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Assessment of the effectiveness of a risk-reduction measure on pluvial flooding and economic loss in Eindhoven, The Netherlands

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Abstract

Cities are increasingly assessing and reducing pluvial flood risk. Quantitative assessment of the effectiveness of risk-reduction measures is required. We use hydraulic simulation with GIS-based financial analysis to assess the pluvial flood risk for Eindhoven, The Netherlands. Analysis is carried out for four scenarios: two rainfall events, with and without separation of the combined sewer-stormwater network. Flooding statistics show how the risk-reduction measure impacts local flooding. Financial analysis demonstrates the saving resulting from the risk-reduction measure. Expected annual damage is reduced by c. €130,500. City authorities are better equipped in making cost-benefit decisions regarding implementation of pluvial flood risk-reduction measures.

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Keywords: Economic impact, flood damage, risk assessment, risk reduction measures, urban flooding.

1. Introduction

Many cities throughout Europe are currently facing surface water (pluvial) flooding problems that derive from rainfall events causing surcharging of sewer-stormwater networks. It is expected that such surcharging will become more frequent throughout Europe in response to climate change and urbanisation (IPCC, 2007; Parry et al., 2007;

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Madsen et al., 2009; Mailhot and Duchesne, 2010). Potential reasons for more frequent inundation events can include outdated sewer-storm water systems and increasing urban area extent (less water infiltrates and larger urban populations are putting more stress on the sewer-stormwater networks). Climate change is expected to increase the frequency and intensity of rainfall events. This means that more water may fall in a given time period, potentially leading to more frequent inundation events, and potentially more flooding damage. Social changes may also have an impact. As nations develop, water use per-capita tends to increase, especially for lower income and developing countries, as home ownership of appliances such as washing machines and high flow-rate showers increases, although the increase in per-capita demand tends to flatten as nations get richer (Duarte et al., 2013). Consequently, although not directly significant in terms of flood volume, decreasing waste water flow through the separation of waste and storm water sewage networks, can be considered as a risk reduction measure, especially taking into account secondary health implications

The financial implications of more frequent pluvial flood events can be significant. It is estimated that the average annual financial cost to Japan as a result of flooding from heavy rainfall is up to $US 10 billion, even with a 50-year return period level of protection (Kazama et al., 2009). Similarly, Stern (2006) states that for the UK, damage from 'flood losses' (pluvial flooding is not considered as an individual threat) is currently c. 0.1% of UK gross domestic product (GDP). Indirect impacts of pluvial flooding also need to be considered. Examples of such impacts include lost working hours due to traffic infrastructure disruption (e.g. Saurez et al., 2005) and health impacts to affected residents, particularly if sewer water flows onto streets, especially in the case of combined sewers, or if pluvial flood water stands stagnant for a long period of time (Kolsky, 1998). Mental health due to stress in the event of flooding can also be affected (Fewtrell and Kay, 2008; Tapsell and Tunstall, 2008), potentially impacting on productivity. More seriously are deaths resulting from flooding incidents, although at the moment relatively little is known about loss of life due to floods.

Recently however, there has been a drive across Europe to reduce pluvial flooding situation in urban areas. There are many methods currently being considered including, but not limited to: the use of water retention basins (e.g. Robinson et al., 2010), the use of green roofs (Stovin et al., 2012), and encouraging water saving and recycling activities. Many of these measures fall under the term 'sustainable urban drainage systems' (SUDS; CIRIA, 2007, and see Stovin et al. (2012) for a brief introduction. Note that SUDS is a European term. In the US it is known as Low Impact Development, while in Australia it is known as Water Sensitive Urban Design). A measure that is being considered more frequently is to disconnect the storm water network from the sewer network (Semadeni-Davies et al., 2008). This improves both the sewer and storm water capacities, and reduces potentially detrimental health impacts when flooding does occur. Many of these pluvial flooding risk reduction measures are being written into 'best practice' guides in numerous European countries (e.g. CIRIA, 2007).

