Assessing financial loss due to pluvial flooding and the efficacy of risk-reduction measures in the residential property sector

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Abstract

A novel quantitative risk assessment for residential properties at risk of pluvial flooding in Eindhoven, The Netherlands, is presented. A hydraulic model belonging to Eindhoven was forced with low return period rainfall events (2, 5 and 10-year design rainfalls). Three scenarios were analysed for each event: a baseline and two risk-reduction scenarios. GIS analysis identified areas where risk-reduction measures had the greatest impact. Financial loss calculations were carried out using fixed-threshold and probabilistic approaches. Under fixed-threshold assessment, per-event Expected Annual Damage (EAD) reached €38.2m, with reductions of up to €454,000 resulting from risk-reduction measures. Present costs of flooding reach €1.43bn when calculated over a 50-year period. All net-present value figures for the

risk-reduction measures are negative. Probabilistic assessment yielded EAD values up to more than double those of the fixed-threshold analysis which suggested positive net-present value. To the best of our knowledge, the probabilistic method based on the distribution of doorstep heights has never before been introduced for pluvial flood risk assessment. Although this work suggests poor net-present value of risk-reduction measures, indirect impacts of flooding, damage to infrastructure and the potential impacts of climate change were omitted. This work represents a useful first step in helping Eindhoven prepare for future pluvial flooding. The analysis is based on software and tools already available at the municipality, eliminating the need for software upgrading or training. The approach is generally applicable to similar cities.

Keywords: doorstep distribution; financial cost-benefit analysis; pluvial flooding; probabilistic risk assessment.

1. Introduction

Many cities throughout Europe experience pluvial flooding (i.e. from rainfall), which is expected to become more frequent in response to climate and social changes (Parry et al., 2007; Madsen et al., 2009; Mailhot and Duchesne, 2010). Other reasons for frequent inundation include outdated sewer-stormwater systems, greater areas of impervious urban fabric, and larger urban populations. Throughout Europe climate change is expected to increase the frequency and intensity of rainfall events (Schmidli and Frei, 2005; IPCC, 2007; Madsen et al., 2009). As nations develop, water use per-capita tends to increase (Duarte et al. 2013), although in the Netherlands, per-capita use is stagnant (Vewin, 2012). These factors mean that more water enters the sewer-stormwater network, adding stress to the system, increasing the likelihood of pluvial flooding.

The financial implications of pluvial flooding can be significant. It is estimated that the average annual financial cost to Japan as a result of pluvial flooding is up to $US 10bn (Kazama et al., 2009). In the Netherlands, between 1986 and 2009 the total damage from pluvial was €674 million (Spekkers et al. 2012). Indirect impacts are also important. Examples include lost working hours (Suarez et al., 2005) and health impacts on affected residents, which can manifest if sewer water flows onto streets or if pluvial flood water stands stagnant (Kolsky, 1998). Mental health can also be affected (Fewtrell and Kay, 2008; Tapsell and Tunstall, 2008), potentially impacting on productivity and health care sectors.

Recently there has been a drive across Europe to improve pluvial flooding protection. One measure relevant here is disconnection of stormwater and sewer networks (Semadeni-Davies et al., 2008), improving network capacity and reducing detrimental health impacts such as cross-contamination. Another is introducing water retention basins (Robinson et al. 2010) into the urban form. These measures, amongst others, are being written into 'best practice' guides in numerous countries (e.g., see CIRIA, 2007).

This paper presents a quantitative assessment of the effectiveness of two risk-reduction measures on pluvial flooding for Eindhoven using a probabilistic cost-benefit approach. We do this using for the first time (to the best of the authors' knowledge) the probability distribution of household doorstep levels to derive probabilistic damage curves, representing a novel risk-assessment application. A hydraulic simulation model was coupled with Geographical Information System (GIS)-based financial loss analysis to estimate pluvial flood risk for Eindhoven. Risk-based flood assessment using GIS has been carried out for Flanders (Kellens et al. 2013), while cost-benefit based assessment of mitigation measures has also recently been demonstrated (Ballesteros-Canovas et al. 2013). Our work represents an extension of previous approaches, introducing pluvial flooding as the focus and the distribution of doorsteps to generate probability distributions. This paper presents the

development of the analysis framework and details the collaboration between Eindhoven and academia. The paper defines a general framework for pluvial flood risk assessment which is applicable to other locations with similar urban characteristics (e.g. parts of Europe and North America).

