level of detailed applied when performing the analysis. If the damage assessment is for a future event, the detail of the hydraulic simulations and calculations should also be considered.

An important restraint is to define the geographical limitations. A spatial extent that is consistent with the purpose of the assessment should be selected. It is recommended that risk assessments should be performed on catchment basis to capture potential cost-benefit transfers between different parts of the catchment. In general, the indirect losses are highly dependent on the size of the considered area. This is because a local flood can have regional consequences in regarding to traffic disruptions, power supply etc. Moreover, in larger areas it might be more reasonable to use crude estimations, while in smaller areas the presence of, for example, flood-sensitive industries can have great impact on the total damage estimate for the area.

In some cases it can also be necessary to define the timeframe investigated. In Australia the recommended timeframe is 3 to 6 months. An extended timeframe is mostly important in the studies, where indirect and intangible losses should to be included (Handmer, Reed and Percovich, 2002).

4.2   First Step: Direct tangible damage

To estimate the direct tangible damage, the first step is to define the number of damage types that will be directly included in the assessment. This is not only based on the available data, but should also reflect the level of detail of the hydraulic calculations.

First, it must be decided if the cost should be a function of the flood characteristics, e.g., the inundation depth, or based on an average unit cost. In the latter case it is only distinguished whether an area or object has been flooded or not. This simplification can be applied if information about the inundation depth is not available or if the available data does not suggest that the consideration of further flood characteristics adds more information to the study. If sufficient hydraulic data is available, it is only suggested to use unit cost approaches, if the flooding is of pluvial type. For the other flood types, it is recommended that stage-depth damage curves are applied. If there are not enough resources or data to make specific stage-depth damage curves for the investigated area, it is recommended to use representative relative stage-depth damage curves.

In general, the level of detail in the analysis is decided by the number of damage types identified. The different elements are pooled into relevant groups for which the damage can be appraised. The number of groups depends on the heterogeneity of the flooded area. The dwelling type in the area can, for example, be so homogeneous that only one stage-depth damage curve is necessary, or so varying, that the buildings have to be further categorized into several subgroups. For direct tangible damages, it is recommended that residential and non-residential buildings and their inventory should as a minimum be included as damage types. Infrastructural damages can be neglected for pluvial flooding but should be included if other flood types are present.

Rescue operations and evacuations were in multiple studies in the UK shown to cause negligible cost compared to the material damages (Chatterton et al., 2010, 2016), and are therefore neglected in the framework presented here.

4.3   Second Step: Indirect tangible damage

There are two main methods to estimate indirect tangible damage, either by considering it as a percentage of the direct tangible damage or by making a more detailed analysis. The suggested percentage values vary between studies. The main advantage of the percentage approach is that no additional input data are required. This method is however subjected to high uncertainty and can therefore be considered an acknowledgement of indirect damage cost, rather than an actual quantification. If there are no hotspots creating particularly high damage costs, we suggest following the recommendation in RAM where the intangible damages are considered as 30% of the direct tangible damages.

A more detailed method to estimate indirect tangible damages is to evaluate where and for how long the flood can cause disruptions. Examples of disruptions are traffic delays, loss of production etc. Key numbers can be used to quantify the disruptions in monetary terms. These key numbers are different for each country, since they largely depend on the value of people's time, which is correlated to the average wages. The evaluation of disruptions requires highly detailed hydraulic simulations, and should only be performed if the hazard assessment allows for it.

Temporary housing of evacuees has been found to be of negligible size in comparison to the material damages (Chatterton et al., 2016), and it is therefore acceptable to exclude this cost.

4.4   Third Step: Direct intangible damages

For direct intangible damages, a preliminary screening should be performed to evaluate to how great an extent any of these losses could actually occur. The assessment should primarily focus on the risk to human health. The evaluation is performed based on the flood characteristics, and the risk of citizens being exposed to contaminated water. The type of flooding consequently needs to be considered in the assessment. Moreover, the inflicted area should be analysed for possible hotspots, cultural heritage sites and vulnerable environment.

To include intangible damages in the damage assessment, they can either be expressed in a common (monetary) metric or multi-criteria techniques can be applied. We argue that intangible damages can only be expressed in monetary terms with large uncertainties and we therefore deem a qualitative assessment using multi-criteria techniques the best option. The result of such techniques can, for example, be spatially varying weighing factors that are applied to the damage estimates depending on hotspots or the number of particularly vulnerable persons living in an area.

4.4   Fourth Step: Indirect intangible damages

As with the direct intangible damages, there is a need for a preliminary evaluation of the flood. The length of the flood can be an important factor, when estimating the impact of a disruption on the citizen's life. The indirect intangible damages are difficult to evaluate and quantify. Therefore, similar to the direct intangible damages, it is recommended that they are recognized in a multi-criteria assessment if there is a high risk of indirect intangible damages occurring.

5. Example: Assessing damage costs for the Elster Creek Catchment, Melbourne

5.1 Catchment

The Elster Creek catchment is located in SE Melbourne in the state of Victoria. The catchment has a size of approximately 45 km2 and a population of 100,000 households. The catchment is contained in the municipalities Glen Eira City, Kingston City, Bayside City and City of Port Phillip (Figure 8).

Recent flood events in 2011 and 2014 in Elwood (Herald Sun, 2014) in the downstream part of the catchment have raised public awareness of flooding issues, in particular in this area. The Elwood area was swampland, originally, but was drained with the building of the Elwood Canal (AECOM, 2012).
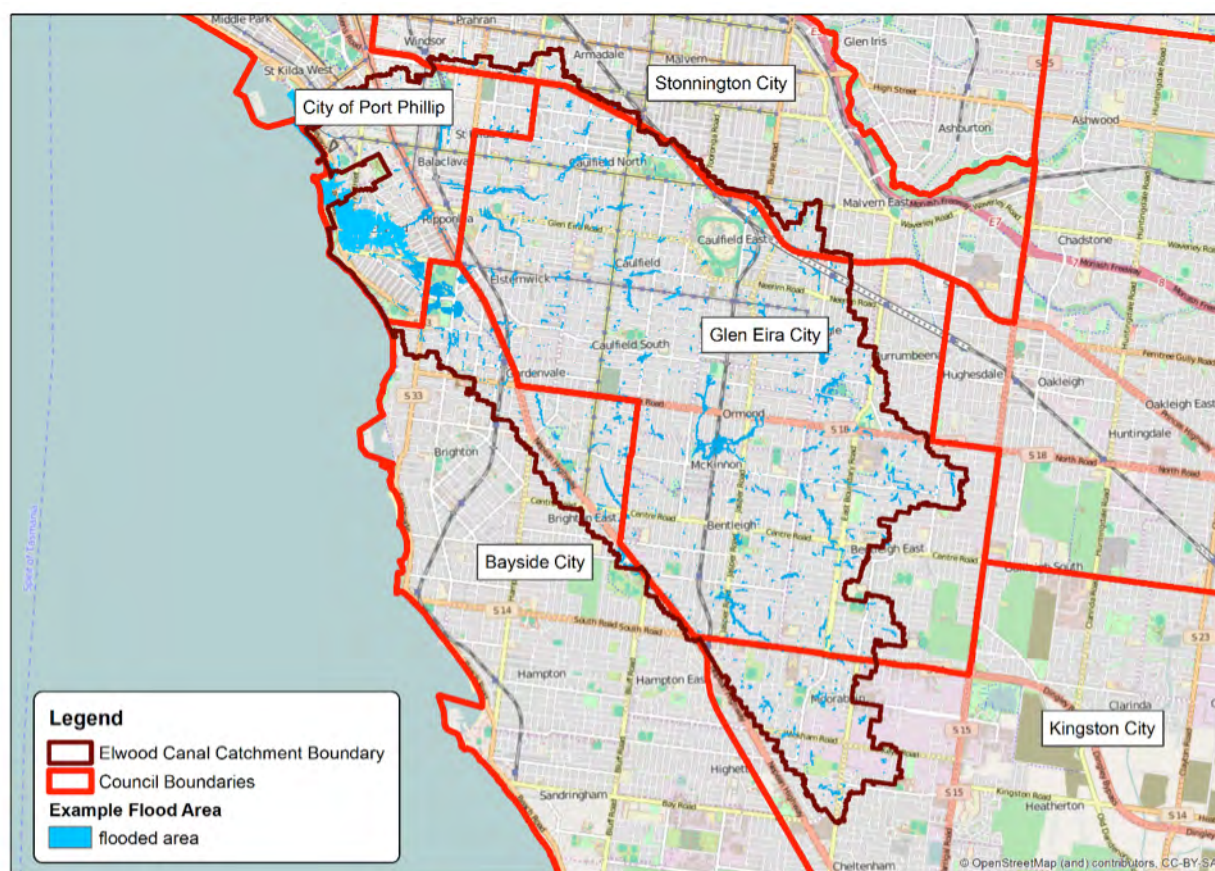
Figure 8:   Map over the Elster Creek catchment with administrative boundaries and areas expected flooded once in 100 years by 2090.