Eindhoven, The Netherlands (Figure 1), is similar to many modern European cities. Gradual expansion on the surface (i.e. urban creep) has not been accompanied by suitable expansion and upgrades of the sewer and storm water networks. The current storage capacity of the Eindhoven network with respect to storing excess rainfall is only c. 10 mm. In addition, much of the current network dates from the 1920s-1970s, and is in the form of a combined sewer-storm flow network. As the city has expanded, the current network has become unsuitable, leading to more frequent surface water flooding generated from rainfall. This has led to rising financial implications because not only are properties flooded more frequently, but more properties are flooded for a given return-period flood event. As a result, various options are currently being investigated in Eindhoven in an attempt to reduce the extent and depth of pluvial flooding due to rainfall events and as a consequence, to reduce the overall financial loss resulting from properties being flooded. This paper presents the quantitative assessment of the effectiveness of a specific measure (decoupling of the sewer and storm networks) on flood risk reduction for Eindhoven. A hydraulic simulation model is used, coupled with GIS-based financial loss analysis to simulate the pluvial flood risk for the city of Eindhoven, with and without the introduction of a specific risk reduction measure. The paper presents the development of the model, as collaboration between the city of Eindhoven and the academia, as part of an ongoing FP7 EU research project (PREPARED, enabling change, www.prepared-fp7.eu).

2. Case study development

This work, undertaken as part of the PREPARED EC FP7 research project, is a collaborative effort between researchers at the University of Exeter (UK), IWW (Germany) and, critically, Eindhoven Municipality (The Netherlands). Thus, local stakeholders and experts have been involved from the beginning, helping to define the direction of the research so that the results would be more beneficial to them, within the wider remit of assessing and proposing risk-reduction measures for pluvial flood events. Local experts in Eindhoven provided information with regard to data availability, and what could reasonably be expected. They also defined the rainfall events of most interest to city planners (Section 3). Colleagues in Eindhoven also suggested the use of the existing in-house hydraulic model to give the on-street flooding results. This approach was suggested for a number of reasons: i) the model already existed, and therefore meant reduced workload for colleagues in Eindhoven (the partner is a municipality, not a research institute, so cannot dedicate as much time to the work); ii) the model could be easily adapted to include proposed risk-reduction measures; iii) the data were readily available and; iv) the results would have direct importance for city planners. Eindhoven colleagues then defined possible and realistic risk-reduction measures to assess, again based on current proposals for reducing the pluvial flood risk in certain parts of the city. At the moment, only 15% of Eindhoven has separate sewer-stormwater networks. This work will also help define the effectiveness of new upgrades, and may help target the location of these upgrades. Finally, it was agreed that a financial analysis would be most beneficial as this allows for easier cost-benefit analysis of options for city officials. This direct financial analysis is one of the key benefits from this research, which also offers a method to be followed by the city for the quantitative evaluation of alternate/modified measures for risk reduction..

In addition to the above, a pre-requisite of PREPARED is to develop, in partnership with 'demonstration cities' (including city officials and water companies), methods and applications to assess risk-reduction measures. Therefore, out approach not only satisfies the needs of the city, but also the requirements of the project, i.e., the use of existing models, the active participation of the local stakeholders, and the demonstration of a methodological approach, which would be applicable to other similar case studies. The next sections describe in more detail the approach adopted, and present some results.

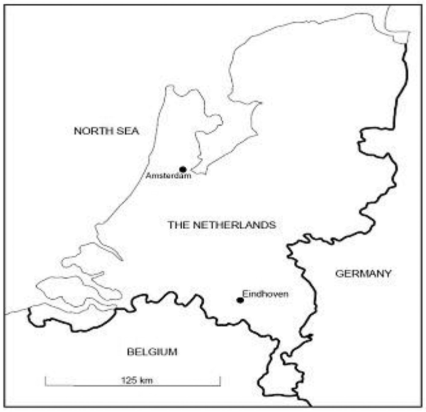


Fig. 1: Map showing the location of Eindhoven in The Netherlands.