2. Methods

2.1 Quantitative risk assessment

For this paper, the 'quantitative' element is the estimation of financial loss from pluvial flooding and the net-present value of risk-reduction. Although there is no single definition for 'risk' (Vatn, 2004), here 'risk' means the product of some likelihood and an impact (Risk = Likelihood * Impact; Kaplan and Garrick, 1981; Moore, 1983). Likelihood is equal to the inverse of the return period of the rainfall events, and the impact is the financial loss. When financial loss estimates are weighted by the rainfall return period and averaged over all simulated rainfall events, the result is an estimate of the Expected Annual Damage (EAD; Stedinger, 1997; Woodward et al., 2013).

2.2 Scenario details and rationale

Nine analyses were carried out (Table 1): three scenarios for three return periods (T) - the 2, 5 and 10 year events. These indicative events with low return periods were chosen because they can be regularly expected in the short-term. Rainfall events with high probability and potentially low damage per-event may sum to considerable damage costs in the long run (Merz et al. 2009). The rainfall return period profiles imposed on the hydraulic model (Section 2.3) were based on current guidelines described in the Dutch national document for sewage design (Figure 1; Rioned, 2004), and are used in Eindhoven for simulating pluvial flooding and sewage design.

The three scenarios are: current day; separation of sewer and stormwater networks in certain parts of the city together with 're-opening' of the River Gender and; separation of the sewer and stormwater networks in certain parts of the city only (Table 1). These measures were chosen by Eindhoven based on engineering decisions that aim to maximise pluvial flood mitigation. Re-opening the Gender a) improves capacity and b) acts as an urban water store. Three further reasons for choosing these scenarios are: 1) the capacity of the existing sewer system is insufficient; 2) re-opening the Gender also aims to improve surface water quality in the municipality and the functioning of the water system; and 3) reduction of combined sewer overflows to the street.

The River Gender (Figure 2) was canalised and became part of the combined sewer network. As development progressed, the river was filled in. The river has a capacity of about $1m^3 s^{-1}$, which is augmented by basin storage in order to reduce peak discharge. In the hydraulic model, the river was hypothetically re-opened, a risk-reduction measure being considered by Eindhoven. At present, most of the Eindhoven network is a combined sewer-stormwater network. About 15% of the network has been separated. In the hydraulic model (Section 2.3), the two networks were separated in city zones 411, 412 and 616 (Figure 2). A total of about 10 km of network was separated within these zones. City authorities believe that these areas would most benefit from separation of the networks.

2.3 Hydraulic Modelling

The hydraulic model simulations were carried out using the Sobek 1D model (Deltares, 2013) and were undertaken by Eindhoven. The baseline model represents the 2012 sewer system without any alterations. To model surface water flows, streets are modelled as un-surcharged pipes so as to reasonably approximate surface water flow. Water surcharging from sewers is

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routed onto the 'streets' where it spreads according to model rules. The baseline was modified to include the two risk reduction scenarios (Table 1, Section 2.2).

Water levels are calculated in Sobek 'manhole' nodes, giving the water level above a datum. To translate these results to GIS format, Thiessen polygons (also known as Voroni polygons, Okabe et al., 2000) were used to create a map where the calculated manhole node water levels were assumed to be the same over a given polygon. Although this method does not approach the accuracy of coupled 1D-2D or 2D flood models (Leandro et al., 2011; Chen et al., 2012), it offers a reasonable representation of where and to what depth flooding can be expected. The method and the results of the model were deemed acceptable by Eindhoven.

2.4 GIS analysis

Hydraulic model results were exported to GIS and analysed for a range of statistics. The study area was divided into 109 zones (Figure 2), representing administrative wards, improving spatial resolution of results and making result interpretation more relevant to the municipality. For each simulation (Table 1) and for each zone, the following statistics were calculated: average on-street pluvial flooding depth (m); maximum on-street flooding depth (m); average depth of flooding where depth > 0.1 m and >0.2 m; area flooded (absolute; % of zone); number of properties affected (absolute; % in zone). Analyses were carried out using ArcMap v9.3.1 (www.esri.com).

Average on-street flooding depth statistics were calculated on model results with depths above street level. Depths < 0 m imply that the sewer-stormwater network did not surcharge. Average and maximum flood depths were calculated using the ArcMap 'zonal statistics' function. For the depth thresholds (0, 0.1 and 0.2 m, Section 2.5), a selection criterion was used to select features with depth greater than the threshold. Flooded area was calculated on model results indicating surface flooding using the 'calculate geometry' function. The number

of properties affected was calculated from the results of flood depths greater than 0 m, 0.1 m and 0.2 m combined with a residential property dataset. An intersect routine was applied where the property layer was spatially compared with the flooding datasets for the thresholds. Where the two layers intersected, the properties were selected and counted for further analysis.