Figure 9 shows building data for the catchment as provided by Melbourne Water. Buildings are marked according to use types from the Victoria Planning Provisions (Department of Environment Land Water and Planning, 2016). It is clear, that the catchment is dominated by residential land use. The commercial buildings are spread over the area. No information on potential flooding hotspots was available for the assessment.

Legend
Elwood Canal Catchment Boundary
Planning Provision Type
Business - B1Z; B2Z; B3Z; B4Z; B5Z
CA; CDZ1; CDZ2; CDZ3
Industrial - IN1Z; IN3Z
Public Land - PDZ
Public Land - PPRZ
Public Land - PUZ1; PUZ2; PUZ3; PUZ4; PUZ5; PUZ6; PUZ7
Public Land - RDZ1
Hiatus
Reserve
Common
Residential - MUZ; R1Z; R2Z; R3Z
Road
Rural - GWZ2
Rural - GWZ4
Special Use - SUZ1; SUZ2; SUZ3; SUZ4; SUZ5; UFZ
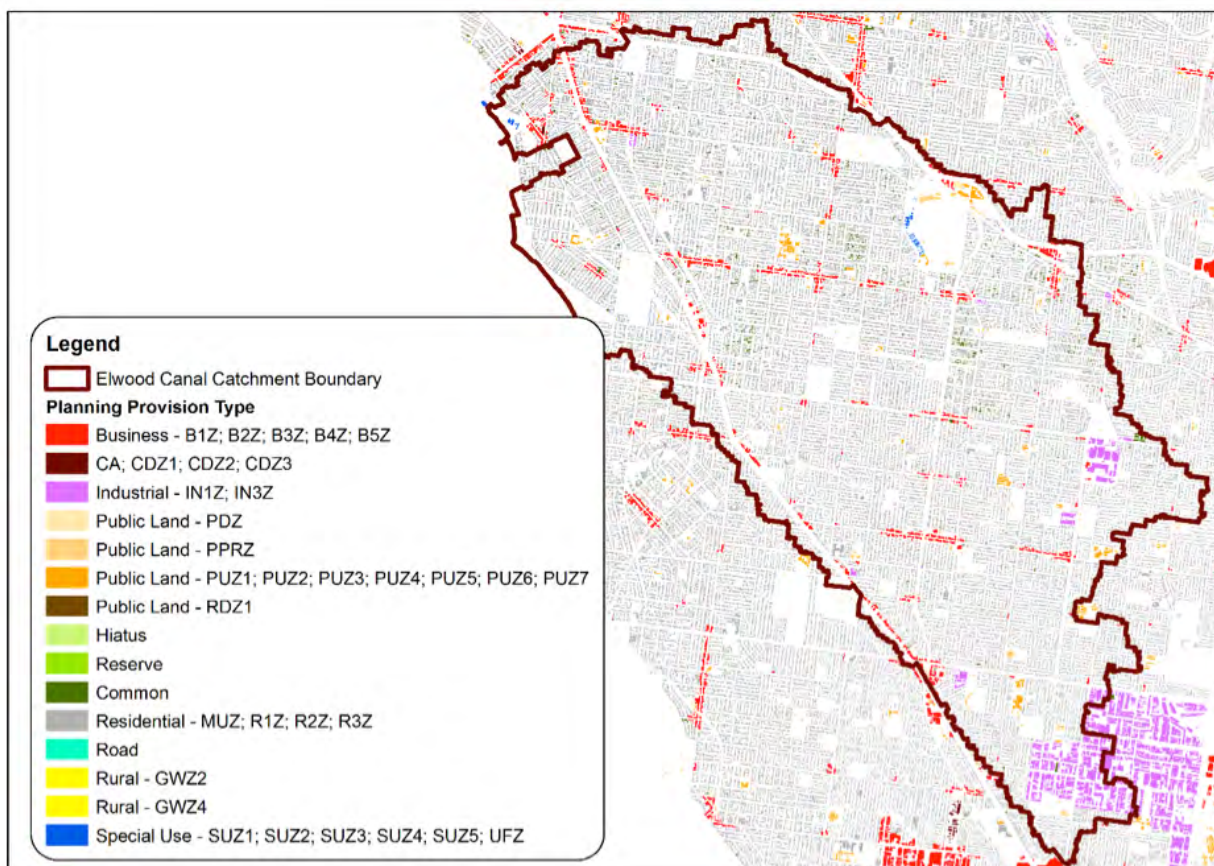
Figure 9: The land use in the area, presented by the different usage types according the Victoria Planning Provisions (Department of Environment Land Water and Planning, 2016).

5.2 Scoping of the damage assessment

The damage assessment focuses on the Elster Creek catchment as seen in Figure 8 and Figure 9. The purpose of the damage estimation in Elwood is to be able to evaluate how much flood damage can be avoided by implementing different flood adaption strategies. In this report, we demonstrate the application of flood damage estimation in the baseline case without any adaptation measures, while further studies will also compare flood damages for different scenarios and adaptation measures. Depth damage curves for residential buildings

5.3 Direct tangible damage

General

Due to the lack of flood and insurance data, no catchment-specific stage-depth damage curves were developed. Instead, existing curves from Australian studies were applied as described below. The damage cost were corrected for inflation using the consumer price inflation index (Reserve Bank of Australia, 2016), see Appendix 1.

Depth-damage curves were available for the following sub-categories:

- Residential buildings
- Industrial and commercial buildings
- Damage to roads

With only 3 considered damage classes, the assessment can be considered rather coarse. The approach was motivated by the fact that more detailed damage curves were not available for Australia. Further, the hydraulic model used for simulating flood hazards was created on a poor data basis and we thus need to assume that the simulation results are somewhat unprecise. The application of a highly detailed damage evaluation in conjunction with such results might feign a precision of the damage estimates which is not supported by the model.

Grouping of building types into damage categories

We have grouped the land use types shown in Figure 9 into classes commercial and residential as follows:

- Commercial
    - ¬ Business - B1Z, B2Z, B3Z, B4Z, B5Z
    - ¬ CA, CDZ1, CDZ2, CDZ3
    - ¬ Industrial - IN1Z, IN3Z
    - ¬ Public Land - PDZ, PPRZ, PUZ1, PUZ2, PUZ3, PUZ4, PUZ5, PUZ6, PUZ7, RDZ1
    - ¬ Special Use - SUZ1, SUZ2, SUZ3, SUZ4, SUZ5
    - ¬ Common
    - ¬ Hiatus
- Residential:
    - ¬ Residential - MUZ, R1Z, R2Z, R3Z
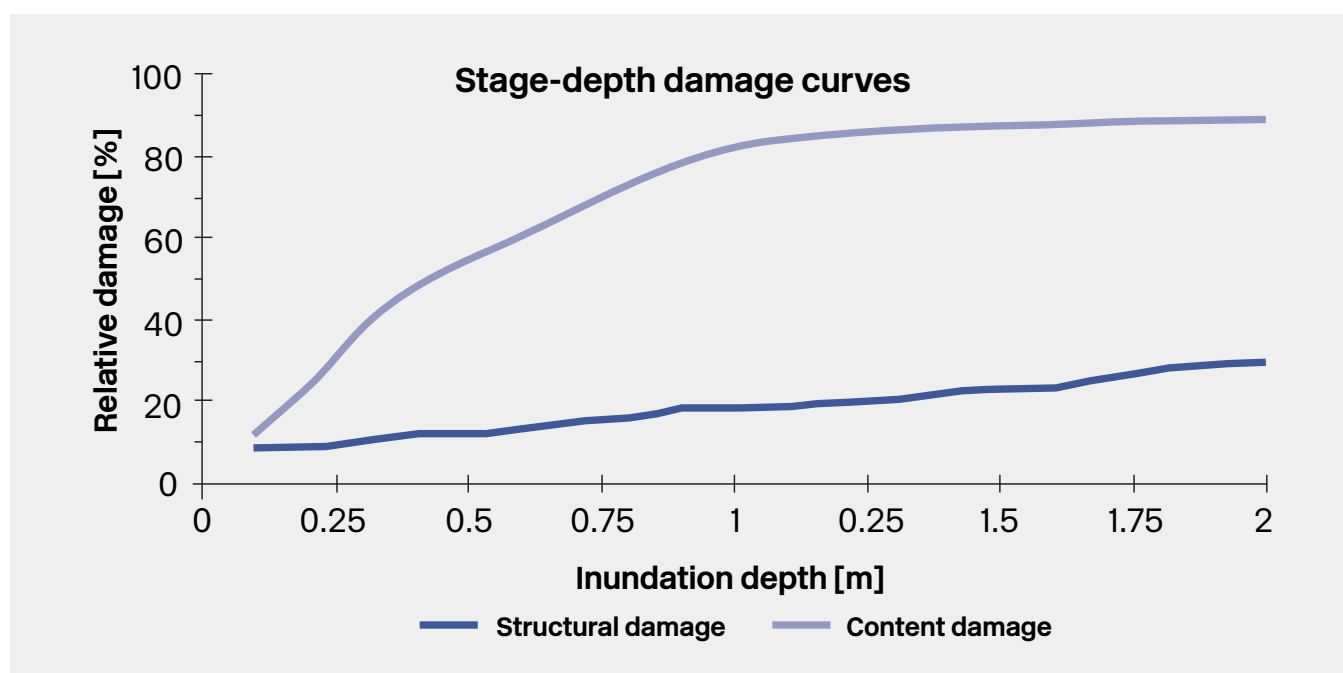   - ¬ Rural - GWZ2, GWZ4
    - ¬ Reserve

Figure 10:   Stage-depth damage curve for residential properties (Handmer, Reed and Percovich, 2002).

As mentioned above, the application of relative stage-depth damage curves requires the definition of a potential damage. Absolute damage values are then computed by multiplying relative damage and potential damage. As suggested by the authors of the applied damage curve, potential damage was defined using house prices in the considered area. When applying this approach, some difficulties arise:

- Firstly, house prices in Melbourne have undergone an explosive development since 1995, while this is arguably not the case for the potential flood damage. To illustrate this development, Figure 11 depicts the actual development of the mean house price in the Melbourne metropolitan area and the development of house prices if these would have increased according to the consumer price index.

- Secondly, house prices are subject to a high degree of spatial variability. For example, in the Elster Creek catchment mean sales prices for houses in the Elwood area were $1.33 M AUD in 2014, while they were only $0.84 M AUD in Bentleigh East. Considering such variations in flood damage assessments gives wealthy areas higher priority for the implementation of flood adaptation measures, which may not necessarily be desirable. Further, it is unlikely that actual flood damage would exhibit the same degree of spatial variation.

As a result of the above considerations, we assumed that potential flood damages would increase in accordance with the consumer price index rather than follow developments on the housing market. We further assumed that potential flood damages would not be affected by spatial variations of housing prices. Thus, we derived the potential flood damage for application with the structural damage curve shown in Figure 10 from the mean house price in the Melbourne metropolitan area for the year 2002 (Department of Environment, Land, 2016) when the damage curves were developed.

Maximum potential content damage was defined by Melbourne Water in their flood Mitigation Prioritization Tool, and applied in this study (Melbourne Water, 2006). Both potential damages were adjusted to 2015 prices using the consumer price inflation index (Reserve Bank of Australia, 2016). The resulting potential damages were:

- House: $452,789 AUD

- Content damage: $60,000 AUD

Applying these potential damages to the relative stage-depth damage curve shown in Figure 10, leads to the absolute stage-depth damage curves shown in Figure 12.
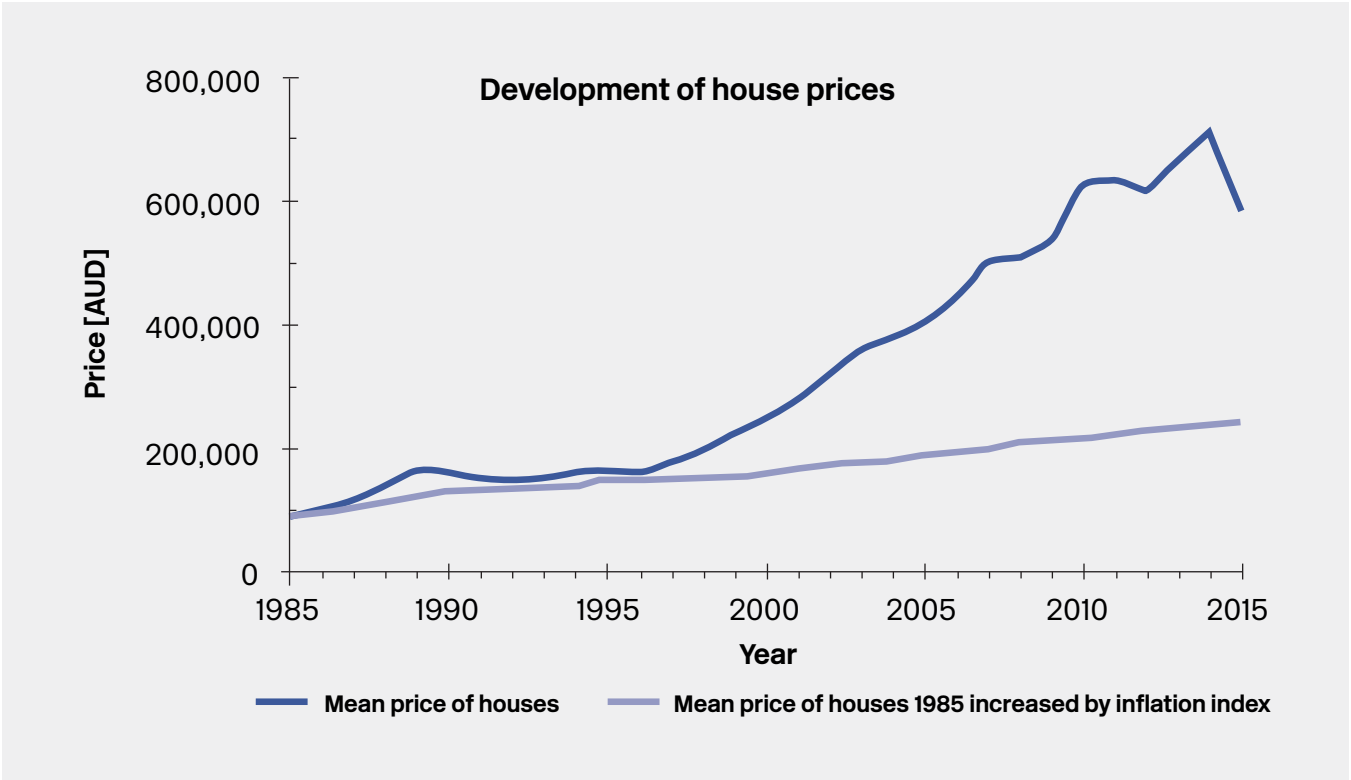
Figure 11: Price development of the sales price of houses in the Melbourne metropolitan area, compared to an inflation of an average sales price in 1985.
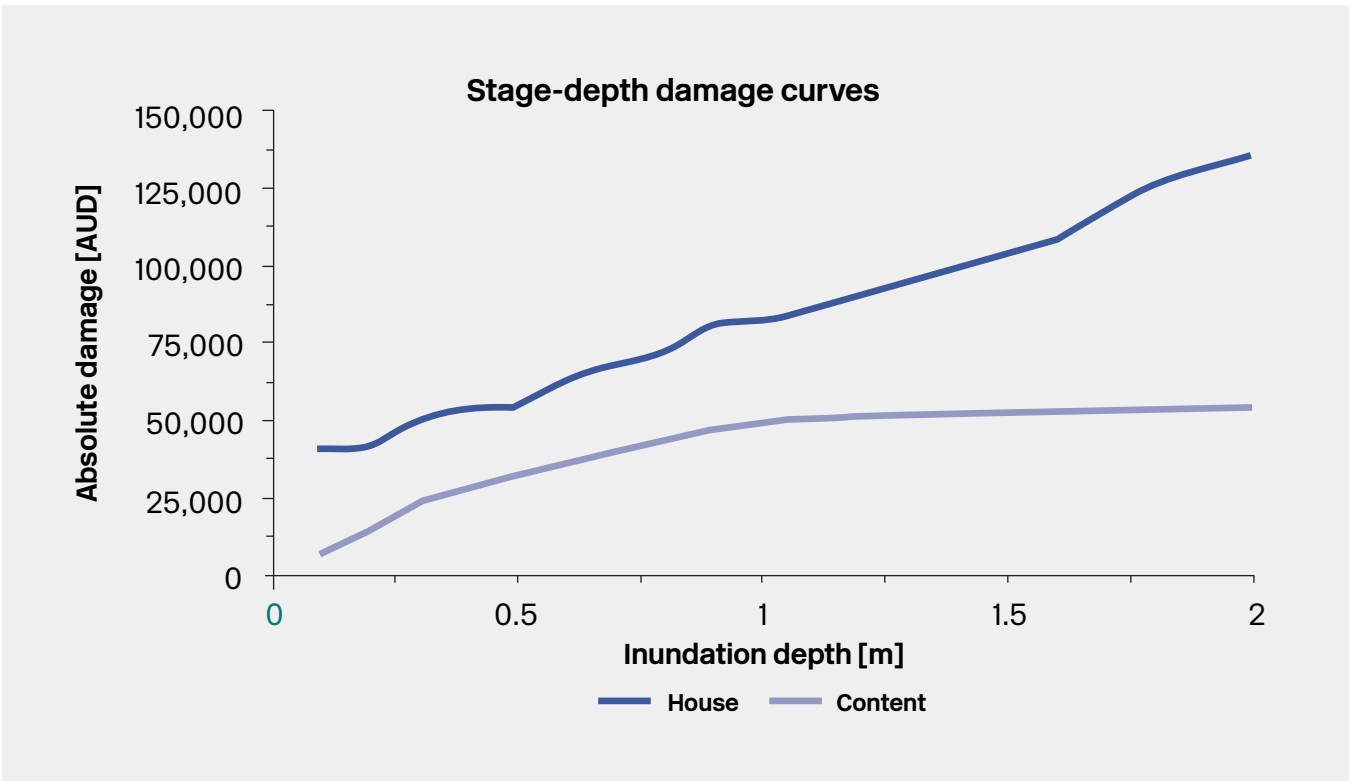