3. Quantitative risk assessment

The main overall aim of the research is to provide improved quantitative risk assessment of the current situation for Eindhoven in the event of pluvial flooding, and for hypothetical futures as set-out in the scenarios, which were developed by the municipality (Section 3.2). Here, the 'quantitative' element is the estimation of financial loss resulting from pluvial flood events with and without (i.e. baseline) risk-reduction measures, which were also defined by Eindhoven. Section 4 deals with the financial loss aspect of this work. For this risk assessment, here, 'risk' is taken to mean the product of some likelihood and an impact. In this sense, likelihood is equivalent to the return period of the rainfall event being simulated (Section 3.1), and the impact is the financial loss (Section 4). Therefore, the expected annual damage (EAD) may be estimated (Woodward et al., 2013). With this in mind, the next sections outline the hydraulic modelling method, the GIS analysis and the financial loss calculations.

3.1. Hydraulic modelling

The, hydraulic modelling results presented in this paper refer to two return-periods (T) in Eindhoven (T=2 years and T=10 years - these are of interest to Eindhoven city planners) and to two scenarios: current day (baseline) and a scenario where the sewer and storm water networks are separated. The latter reflects the most favoured and feasible measure by the city of Eindhoven, in order to reduce flood risk. Geographical Information System (GIS) analysis is used to examine the areas flooded, flood depth statistics, and to estimate the number of properties exposed to pluvial flooding under each model simulation. From this, estimates of financial loss for each scenario are carried out. The hydraulic model simulations were carried out using the Sobek software (Deltares, 2013), with the entire Eindhoven sewer system represented within the model. The baseline model represents the 2012 sewer system without any alterations imposed (i.e. present-day configuration). In order to model surface water flows, streets are modelled as pipes in the software so as to create a good approximation of the flow system. Surcharging water is routed onto the 'streets' were it is allowed to spread according to model rules.

The baseline model was then modified to include a hypothetical risk reduction scenario: the combined sewer-stormwater system is separated (see Section 3.2).

System water levels are calculated in sewer well nodes within the model. To translate these results to GIS format, Thiessen polygons (also known as Voroni polygons, Okabe et al. (2000)) are used to create a map with the calculated water levels spread over an area. Although this method is not ideal, and does not approach the accuracy of fully coupled 1D-2D models (Leandro et al., 2011; Chen et al., 2012), it gives a reasonable representation of where flooding occurs in Eindhoven and to what depth flooding can be expected on city streets. Since off-line estimation of flood damage was the scope of the simulations, and not a more demanding (in terms of hydraulics) application (e.g. real time warning system), the accuracy achieved by this model was sufficient for the purpose of the risk reduction model developed here.

3.2. Model scenarios

For this study, four analyses were carried out. The first scenario consists of modelling pluvial flooding from the current (baseline) sewer and stormwater network conditions under the 2 and 10-year return period rainfall events as described in the Dutch guidelines for sewage design (Figure 2; Rioned, 2004). These rainfall profiles were imposed on the hydraulic model which then calculated where and to what extent the combined sewer-stormwater system surcharged to the streets. Where this occurred, water was routed over the streets according to the method described in Section 2.1.

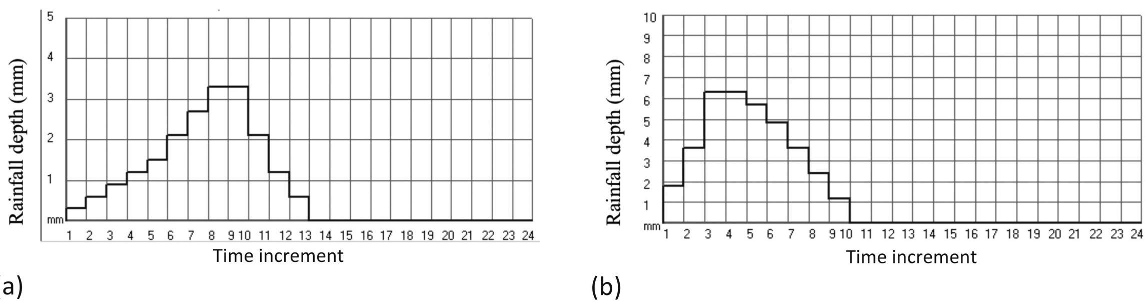


Fig. 2: Hyetographs for (a) the 2-year return period and (b) the 10-year return period event. Time increments on the x-axis are in 5-min intervals.