2.5 Fixed-threshold financial loss analysis

Most flood risk studies including damage estimations focus on direct tangible damage. Direct tangible damage commonly means damage to properties and content or other assets. The term tangible is used for damages able to be expressed in monetary terms.

To estimate direct tangible damage from flooding, commonly depth-damage curves are used (Moel and Aerts, 2010) where a function describing the damage in relation to inundation depth is used. Depth-damage functions are often used for flood risk analysis from fluvial flooding, where inundation depths can reach several meters.

Since pluvial flood depths rarely exceed one meter, recent studies use the threshold method (Stone et al. 2013):

$$COST = CV * NUM + BV * NUM \quad if \quad WD > TH \tag{1}$$
$$COST = 0 \quad if \quad WD \leq TH \tag{2}$$

It is assumed that fixed damage occurs for each building when water depth (WD) exceeds the threshold (TH, e.g., level of doorstep), regardless of duration. Damage costs (COST) are calculated from the sum of the average content value damage (CV) multiplied with the number of flooded buildings (NUM) plus the average building value damage (BV) multiplied by NUM.

For the fixed-value analysis, 0.1 and 0.2 m doorstep level threshold values were used to determine the number of flooded properties. The 0.1 m threshold was used after a survey in Rotterdam, The Netherlands, found this to be the average doorstep level (Stone et al., 2013), while the 0.2 m threshold is an assumption that has been used in nearby European locations (Zhou et al., 2012a).

For the damage estimation, values from Stone et al. (2013) have been used. The reference damage values for 2012 have been inflated using an annual inflation of 1.7%. The 2013 values for damage per-property are: €951 for CV and €1,430 for BV.

Damage to cellars is not considered. Only direct damage to buildings and building content is taken into account. No further direct or indirect tangible damages (traffic interruptions, business loss, disruption of electricity etc.) or intangible damages (health impacts) are included.

The expected annual damage (EAD) was estimated:

$$EAD = \sum_{i=1}^{n} (p_i * COST_i) \tag{3}$$

where p is the event probability and n is the number of events. The sum includes the multiplication of probability with the costs for each event i. Rainfall events between the return periods 2, 5 and 10 are neglected, as are events below the lowest return period (2) and above the highest return period (10). Thus the EAD as calculated here is likely an underestimation, but is sufficient to compare the relative costs and benefits of different risk-reduction measures.

2.6 Probabilistic financial loss analysis

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The threshold approach uses single values for the doorstep level (0.1 m and 0.2 m) above which there is damage. Because there is likely to be a distribution of doorstep levels, this assumption is not valid, potentially leading to significant over- or under-estimation of the number of properties affected, and therefore of the EAD and the cost-benefit analysis.

The fixed-threshold analysis is improved by introducing a probability distribution for doorstep levels. In Rotterdam, 4664 doorstep levels were measured as part of the Dutch National Research programme 'Knowledge for Climate' (http://knowledgeforclimate.climateresearchnetherlands.nl/). The measurements were converted to probability and cumulative density functions at 2 cm intervals (PDF and CDF respectively, Figure 3). Lower and upper 95% confidence intervals were estimated on the CDF. Although the measurements are from Rotterdam, they are used as a reasonable approximation for Eindhoven in the absence of better data. Rotterdam and Eindhoven are both relatively recently developed cities (mainly post-1945), are in the same country, and the architectural style is likely to be similar.

The CDF describes the proportion of houses in the sample with doorstep level equal to or less than the level being considered. All properties in the sample have doorstep levels equal to or less than 112 cm. Another way to frame this is that the CDF indicates the probability that a property in the sample will be flooded at a given water depth. For example, with water depth of 14 cm, approximately 61% of properties are expected to flood. With a level of 60 cm that increases to 98% while at a level of 2 cm, it is 12% (Figure 3).

The CDF of doorstep levels is used to create analogous CDFs for the number of properties flooded for a given water depth. For each scenario (Table 1), the number of properties flooded was multiplied by the probability at different flood depths according to the CDF. Damages were calculated along with the EAD for every scenario. EAD is estimated at 2 cm intervals 0

to 170 cm, leading to multiple values for present costs from pluvial flooding, for the benefit resulting from installation of the risk-reduction measures and for the net-present value of the measures (Section 2.7). Decision makers have improved information regarding the likely range of EAD values and their probability, and a more comprehensive cost-benefit analysis.