Figure 12: Absolute stage-depth damage curves for residential buildings and content applied in this study.

Depth damage curves for commercial buildings and industry

To assess flood damages for the sub-category commercial and industrial buildings, an absolute stage-depth damage curve provided by the Melbourne Water flood Mitigation Prioritization Tool was applied (Melbourne Water, 2006). The inflation-adjusted curve (Reserve Bank of Australia, 2016) is illustrated in Figure 13.

Other than the depth damage curve for residential buildings, this curve defines flood damages depending on the size of the building foot print in square meters. The reason for this approach is that damages in the commercial class can vary widely depending on the type of building which is flooded. For example, given the same inundation depth, flood damages for a small tool shop would be expected to much smaller than for an industrial production facility.

Damages to roads

In Australia, one of the most commonly applied valuations of road damage is originating from the RAM model and has been presented in the Disaster Loss Assessment Guideline. Major sealed roads were valuated at $59,000 AUD per km. This value is a summation of the three following damages (Handmer, Reed and Percovich, 2002):

- Initial repairs: $32,000 AUD/km

- Subsequent accelerated deterioration of roads: $16,000 AUD/km

- Initial bridge repair and subsequent increased maintenance: $11,000 AUD/km

After inflation adjustment to 2015 prices, a damage of $89,090 AUD should be considered per km of road flooded above a threshold of 0.3 m.

Assessing damages based on road length is difficult to implement automatically in a GIS environment and not practically meaningful, as it raises further questions as to what portion of the road width should be flooded to consider a road stretch as flooded. To avoid these issues, we have converted the above named damage into a damage per square meter of flooded road based on the observation that major roads in the catchment would typically be approximately 24 m wide. The result is a unit cost of $3.71 AUD per square meter of road area flooded above a threshold of 0.3 m.
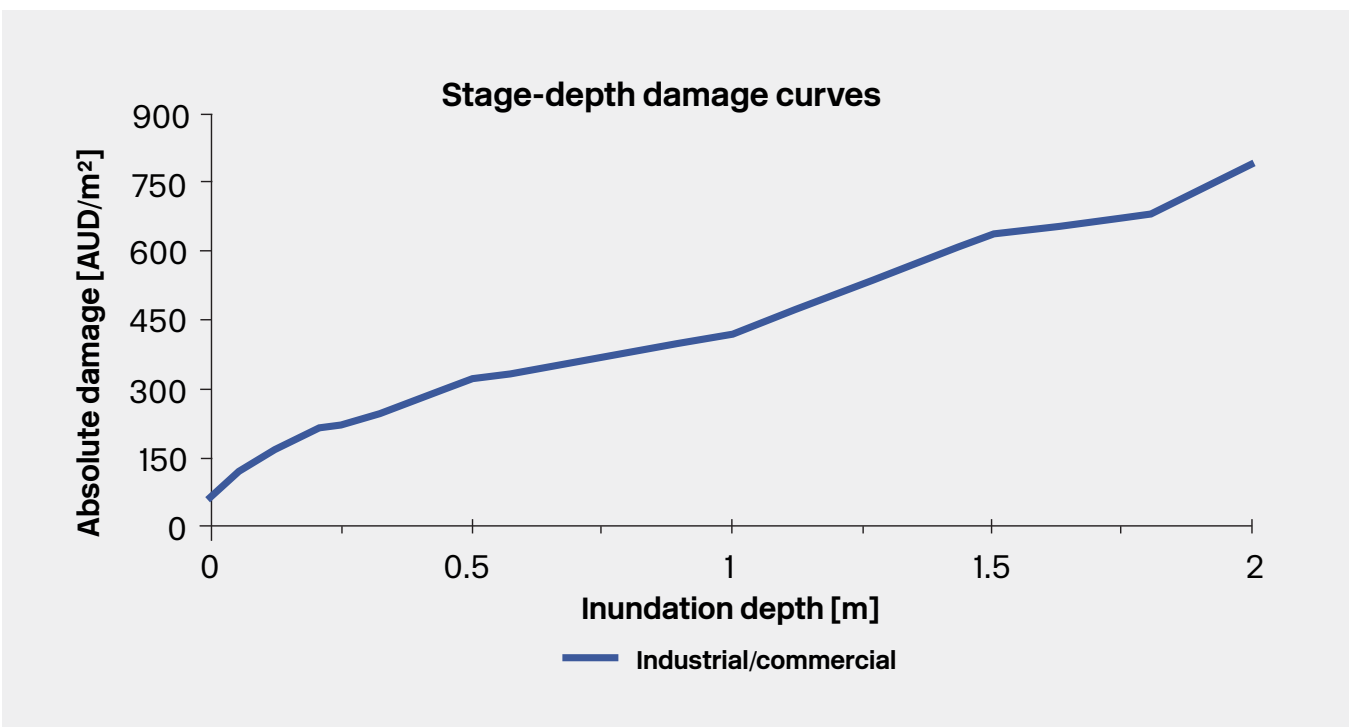

Figure 13: Absolute stage-depth damage curves for industrial and commercial buildings (Melbourne Water, 2006). Inflation adjusted using the consumer price index (Reserve Bank of Australia, 2016).