In addition to modelling pluvial flooding under the two return periods for the baseline scenario, two other model simulations were also carried out: implementing a risk reduction measure for both return periods. The particular measure is the separation (uncoupling) of the sewer and storm water networks. At present, most of the Eindhoven network is a combined sewer-storm water network. There is currently a drive in many countries to separate these two systems, and Eindhoven is no different. In fact, some of the city has already been separated, and the city is expanding the uncoupling process. In the model simulations, the two networks were hypothetically separated in two of the city zones - zones 612 and 615 (see Figure 3), and the impact on pluvial flooding assessed. As a result, the impact of the disconnection decreases with increasing distance from the disconnection. The rationale for this is that the focus for Eindhoven is re-opening of the river Gender, and therefore the 'zone of influence' (i.e. floodplain) of the Gender was used to inform those areas most likely to benefit from disconnection of the sewer-stormwater network.

These results could have direct consequences for pluvial risk reduction decision making in Eindhoven. Table 1 summarises the simulations that were carried out.

Table 1: Summary of the pluvial flooding simulations undertaken. T is the return period simulated..

Scenario number	Scenario description
1a	T=2 baseline scenario
1b	T=2 disconnection of sewer and stormwater networks
2a	T=10 baseline scenario
2b	T=10 disconnection of sewer and stormwater networks

4. GIS analysis and results

The results from the pluvial flooding model simulations were exported to GIS format (both vector and raster datasets were used) and analysed for a range of flooding statistics. The Eindhoven study area was divided into 109 city zones (Figure 3) to improve the resolution of results and to make to results more relevant to the Municipality. The zones were delineated by the city of Eindhoven, and represent administrative boroughs or districts within the city.

For each simulation and each city zone, the following statistics are presented from the hydraulic flood model results: average on-street pluvial flood depth (m); maximum on-street pluvial flood depth (m); average depth of flooding for depths > 0.2 m; area flooded (% of zone); number of properties affected (% in zone). The analyses were carried out using ArcMap Version 9.3.1. For the average on-street flooding depth, statistics were only calculated on model results with depths greater than 0 m. It is noted that damage to cellars is not included in this analysis, therefore estimates of loss should be considered to be minimum values. Model depths less than 0 m imply that the sewer-storm water network did not surcharge. Average and maximum flood depths were calculated using the ArcMap 'zonal statistics' function from a raster dataset. Likewise, flooded area per zone was also only calculated based on results greater than 0 m, and was calculated using the 'calculate geometry' function from a vector dataset. For the number of properties affected per zone, this was calculated from results with depths greater than 0.2 m and a property vector dataset for Eindhoven. It was assumed that due to curbs and house levels being raised slightly from the street or pavement level, water depths less than 0.2 m did not enter properties. Using GIS, an intersect routine was carried out where the property GIS layer was spatially compared with the layer containing flooding results exceeding 0.2 m. Where the two layers intersected, the properties were counted using ArcMap.

Table 2 presents summary results for the percentage of properties flooded and the percent area flooded for a sample of city zones (full results are not presented due to lack of space).