2.7 Cost-benefit estimations

Cost-benefit estimations were made over a 50-year period starting in 2013 and ending in 2062. This time horizon was chosen because the average lifetime of new sewer channels is at least 50 years (LAWA, 2003; Rioned, 2004). Climate change impacts were not considered as this was out of scope for this work. The net-present value of each risk-reduction scenario is calculated. For each scenario, the damages avoided with risk reduction (benefits) are compared with the present value of costs (for implementation and operation) of the measures to check whether benefits outweigh costs in the long run. To calculate present values, both benefits and costs are discounted. The rationale is that the further in the future costs or benefits occur, the lower the weight assigned to it. This weighting of benefits and costs is achieved by using a discount rate (see Pearce et al., 2006 for details and comprehensive discussion on CBA, discounting and present value calculation).

Benefits (B_t) are the reduction in EAD due to risk-reduction measures, estimated for each period of the analysis. Benefits are inflated beforehand. The reason to inflate benefits is that the *nominal* value of damage costs in the future will be higher than today, hence saved damages as included in the calculation of the EAD reduction will have higher nominal value. The sum of inflated and discounted benefits equals the present value of benefits of a scenario, *k*. The two risk reduction scenarios (Table 1) are considered for *k*. The formal representation of the present value of benefits, PV(B), is:

$$PV(B)_k = \sum_{t=0}^{50} \frac{B_t}{(1+r)^t} \qquad (4)$$

B_t equals the inflated benefit in the time range, t ($t=0$ represents 2013 and $t=50$ represents 2062). A 3% discount rate, r, is applied (Zhou et al. 2012b). Arnbjerg-Nielsen and Fleischer (2009) suggest discount rates between 1% and 6% for developed countries. Therefore, our rate is in line with common practice. Inflation is done using an annual rate of 1.7% (Stone et al. 2013).

Data on investment and operational expenditure (cost) of the risk-reduction measures were provided by Eindhoven. It was assumed that investment expenditure is made between the present day and 2020. During this time, it was assumed that there is no operational expenditure, which starts in the year following completion of investment (i.e., 2021). Investment expenditure is not inflated, while operational expenditure is, due to the assumption that investments are contractually fixed prices. For operational expenditure nominal prices are likely to rise. To calculate the present value of costs, all expenditures for investments and operation along the time horizon are discounted. This has been done for each cost C in each period t of the analysis using a 3% discount rate. The sum of all discounted costs equals the present value of costs, PV(C):

$$PV(C)_k = \sum_{t=0}^{50} \frac{C_t}{(1+r)^t} \qquad (5)$$

The calculation of *net*-present value, NPV, for each scenario, k, is the difference between the present value of benefits and the present value of costs:

$$NPV_k = PV(B)_k - PV(C)_k = \sum_{t=0}^{50} \frac{B_t - C_t}{(1+r)^t} \qquad (6)$$

The NPV can be interpreted as the total damage saved over the calculation period relative to a do-nothing scenario minus the costs of implementing and operating the measures over that period. Positive figures indicate measure(s) of a scenario to be cost-beneficial and vice-versa, based on the assumptions and omissions included in the analysis (Section 5).

3. Case study development

Eindhoven, The Netherlands, is similar to many modern European cities. Urban expansion has not been accompanied by suitable expansion of the sewer and stormwater networks. The current storage capacity for excess rainfall in the Eindhoven network is 10 mm. Only 15% of the combined sewer-stormwater network has been separated. Much of the current network dates from the 1920s-1990s. The city is investigating the best way to proceed with decoupling of the rest of the sewer-stormwater network. Decoupling of the systems is being considered because increasing urbanisation and climate change have led to the current system becoming outdated and no longer fit-for-purpose, leading to rising financial implications. Not only are properties flooded more frequently, but more properties are flooded for a given return-period event, and properties that may not previously have been flooded are now being affected.

Local experts provided data and the hydraulic model, defining the rainfall events of most interest (Figure 1) and suggesting using the existing in-house hydraulic model to simulate pluvial flooding. This approach was suggested for a number of reasons: i) the model already existed; ii) the model could be easily adapted to include proposed risk-reduction measures; iii) necessary data were available; iv) any modelling and methodologies carried out during this study could be further used by the municipality, i.e., it results in capacity building and; v) the results would have direct relevance for city planners. Because results derive from an existing model, they are more likely to be trusted by local decision makers. This work will help define the effectiveness of upgrades, and may help target the location of upgrades. A financial

analysis was deemed most beneficial as this allows for simpler, more direct cost-benefit analysis of options. This financial analysis is one of the key benefits for Eindhoven.