5.4 Indirect tangible damage

A number of major roads are located in potentially flooded areas in the catchment (Figure 8). Flooding of these roads would be expected to cause traffic delays. We did not assess the cost of these delays on a catchment-specific basis because the data required for such an assessment were not available and because the complexity of this approach was deemed not justified considering the quality of modelling results and potentially available input data. Therefore, we resorted to the recommendation of RAM, where indirect, tangible damages are considered to be in the order of 30% of the direct tangible damages (Handmer, Reed and Percovich, 2002).

5.5 Intangible damage

Intangible damages were not considered in this study because relevant input data such as information on flooding hotspots or the number of persons at risk was not available. However, we do note that significant flood depths posing a risk to life can occur particularly in the area along the coast and the canal. We suggest that these risks are taken into consideration when developing flood adaptation measures for the catchment.

5.6 Hazard assessment

Flood hazard was simulated in the 1D-2D hydrodynamic model MIKE FLOOD using a surface grid resolution of 10m. Pipe and elevation data for the hydraulic model were provided by the City of Port Philip and Melbourne Water. Flood risk in the catchment is both pluvial and coastal. The hazard model thus considers rainfall as input to the 1D model of the pipe network, while sea water level is considered as a boundary condition for the 2D model as well as at the outlets from the pipe network.

To illustrate the application of the damage assessment framework, we performed hydraulic simulations for three different events:

A. 69 mm rainfall over a duration of 4.5 hours, 0.0 m sea level

B. 29 mm rainfall over a duration of 4.5 hours, 1.9 m sea level

C. 0 mm rainfall over a duration of 4.5 hours, 2.1 m sea level

According to an analysis of extreme rainfall and sea level in the catchment using annual maximum series (Nobre, 2015), and assuming changes of rainfall and sea level as foreseen by (CSIRO and Bureau of Meteorology, 2015) for climate change scenario RCP4.5, these events would approximately have a return period of 100 years in 2090.

Figure 14 to Figure 16 illustrate flood extents for the considered events. Clearly, events B and C cause flooding in the coastal areas downstream, while the intense rainfall in event A causes widespread flooding over the catchment.
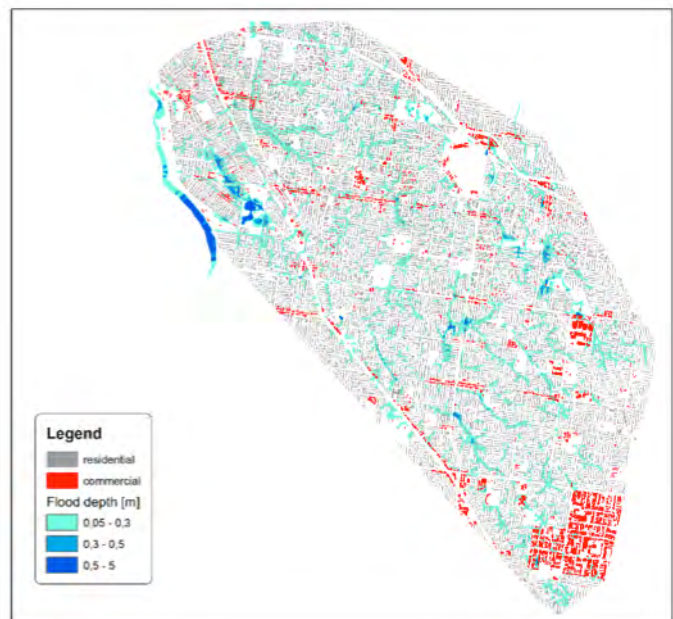

Figure 14: Landuse and flood area for event A. Total rainfall was 69 mm in 4.5 hours and sea level was assumed to be 0 m.
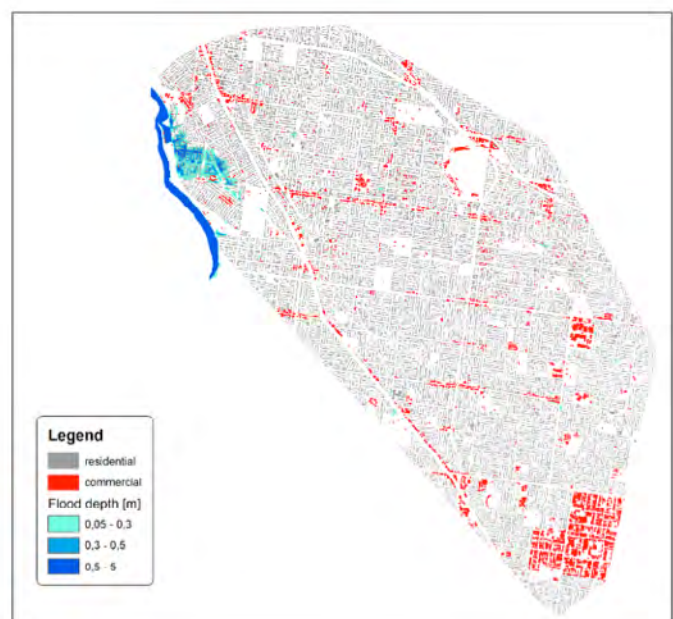

Figure 15: Landuse and flood area for event B. Total rainfall was 29 mm in 4.5 hours and sea level was assumed to be 1.9 m.

5.7 Flood damage assessment

Considering the damage functions described in the previous chapters, we obtain the direct, tangible flood damages shown in Table 6 for the three considered events. The following key points should be noticed:

- The majority of damages occurs in residential properties, as the catchment is dominated by residential properties.
- Damages caused by rainfall are of similar dimension as those caused by coastal flooding with the same return period. Pluvial flooding leads to larger damages on commercial properties, as it affects commercial properties in upstream areas.
- For the considered events, pluvial flooding occurs with smaller depths than coastal flooding. Similar numbers of flooded buildings thus lead to smaller flood damages.

Figure 17 to Figure 19 show how flood damage is distributed in the catchment for the different events. For this purpose, we divided the catchment into cells of 500 by 500 m and aggregated the damages within each cell. Flood damages are spread somewhat evenly throughout the catchment for event A, which is driven by extreme rainfall, while the largely coastal flooding in events B and C leads to pronounced flooding hotspots in Elwood.

Figure 16: Landuse and flood area for event C. Total rainfall was 0 mm in 4.5 hours and sea level was assumed to be 2.1 m.

Table 6: Direct tangible and intangible damage estimates for the considered events divided into the three damage types.

Damage	Residential	Commercial	Road	Total	Total incl. intangible (+30%)
A - 69 mm rainfall, 0.0 m sea level					
AUD	297.5 M	102.2 M	0.4 M	**400.2 M**	**520.2 M**
Flooded objects	5903 buildings	1552 buildings	119,900 m2	-	-
B - 29mm rainfall, 1.9 m sea level					
AUD	60.5 M	10.9 M	0.3 M	**71.8 M**	**93.4 M**
Flooded objects	970 buildings	113 buildings	90,500 m²	-	-
C - 0mm rainfall, 2.1 m sea level					
AUD	87.7 M	5.5 M	0.6 M	**93.8 M**	**121.9 M**
Flooded objects	1186 buildings	54 buildings	158,500 m²	-	-

Figure 17: Total flood damage accumulated over areas of 500x500m for event A

Figure 18: Total flood damage accumulated over areas of 500 x 500 m for event B.