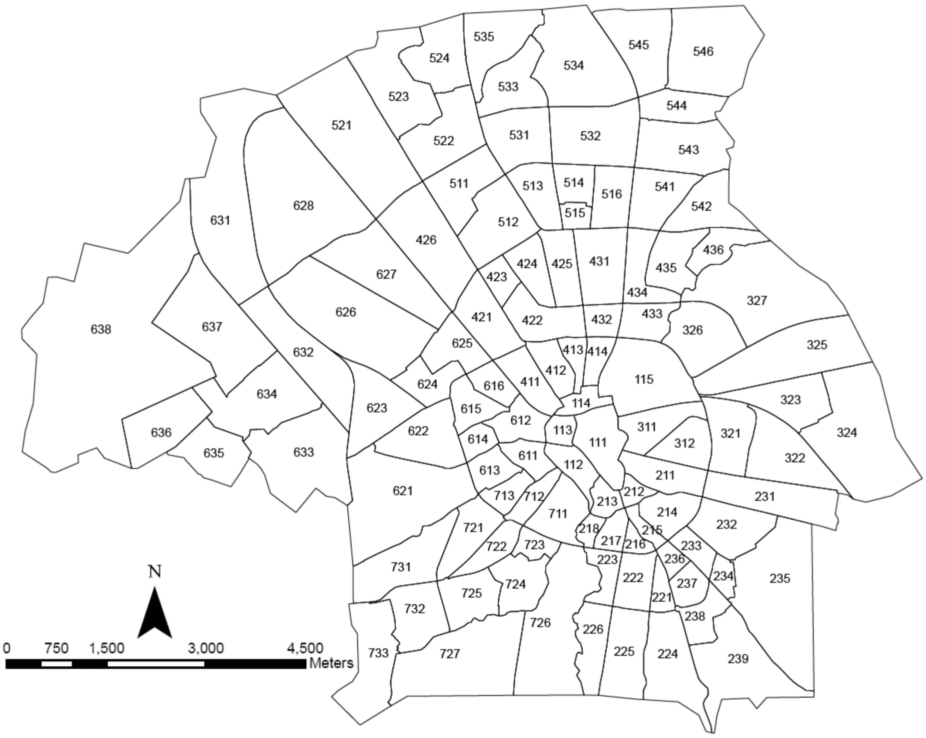


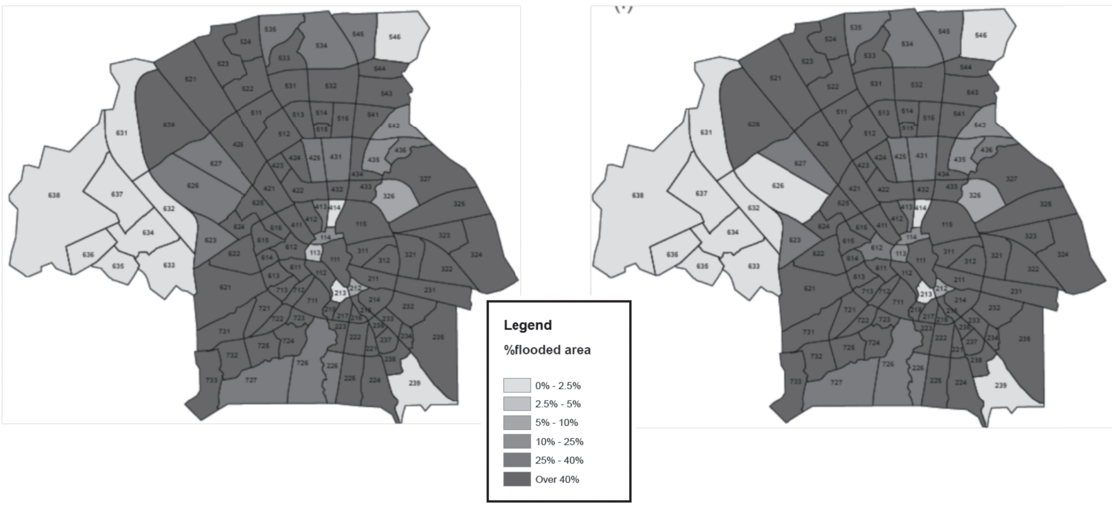
Fig. 3: The Eindhoven city zones analysed.

Table 2: Summary statistics for % flooded buildings and % flooded area in some of the city zones (Figure 3)

			T=2 baseline		T=10 baseline		T=10 disconnection scenario	
Zone number	Total properties	Zone area (km^2)	% properties flooded	% area flooded	% properties flooded	% area flooded	% properties flooded	% area flooded
111	921	0.666	0	4	13	34	13	33
115	149	1.246	0	3	17	28	17	27
612	1440	0.420	2	12	19	53	10	32
615	1274	0.402	1	49	66	90	59	76
616	61	0.298	0	2	18	35	15	31
624	1571	0.446	0	23	64	91	59	91
625	235	0.525	0	0	29	80	28	73

For most city zones, there is negligible change to either the area flooded (Figure 4) or the number of properties flooded for a given return period event and risk reduction scenario (e.g. zones 111-115, Table 2). That is, generally the risk reduction measures have relatively little impact on flooding and property damage. There are also a number of zones that do not get flooded under any scenario.