Because Eindhoven's urban typology, structure, development and sewer-stormwater system is broadly similar to many Western cities, the approach to risk assessment in this work is applicable to cities with similar urban properties to Eindhoven.

4. Results

4.1 GIS analysis

Tables 2 and 3 present summary results for: the number of properties flooded (0, 0.1 and 0.2 m thresholds) for all scenarios and the damage per-event (0.1 and 0.2 m thresholds) and; the average flood depth and percent area flooded in selected city zones. Table 3 shows results only for the 2 and 10-year baseline and the 10-year 'b' scenario (Table 1). Results for every scenario and city zone are presented in the online appendix/supplement. Figure 4 shows spatial results for the percent area flooded for each scenario.

From Tables 2, 3, the online appendix/supplement and Figure 4, it is shown that, for most zones, there is negligible change to the area flooded or the number of properties flooded for a given return period event and risk reduction scenario. Between return periods there is significant change to both indicators. There are many zones with either no flooding, or no flooded properties for any scenario, for which the risk reduction measures cannot be expected to have any impact.

However, there are zones in which the risk reduction measures do show considerable impact. For details of the scenarios given in this section, see Table 1. For example, in zone 612 the percent area flooded is reduced from 12% under the 1a scenario to 4% under the 1b and c scenarios, and from 53% to 29% under the 3b scenario (Table 3) and 32% under the 3c

scenario. Reduction in flooded area means that fewer properties are affected (Table 2). While the largest reductions to flooded area and the number of properties affected are in zones that were specifically targeted, the measures also have impacts in other zones.

4.2 Fixed-threshold financial loss and cost-benefit analysis

Table 2 shows the results for the *per-event damage* for the 0.1 and 0.2 m thresholds. Greater differences between scenarios are observed with increasing return period. Damage is considerably greater at the 0.1 m threshold. When compared to the baseline, for the 'b' scenarios (Table 1) the per-event damage reduction is €95,000 for T=2, €1,081,000 for the T=5 and €1,898,000 for the T=10 scenario. For the 'c' scenarios the damage reduction is c. €136,000 for the T=2, €962,000 for the T=5 and €780,000 for the T=10 event. The lower values for the 'c' scenarios are a result of the Sobek routing of water over the terrain for these simulations.

In terms of the risk assessment definition in Section 2, these results are reframed as an EAD. For the baseline scenarios, the EAD is €38.2m at the 0.1 m threshold and €16.8m at the 0.2 m threshold. For 'b' scenarios, EAD is €37.3m at the 0.1 m threshold and €16.3m at the 0.2 m threshold. For the 'c' scenarios, EAD is €37.4m at the 0.1 m threshold and €16.5m for the 0.2 m threshold. The EAD reduction at the 0.2 m threshold when compared to the baseline for the 'b' scenario is €454,000 and €338,000 for the 'c' scenario.

Using the method in Section 2.7, a cost-benefit analysis was carried out. Under the baseline scenario for the 0.1 m threshold, the total present value of *costs* is c. €1.43bn. For the 'b' scenario, this is reduced to €1.39bn, while under the 'c' scenario it is €1.40bn. For the 0.2 m threshold under the baseline scenario, the total present value of damage costs was c. €627m. Under the 'b' scenario it was €610m, while under the 'c' scenario it was €614m.

With respect to implementing the risk-reduction measures, the separation plus Gender re-opening measures are estimated to cost €56m, while the separation-only measure costs €46.5m.

By implementing the separation plus Gender re-opening risk-reduction measures, the total *benefit* relative to the baseline under present values is €35.7m under the 0.1 m threshold and €29.1m under the 0.2 m threshold. For the separation-only scenario, the savings are €16.9m under the 0.1 m threshold and €12.6m under the 0.2 m threshold.

For the 0.1 m threshold under the separation plus Gender re-opening scenario, the *net-present value* of the risk-reduction measures is €-20.3m, while under the separation-only scenario, it is €-17.5m. Under the 0.2 m threshold, NPV for the separation plus Gender re-opening scenario is c. €-39m. Under the separation-only scenario it is €-34m. It is noted that the time frame for the NPV calculation was 50 years, whereas the calculation of the EAD used only three rainfall events with a maximum return period of 10 years. Nevertheless, a statement about the cost-benefit of the measures could be derived from the three "indicator" rainfall event calculations. The advantage of working only with a few "indicator" return periods is that difficult and time consuming model calculations for all possible return periods is avoided.