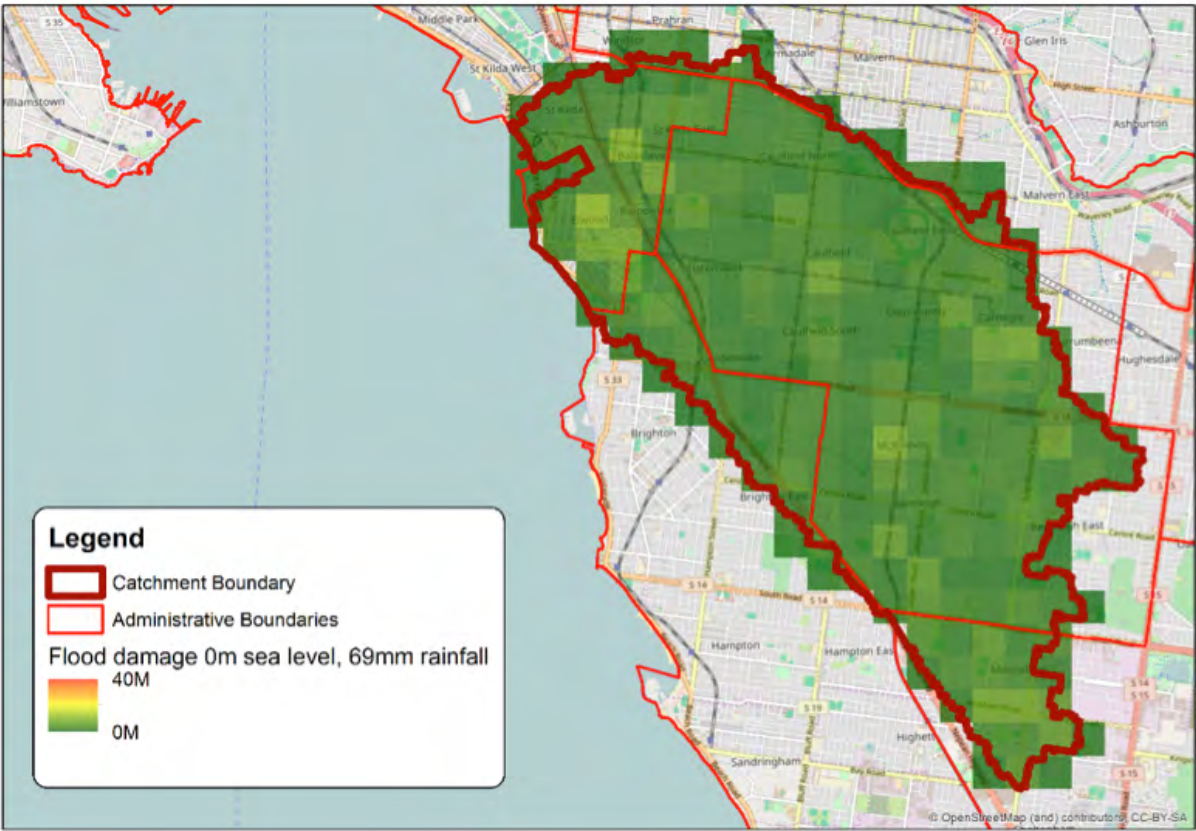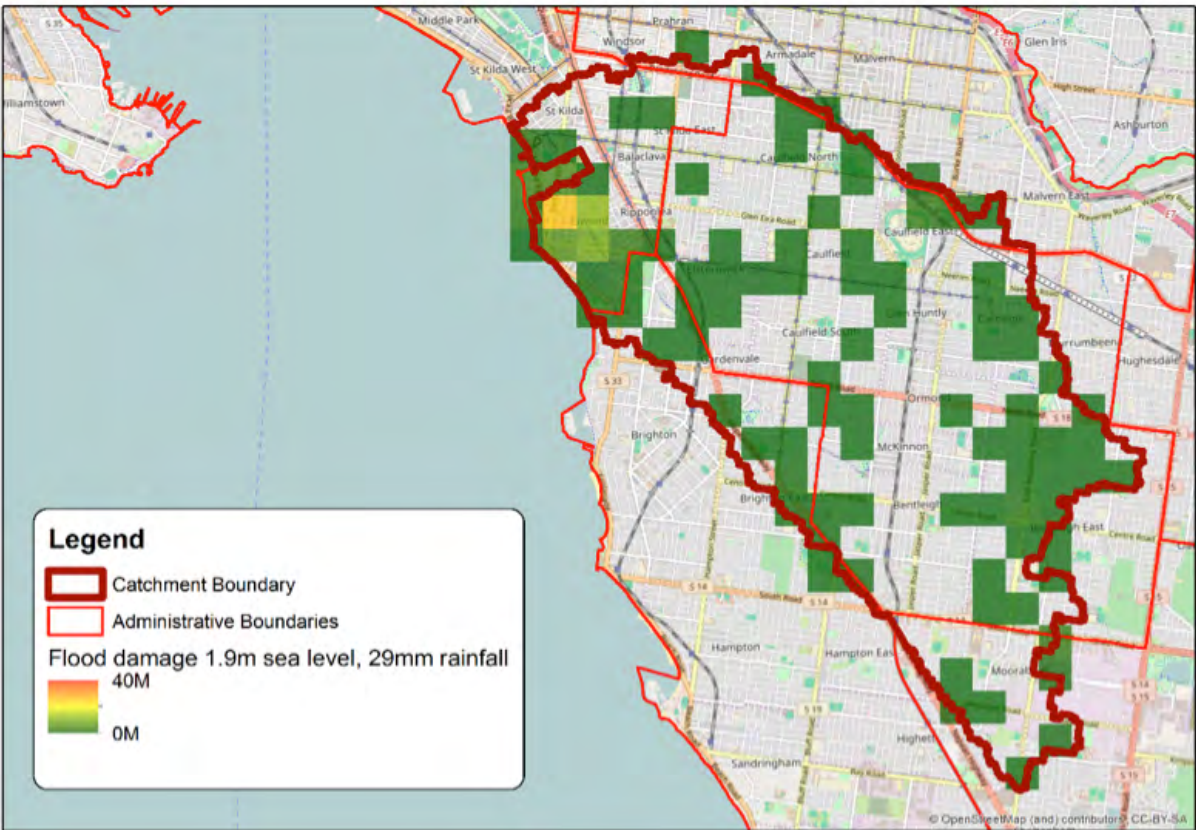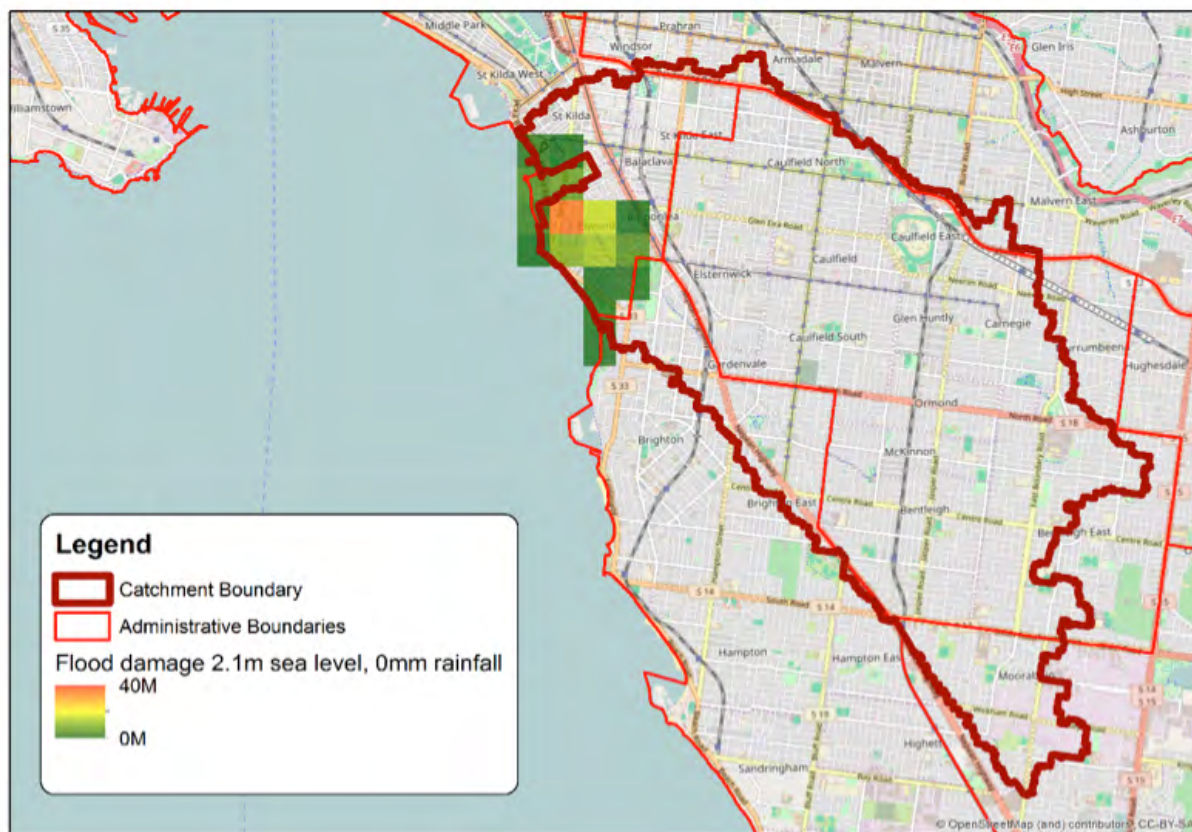*Figure 19: Total flood damage accumulated over areas of 500 x 500 m for event C.*