However, there are some zones where the risk reduction measure does show considerable impact on reducing flooding and property damage. For details of the scenario numbers given in this section, see Table 1. For example, in zone 612 the percent area of flooding is reduced from 53% under the 2a scenario to 32% under the 2b scenario (Table 2). Such reductions have implications for flooded properties. Under the 2a scenario, 19% of properties were flooded, while under the 2b scenario, this reduced to 10%. As another example, in zone 615, for the 2a scenario, 90% of the area was flooded with 66% of properties flooded, while for the 2b scenario, the area flooded is reduced to 76% and number of properties flooded was reduced to 59% (Table 2). So, although the overall figures do not vary considerably for the city as a whole, they are significant for localised flooding, in specific areas.



(a) (b)

Fig. 4: Percentage of city zones flooded for (a) the 10-year baseline and; (b) the 10-year disconnection scenarios

5. Financial loss analysis and results

5.1. Methodology

Most flood risk studies which include damage estimations focus on direct tangible damage. Direct tangible damage commonly means damage to properties and content or other assets at risk in a flooding event. The term tangible is used for all damages being able to be expressed in monetary terms.

To estimate the direct tangible damage commonly depth damage curves are used. Here a function describes the damage (e.g. to properties) in relation to the inundation depth. These functions can express the absolute damage to a building being flooded, or the relative damage expressed in percentage from the original value of the building. Depth-damage functions are often used for flood risk analysis from fluvial flooding, where inundation depths can reach several meters.

Since pluvial flood events hardly ever exceed inundation depths of one meter or more, recent studies use another approach which can be referred to as the threshold method. On the basis of Stone et al. (2013), the threshold approach can be illustrated with the following equations:

$$COST = CV * NUM + BV * NUM \quad if \;\; WD > TH \tag{1}$$

$$COST = 0 \quad if \;\; WD \leq TH \tag{2}$$

Here it is assumed, that a fix amount of damage occurs for each building as soon as water exceeds the threshold. When water level (WD) exceeds the threshold (TH) of a building (e.g. level of doorstep), then the damage costs (COST) is calculated by the sum of the average content damage for a building (CV) multiplied with the number of flooded buildings (NUM) and the average building damage for a building (BV) multiplied with the number of flooded buildings (NUM). So following the concept outlined in Stone et al. (2013) the damage is either a fixed damage value or zero and the assumed damage does not vary by higher inundation depths as it does in the depth damage concept when using depth-damage curves.

The same approach has been used by Zhou et al. (2012) in a Danish case study for pluvial flooding. They assumed a fixed damage amount for each house if flood water reaches the critical threshold of 20 cm (Zhou et al., 2012).

For the damage estimation in this paper the threshold method of Stone et al. (2013) was used. As a reference figure for the average content value damage (CV; € 935) and the average building damage (BV; € 1406), values from Stone et al. (2013), based on a database of the Dutch Association of Insurers have been used here. The 2012 values have been inflated using an annual inflation of 1.7 %. The 2013 values are therefore: for CV € 951 and for BV € 1430.

5.2. Results

Overall a total of 1465 properties are estimated to be flooded by at least 20 cm within the T=2 baseline scenario (1a). Using the threshold method as described above, it can be assumed that property damage reaches € 2.09M and content damage reaches € 1.39M. Thus a T=2 pluvial flood causes a total damage of € 3.48M to Eindhoven's properties and property contents (Table 3).

When using the same calculation scheme on GIS data including the risk reduction measure "disconnection of sewer and stormwater networks" this damage declines. Since a total of 1408 properties are flooded within the T=2 disconnection of sewer and stormwater networks scenario, damage to properties declines to € 2.01M and damage to content declines to € 1.33M. So total damage for the scenario 1b is approximately € 3.35M (Table 3).

The results for scenario 2a and 2b show a greater difference. In the T=10 baseline scenario a total of 37,508 buildings are flooded. Thus damage to properties reaches € 53.6M and damage to content reaches € 35.6M. The total damage for scenario 2a sums up to € 89.2M. In the T=10 disconnection of sewer and stormwater networks scenario 37,181 properties are flooded. So damage to properties can be assumed with € 53.1M and damage to content with € 35.3M. So the total damage assumption for scenario 2b is € 88.5M (Table 3).