4.3 Probabilistic financial loss and cost-benefit analysis

The probabilistic analysis was applied to all buildings affected by flood depths > 0 m (Table 2). The total number of buildings flooded (Table 2) is scaled by the CDF (Figure 3) with subsequent analyses being affected. For example, under the 2 year return period baseline scenario, a total of 5,338 properties are flooded with the 0.1 m fixed threshold. With the probabilistic methodology, the maximum number of flooded properties for the 1a scenario is 22202 at a water level equal to or greater than 1.06 m (Figure 5). By comparison, at 0.1 m flood depth, a total of 10952 properties were affected using the probabilistic analysis,

suggesting that the fixed-threshold analysis may be underestimating damages (or vice-versa), with consequences for the cost-benefit analyses.

The per-event EAD for the baseline, separation and Gender re-opening, and separation-only scenarios is shown in Figure 6. For the baseline, the maximum EAD reached is over twice that of the fixed-threshold analysis (€77.1m vs. €38.2m). For the 'b' scenarios (Table 1), the maximum EAD is €75.8m, while for the 'c' scenarios it is €75.84m. The EAD rises most steeply up to c. 0.2 m. Half of the maximum EAD is reached with a flooding depth of c. 0.1 m. Maximum EAD is obtained at 1.06 m in all scenarios.

The costs for implementing the two risk-reduction scenarios are the same as reported in Section 4.2. Maximum net-present costs are €2.87bn for the 'a' scenarios and €2.82bn for the 'b' and 'c' scenarios, again more than double those estimated for the fixed-threshold analysis.

Results of the net-present value calculations are shown in Figure 7. Positive net-present value is observed for the separation-only scenario, indicating that with the assumptions and omissions in this work (Section 5), this measure may be value-for-money over the 50-year analysis period. The separation and Gender re-opening does not quite attain positive net-present value because of the increased cost of including a second measure. It is noted that the best net-present value figures are attained at the deepest levels of flooding when most buildings are affected, increasing the cost of flooding. As the flooding depth decreases, the costs and NVP associated with flooding decrease with increasing probability (Figure 7).

5. Discussion

This work shows that substantial financial savings can be made through implementing risk-reduction measures. Combining the separation of the sewer-stormwater networks with the re-opening of the River Gender offers the greatest potential for savings, but increases the costs.

For the fixed-value threshold analysis, all net-present values are negative, implying that according to this analysis, they do not represent value-for-money. Probabilistic assessment gives EAD and present value of costs more than double those of the fixed-threshold assessment and is due to the increased number of buildings flooded at high water levels. However, when the probability distribution of the doorstep measurements (Figure 3) is considered, it is shown that this damage would only occur in extreme events with low probability. This has implications for net-present value estimates. It is highlighted that the most positive net-present value figures are 'best-cases', and occur when more buildings are affected by pluvial flooding. Under lower flood depths, negative net-present values are observed with greater probability (Figure 7).

The damage and NPV estimations are probably underestimations. Apart from damage to buildings and contents, no further direct or indirect damages (traffic interruptions, business loss, disruption of electricity, lost working days due to stress, etc.) were estimated, and only residential properties were considered (data for industrial, municipality, commercial and other buildings were not available). It is possible to estimate damage in other sectors using a 'typical damage share' (Freistaat Sachsen, 2003). However, this approach requires the assumption that the damage share in the study location is 'typical', introducing further uncertainty. Cellars were not included. No estimation was included regarding damage to vehicles or to roads and pavements

With respect to climate change, it is expected that the frequency of a given magnitude event will increase. This means that a current 1-in-5 year return period event may become a 1-in-3 year event for example, changing the likelihood from 0.2 to 0.33, increasing the EAD. Assuming that investment and operational costs remain the same, then NPV may become positive depending on the magnitude of climate change effects for a particular rainfall event.

Changes in urbanisation are potentially more uncertain, and could act to increase or decrease the EAD for a particular scenario depending on how development proceeds.

When other potential impacts are considered, it is likely that the risk-reduction measures analysed here actually have a positive NPV. More work is required to confirm this hypothesis, which is outside the scope of this paper, but which is being considered for further research.