Conclusions regarding vulnerability and risk for Elster Creek

The damage assessment is based on a detailed 1D-2D hydraulic modelling approach and simple damage curves mainly coming from previous Australian studies. Only direct tangible and intangible damages can be assessed based on the available information. We draw the following conclusions for this case study:

- Significant flood risks are present in the catchment. Coastal and pluvial flood risk appear to be of comparable magnitude. However, coastal risk is concentrated in Elwood in the downstream part of the catchment, while pluvial flood risk is somewhat equally distributed throughout the catchment.

- The distribution of pluvial flood risk all over the catchment suggests that adaptation measures tackling this issue should be developed in a catchment-wide effort, focusing on local retention, reduction and slowing of runoff and urban planning policies. Pipe modifications that improve the drainage of upstream areas are likely to increase flood risk in the downstream part of the catchment. Similarly, it is unlikely that the City of Port Philip can significantly reduce pluvial flood risk without the support of other city councils.

- The mitigation of coastal flood risk is likely to require major investments into infrastructures such as gates, pumping stations, large retention areas and / or dikes.

- Interpretation of how rapid developments on the real estate market impact damage estimates are very important for this case study. In particular, strong spatial variations in housing prices could lead to a neglect of less wealthy areas when designing flood adaptation measures.

- Simulated flood damages increase strongly for rainfalls slightly larger than the 52 mm considered in this study (not shown), making damage estimates for future scenarios under climate change rather uncertain. This needs to be considered in the design of flood adaptation measures, because the rainfall projections identified by CSIRO are rather low compared to other projections available in the scientific literature.

- The hydraulic model applied for flood hazard assessment in this study was developed based on pipe network data containing numerous gaps and inconsistent information. The results provided here do need to be considered carefully. The design of flood adaptation measures should be preceded by comprehensive data collection and the development of more reliable models through consultants. Such efforts can usually be justified by reduced planning uncertainty leading to smaller risks of failing investments into infrastructure.

6. Conclusion

We have studied the scientific and practical literature from Australia, the United Kingdom, Germany and Denmark to identify which approaches can currently be considered state of the art for flood damage assessment. A wide variety of approaches exists. These largely distinguish themselves in the level of detail applied for the damage assessment and in the number of damage classes considered. We come to the following conclusions:

- Flood damage assessment in an urban planning context should usually be made on a financial rather than an economic basis, i.e. losses suffered by individuals in the catchment should not be offset by gains in other locations. Our argument for this recommendation is that the objective of city planners is usually to minimize losses to local stakeholders through the design of flood adaptation. A different perspective may be applied when, for example, a state or national government allocates budgets for flood adaptation.

- Large efforts for assessing the vulnerability of urban areas to flooding were made in the United Kingdom and in Germany. Work in the UK has focused on developing synthetic databases that describe the potential damage caused by flooding of different property types in high level of detail, while German research has focused on empirical assessment of flood damages, largely using telephone interviews, and subsequent development of approaches to assess vulnerability based on these data. In both cases, data are not easily accessible and need to either be purchased on a subscription basis or obtained through personal agreement.

- Australian studies have applied a variety of approaches. However, in particular RAM and ANUFLOOD have been and are applied in a large number of studies. These approaches have been criticized because they were developed on a very limited data basis and have not been updated for a long period. Nevertheless, they are the most easily accessible means to assess vulnerability to flood damages in an Australian context.

- The level of detail applied in assessing vulnerability to flood damages needs to be decided based on the available data basis, the applied modelling approach and the type of flooding. Unit cost approaches were found to yield acceptable results in Danish studies where pluvial flooding was dominant, while detailed property databases in the UK allow for very detailed assessments. Such approaches should only be applied in conjunction with detailed modelling approaches, such as 1D-2D hydraulic modelling in high resolution. We could not identify any studies that assessed whether damage assessments in high detail actually help to reduce the uncertainty of flood damage assessments.

- All considered studies have as a minimum considered direct tangible damages. This damage class can be assessed with the least uncertainty. Direct intangible damages have been considered in a number of studies and can be easily included in the damage assessment using, for example, percentage estimates based on experience. The quantification of this damage class is subject to significantly larger uncertainties and it is a topic of on-going research. Intangible damages should be included in the damage assessment if there is a significant risk for loss of life or health impacts due to, for example, dike breaches or steep topographies, or if the study area contains properties of particular importance, such as cultural heritage. The quantification of damages in this class in monetary terms is difficult because input data for a reliable assessment are usually not available and because ethical considerations need to be made. Multi-criteria assessments are an attractive solution for this dilemma.

- Care needs to be taken when applying stage-depth damage curves that define potential flood damages based on housing prices. Rapid developments on the real estate market can lead to very unrealistic damage estimates.

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8. Appendix

8.1 Correction factors for inflation adjustment to 2015 prices

Table 7: Inflation rates of the currencies DKK, Euro, English pound and Australian dollars, together with the conversion to Euros obtained in April 2016 (Bank of England, 2016; Danmarks statistik, 2016; Reserve Bank of Australia, 2016; Triami Media BV, 2016)

Year	Denmark	Germany	England	Australia
2014	1.00	1.00	1.00	1.02
2013	1.01	1.01	1.03	1.04
2012	1.02	1.03	1.07	1.07
2011	1.04	1.05	1.10	1.08
2010	1.07	1.07	1.16	1.12
2009	1.10	1.08	1.21	1.15
2008	1.11	1.08	1.20	1.17
2007	1.15	1.11	1.25	1.22
2006	1.17	1.14	1.31	1.25
2005	1.19	1.16	1.35	1.30
2004	1.21	1.17	1.38	1.33
2003	1.23	1.19	1.43	1.36
2002	1.25	1.21	1.47	1.40
2001	1.28	1.22	1.49	1.44
2000	1.31	1.25	1.52	1.51
Euro conversion	0.134	1	1.257	0.683

8.2 Damage Cost Applied in Australian Studies

Table 8. Overview of damage cost recommended by the Disaster Loss Assessment Guidelines (Handmer, Reed and Percovich, 2002)