To sum up this static damage analysis and risk reduction analysis shows a positive risk reduction by the measure "disconnection of sewer and stormwater networks" for the T=2 scenario and also for the T=10 scenario. This risk reduction amounts to a reduction of damage worth c. € 136,000 for the T=2 and worth c. € 780,000 for the T=10 scenario.

Table 3: Summary of damage analysis results

Scenario		Flooded properties	Damage to properties (€)	Damage to content (€)	Total damage (€)
1a	T=2 baseline	1465	2.09M	1.39M	3.48M
1b	T=2 disconnection	1408	2.01M	1.33M	3.35M
2a	T=10 baseline	37508	53.6M	35.6M	89.2M
2b	T=10 disconnection	37181	53.1M	35.3M	88.5M

In terms of the risk assessment definition given in Section 3, these results are reframed as an expected annual damage (EAD), which is estimated by averaging the individual damages across a number of different events (in this case the different return periods) using weights based on the return periods. This means that the EAD reduction as a result of the risk-reduction measures can also be assessed. For the baseline scenarios, the EAD is €10.66M, while for the disconnection scenarios the EAD is €10.525M, an EAD reduction of c. €130,500.

6. Discussion and Conclusions

Results from this work indicate that while for most Eindhoven city zones there is little impact when pluvial flood risk-reduction measures are implemented, there is considerable impact for some zones (Section 3). While this may not immediately seem like a positive result, when the financial implications are examined, the benefit of such risk-reduction measures becomes apparent. Under the T=2 scenarios, the total reduction in damage (i.e. to buildings and contents) is c. € 136,000, while under the T=10 events, this increases to c. € 780,000. It is noted that this 10-year rainfall event is not modified for climate-change impacts, and it is expected that this event will become more frequent in the future. This is the estimated financial saving expected in Eindhoven for every flood event of these magnitudes when the flooding depth exceeds 0.2 m. Because these potential savings are made for every flood event, and not just once, any cost of implementing the risk-reduction measures will be paid back over time. EAD also reduces by c. €130,500 as a result of implementing the risk-reduction measures.

Therefore, this kind of analysis will allow Eindhoven to choose the most suitable risk-reduction measure in terms of a cost-benefit analysis. However, they can also choose by other metrics such as which measure most effectively decreases the area flooded in any given flood event. This may also have the effect that insurance premiums do not rise so quickly, meaning more people can afford better protection against pluvial flooding.

While the tangible benefits are obvious (Table 3), other impacts of the risk-reduction measures may not be as immediately apparent, buy can be just as important. For example, by reducing the flooded area and depth, it is likely that the time that flood water is standing on the surface is also reduced. This can lead to health benefits, as stagnant, potentially polluted water is not on streets for so long. Less deep water standing for less time may also impact on traffic flows, potentially leading to lower economic losses resulting from people not being able to travel to work for example. By reducing the area and depth of flooding, there will be reductions in post-event clean-up operations, helping the city council to save money. Our results show that while considerable financial savings can be made by implementing risk-reduction measures with respect to pluvial flooding, other non-tangible benefits should also be accounted for and considered when a cost-benefit analysis is carried out.

While this work is a good start, and highlights some of the benefits of carrying out targeted pluvial flood risk assessment and the impacts of implementing risk-reduction measures, there is potential for further research. For example, here we show results only for four scenarios. Future work will add an additional risk reduction measure to each of these return-period simulations, and will add an additional return period, taking the number of scenarios to nine. In addition, the financial loss calculations presented here represent a static analysis. Future work will incorporate a dynamic financial loss analysis to these results. Finally, we will undertake a full cost-benefit analysis with respect to the cost of the risk-reduction measures and the (non-) tangible benefits that they bring to Eindhoven. Moreover a stochastic approach is currently being implementing, introducing uncertainty to the model.

The acceptance of risk-reduction measures by local citizens will also have to be considered. This will then ensure that the work is of direct relevance to Eindhoven, who can use it to make better informed decisions regarding pluvial risk-reduction measures in the city and the planning process for gradual separation of pluvial and waste water sewers. Future work will add a suite of five more scenarios, dynamic financial loss calculations and a full cost-benefit analysis.

7. Acknowledgements

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