6. Conclusions

A quantitative risk assessment of the financial impact of pluvial flooding on residential properties in Eindhoven, The Netherlands, is presented. Eindhoven municipality technical personnel selected scenarios, applied the hydraulic model and assessed results. The impact of implementing two risk-reduction measures was compared to the present day situation. The process involved three general stages:

- hydraulic modelling of flooding scenarios;

- GIS analysis to extract flooding statistics and derive financial loss estimates;

- probabilistic assessment of financial damage. To the best of our knowledge our approach exploiting doorstep height distributions, is novel.

The process is generally applicable, and can be adapted for any similar city to Eindhoven, with the model(s) and data tailored to suit the study of interest.

Results show that most risk-reduction measures have negligible impact on flooding statistics in Eindhoven. Fixed-threshold analysis yields per-event flood damage estimates up to €89.3m. EAD reached €16.84m, with EAD reductions of up to €454, 000. Net-present costs reach €1.43bn. Fixed-threshold net-present value analysis for the risk-reduction measures indicates that under present values the proposed risk-reduction measures have greater cost than benefit.

Probabilistic assessment yielded total damage and EAD values more than double those of the fixed-threshold analysis. This is expected only to occur under extreme flooding with low probability, with most EAD values being below the maximum. Net-present value attained positive values for the separation-only risk-reduction measure. This is only observed under extreme flood depths.

Because our study omitted various factors (climate change, other sectors, indirect impacts), these results represent an underestimation of damages and could be improved upon with further research. Despite this, the work offers improved information to Eindhoven city planners, who will be able to better assess the effectiveness of pluvial flood risk reduction measures. By having better estimates for EAD and NPV and by having mapping showing the spatial distribution of damage 'hot-spots', planners are in a better position to make more informed decisions. By using local information and models, results will have more credibility to city planners. This work represents a useful first step and methodology for helping Eindhoven prepare for pluvial flooding, based on software, models and tools already available at the municipality, eliminating the need for software upgrading and/or personnel training.

7. Acknowledgements

8. References

Arnbjerg-Nielsen, K., Fleischer, H.S. 2009. Feasible adaption strategies for increased risk of flooding in cities due to climate change. Water Science & Technology. 60(2), 273-281.

Ballesteros-Canovas, J.A., Sanchez-Silva, M., Bodoque, J.M., Diez-Herrero, A. 2013. An integrated approach to flood risk management: A case study of Navaluenga (Central Spain). Water Resources Management. 27(8), 3051-3069. doi: 10.1007/s11269-013-0332-1

Chen, A., Evans, B., Djordjević, S., Savić, D.A., 2012. Multi-layered coarse grid modelling in 2D urban flood simulations. Journal of Hydrology 426-427, 1-16.

CIRIA. 2007. C697, The SUDS Manual. Available at http://www.ciria.org/. Last accessed May 2013.

Deltares, 2013. Sobek Hydraulic Model v. 2.12.003. www.deltaressystems.com

Duarte R, Pinilla V, Serrano A. 2013. Is there an environmental Kuznets curve for water use? A panel smooth transition regression approach. Economic Modelling. 31: 518-527.

Fewtrell L, Kay D. 2008. An attempt to quantify the health impacts of flooding in the UK using an urban case study. Public Health. 122(5): 446-451.

Freistaat Sachsen. 2003. Bericht der Sachsischen Staatsregierung zur Hochwasserkatastrophe im August 2002. Report of the Federal Government of Saxony on the Flood Catastrophe in August 2002.

IPCC. 2007. Climate change 2007: The physical science basis, summary for policymakers. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, Switzerland.

Kaplan S, Garrick BJ. 1981. On the quantitative definition of risk. Risk Analysis. 1: 11-27.

Kazama S, Sato A, Kawagoe S. 2009. Evaluating the cost of flood damage based on changes in extreme rainfall in Japan. Sustainability Science. 9: 61-69. doi: 10.1007/s11625-008-0064-y.

Kellens, W., Vanneuville, W., Verfaillie, E., Meire, E., Deckers, P., De Maeyer, P. 2013. Flood risk management in Flanders: Past developments and future challenges. Water Resources Management. 27, 3585-3606. doi: 10.1007/s11269-013-0366-4

Kolsky P. 1998. Storm drainage. Intermediate Technology Publications, London.

LAWA. 2003. Leitlinien zur Durchführung dynamischer Kostenvergleichsrechnungen (KVR-Leitlinien). Kulturbuchverlag Berlin GmbH, Hannover, 186 S. (In German).