Direct tangible damage						Indirect tangible damage		Direct intangible damage		Reduction factors	
Buildings		Roads per km of road inundated [EUR/km]		Agriculture [EUR/per livestock]		Transport disruption per vehicle hour [EUR/hr]		Health [EUR/person]		Warnings [multiplying factor]	
Nonresidential buildings > 1000 m² [EUR/m²]		Major sealed roads		Dairy		Car - non business	12	Death	1243060	Less than 2 hours	
Low (officies, sporting pavilions, churches)	43	Initial repairs	30598	High	622	Car business	30	serious injury	303115	Experienced community	0.8
Medium (libraries, clothing business, caravan parks)	76	subsequent accelerated deterioration of roads	15299	Average	535	Bus or truck	23	minor injury	10136	Inexperienced community	0.9
High (electronics, printing)	191	Initial bridge repair and subsequent increased maintenance	10518	low	440	Articulated truck	27			2-12 hours	
Other buildings [EUR/unit]		Total cost to be applied	56415	Beef						Experienced community	0.8-0.4
residential building	19602	Minor sealed roads		High	459					Inexperienced community	0.8-0.4
Public building	19602	Initial repairs	9562	Average	392					Greater than 12 hours	
		subsequent accelerated deterioration of roads	4781	low	325					Experienced community	0.4
		Initial bridge repair and subsequent increased maintenance	3346	Sheep for wool						Inexperienced community	0.7
		Total cost to be applied per km of road inundated	17689	High	32						
		Unsealed roads		Average	26						
		Initial repairs	4303	low	22						
		subsequent accelerated deterioration of roads	2151	Sheep for lamb							
		Initial bridge repair and subsequent increased maintenance	1530	High	48						
		Total cost to be applied per km of road inundated	7984	Average	43						
				low	33						

8.3 Damage cost applied in Danish case studies

Table 9: Unit damage cost applied in Danish studies

	Direct tangible damage								Indirect tangible damage		Direct intangible damage	
Study	Building damage		Road damage costs		Other direct tangible costs		Agriculture damage costs					
(Olsen et al., 2015)	Residential [EUR/unit]	13500	Road [EUR/unit]	6750	Manhole [EUR/unit]	1350					Water pollution [EUR/unit]	67400
	Commercial [EUR/unit]	71150										
	Public institution [EUR/unit]	62150										
(COWI, 2014)	Basement [EUR/unit]	509										
	first floor [EUR/unit]	1107										
	Business [EUR/unit]	28140										
	Production loss [EUR/unit]	21440										
	Business content [EUR/unit]	18090										
(Arnbjerg-Nielsen et al., 2007)	Basement [EUR/unit]	3853	Road [EUR/unit]	154100	well damage [EUR/unit]	4623			Traffic interruptions (EUR/person/hr)	20	People becoming ill [EUR/person]	1110
	Ground floor [EUR/unit]	77050			pump stations [EUR/unit]	154100			Electric supply [EUR/number of households]	259	People in risk of disease [EUR/person]	374
	Food warehouse [EUR/unit]	29279			transformer stations [EUR/unit]	154100			Municipal administration work [EUR/hr]	46		
	Other Warehouse [EUR/unit]	60870										
	Basement [EUR/m²]	71	Infrastructure [EUR/m²]				Beef [EUR/unit]	363	Production loss [EUR/unit]	22248	Noise	
	First floor [EUR/m²]	154	clean-up	0.4			Pig [EUR/unit]	129	Delayed time [EUR/hr]	24	Nature (municipalities)	
	Business [EUR/m²]	29201	rebuilding	395			Crops [EUR/ha]	420	Extra driving time [EUR/hr]	36	Carbon storage	
	Business content [EUR/m²]	18772	traffic interruption	36					Electric down break [EUR/unit]		Water savings	
									Private	276		
									Public institution	829		
									Industry	829		

Study	Building damage		Road damage costs		Other direct tangible costs		Agriculture damage costs		Indirect tangible damage		Direct intangible damage	
Smørumnedre, Egedal 2016 (DHI, 2015)	Residential [EUR/m²]	80					Agriculture [EUR/m²]	0.27				
	Industry [EUR/m²]	134										
	Public real estate [EUR/m²]	402										
	Vacation houses [EUR/m²]	54										
	Cultural and listed buildings [EUR/m²]	1340										
	Waste deposits [EUR/m²]	13										
Skabelon til klimatilpasning (Region Midtjylland, 2013)	Residential [EUR/m²]	75	Highway [EUR/m²]	5.6			Agriculture high yield [EUR/m²]	0.08				
	Industry and trade [EUR/m²]	125	Other road [EUR/m²]	1.3			Agriculture medium yield [EUR/m²]	0.07				
	Public real estate [EUR/m²]	376	Railway [EUR/m²]	11			Agriculture low yield [EUR/m²]	0.04				
	Vacation houses [EUR/m²]	50										
	Cultural and listed buildings [EUR/m²]	1252										
	waste deposit [EUR/m²]	13										
	Cemetery [EUR/m²]	13										
	Prehistoric momentums [EUR/m²]	376										
(Zhou, 2012)	House [EUR/unit]	68340	Road [EUR/unit]	136680	Manholes [EUR/unit]	4100			Administration costs [EUR/hr]	41	Health [EUR/person]	941
	Basement [EUR/unit]	3417							Traffic delays [EUR/hr]	17	Lakes [EUR/unit]	68340

Study	Direct tangible damage								Indirect tangible damage		Direct intangible damage	
	Building damage		Road damage costs		Other direct tangible costs		Agriculture damage costs					
Klimatilpasnings plan 2014 baggrunds rapport (VandCenterSyd, 2014)	House [EUR/m²]	203	freeway	338	inner city	5000	Agriculture	0.17				
	Multiple storage house [EUR/m²]	203	Road <3m and recreational areas [EUR/m²]	14			Agriculture (grass) [EUR/m²]	0.17				
	Dorm [EUR/m²]	189	Road >3 m [EUR/m²]	68			Forrest [EUR/m²]	0.09				
	Basement [EUR/m²]	68	Railway [EUR/m²]	338			Nature [EUR/m²]	0.01				
	Industry with agriculture [EUR/m²]	203					§3 protected nature [EUR/m²]	0.01				
	Industry with production [EUR/m²]	677					inner city [EUR/m²]	677				
	Electrical, water, waste-plants [EUR/m²]	338										
	Office, trade, public [EUR/m2]	135										
	Transport building [EUR/m²]	271										
	Service business [EUR/m²]	203										
	other building for trade	338										
	School [EUR/m²]	203										
	Hospital [EUR/m²]	338										
	Public institutions [EUR/m²]	203										
	Garage [EUR/m²]	34										

Table 10. Stage depth damage curves applied in Danish case studies

Study	Inundation depth [cm]	10	20	30	40	50	60	70
(Halsnæs and Kaspersen, 2014)	Service and industry [EUR/unit]	70462	140925	211387	281849	352312	422774	493236
	Multiple storage buildings [EUR/unit]	46247	92494	138741	184988	231234	277481	323728
	Houses [EUR/unit]	16918	33835	50753	67670	84588	101505	118423
	Vacation houses [EUR/unit]	846	1692	2538	3384	4229	5075	5921
	Monuments [EUR/unit]	33835	67670	101505	135340	169175	203010	236845
	Churches [EUR/unit]	338350	676700	1015050	1353400	1691750	2030100	2368450
	Listed buildings [EUR/unit]	33835	67670	101505	135340	169175	203010	236845
	Statues and sculptures [EUR/unit]	33835	67670	101505	135340	169175	203010	236845
	Museums [EUR/unit]	33835	67670	101505	135340	169175	203010	236845
	Aquatic environment [EUR/unit]	125000	250000	375000	500000	625000	750000	875000
	Inundation depth [cm]	2,5	5	10	15	20	30	50
	Basement [EUR/m2]	9	18	36	54	72	107	179
	Road [EUR/m2]	9	18	36	54	72	107	179
	Railway [EUR/m2]	45	89	179	268	358	536	894
	Inundation depth [cm]	0.15	0.30	1	5	10	20	50
	Health [EUR/person]	11	22	73	366	733	1466	3664
(DHI, 2015)	Inundation depth [cm]	0.2-20	20-40	>40				
	Residential	0	335	837.5				
	Residential with basement	67	335	837.5				
	Public	0	670	1675				
	Public with basement	134	670	1675				

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