Leandro, J., Djordjević, S., Chen, A.S., Savić, D.A., Stanić, M., 2011. Calibration of 1D/1D urban flood model with 1D/2D model results in the absence of field data. Water Science and Technology, 64(5), 1016-1024.

Madsen H, Arnbjerg-Nielsen K, Mikkelsen PS. 2009. Update of regional intensity-duration-frequency curves in Denmark: tendency towards increased storm intensities. Atmospheric Research. 92(3): 343-349.

Mailhot A, Duchesne S. 2010. Design criteria of urban drainage infrastructures under climate change. Journal of Water Resources Planning and Management. 136(2): 201-208.

Merz B, Elmer F, Thieken AH. 2009. Significance of "high probability/low damage" versus "low probability/high damage" flood events. Natural Hazards and Earth System Science. 9(4), 1033-1046.

Moel de. H, Aerts J.C.J.H. 2011. Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. Natural Hazards. 58: 407-425. doi: 10.1007/s11069-010-9675-6.

Moore P.G. 1983. The business of risk. Cambridge: Cambridge University Press, UK.

Okabe, A., Boots, B., Sugihara, K., Chiu, S.N., 2000. Spatial Tesselations: Concepts and applications of Voroni diagrams. 2nd Edition. John Wiley. 671pp.

Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE. 2007. IPCC Forth Assessment Report: Climate Change 2007 (AR4): Working Group 2 Report, Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK. 976pp.

Pearce D, Atkinson G, Mourato S 2006. Cost-Benefit Analysis and the Environment - Recent Developments. OECD Publications, Paris, ISBN/ISSN 92-64-01004-1, 316 pp.

Rioned, S., 2004. Leidraad Riolering; C2100 rioleringberekeningen hydraulisch functioneren. (In Dutch).

Robinson M, Scholz M, Bastien N, Carfrae J. 2010. Classification of different flood retention basin types. Journal of Environmental Sciences. 22(6): 898-903.

Schmidli J, Frei C. 2005. Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th Century. International Journal of Climatology. 83: 139-151.

Semadeni-Davies A, Hernebring C, Svensson G, Gustafsson L-G. 2008. The impacts of climate change and urbanisation on drainage in Helsginborg, Sweden: Combined sewer system. Journal of Hydrology. 350(1-2): 100-113.

Spekkers MH, ten Velduis JAE, Kok M, Clemens FHLR. 2012. Analysis of pluvial flood damage based on data from insurance companies in the Netherlands. Available at: http://www.hkv.nl/documenten/Analysis_of_pluvial_flood_damage_based_on_data_MK.pdf

Stedinger J.R. 1997. Expected probability and annual damage estimators. Journal of Water Resources Planning and Management. 123(2): 125-135.

Stone, K., Daanen, H., Jonkhoff, W., Bosch, P. 2013. Quantifying the sensitivity of our urban systems. Impact functions for urban systems. Deltares, Dutch National Research Programme Knowledge for Climate, Utrecht. 88 pp.

Suarez P, Anderson W, Mahal V, Lakshmanan TR. 2005. Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston Metro Area. Transportation Research Part D: Transport and Environment. 10(3): 231-244.

Tapsell SM, Tunstall SM. 2008. "I wish I'd never heard of Banbury": The relationship between 'place' and the health impacts from flooding. Health and Place. 14(2): 133-154.

Vatn J. 2004. Risk Analysis. ROSS (NTNU) 20040x. Norwegian University of Science and Technology. Trondheim, Norway.

Vewin (Association of Dutch Water Companies). 2012. Drinking water statistics 2012: The water cycle from source to tap. 92pp. Available at: http://www.vewin.nl/SiteCollectionDocuments/Publicaties/Drinkwaterstatistieken%202012/Vewin%20Drinkingwaterstatistics%202012%20lowres.pdf

Woodward, M., Gouldby, B., Kapelan, Z., Hames, D., 2013. Multiobjective optimisation for improved management of flood risk. ASCE Journal of Water Resources Planning and Management. doi: 10.1061/(ASCE)WR.1943-5452.0000295.

Zhou, Q., Mikkelsen, P.S., Halsnæs, K., Arnbjerg-Nielsen, K., 2012a. Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. Journal of Hydrology 414–415, 539–549.

Zhou Q, Halsnæs K, Arnbjerg-Nielsen K 2012b. Economic assessment of climate adaptation options for urban drainage design in Odense, Denmark. Water Science & Technology, 66(8), 1812-1820.