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Final report: Quantitative Risk Assessment models and application to the Eindhoven case study

SEVENTH FRAMEWORK
PROGRAMME

Final report: Quantitative Risk Assessment models and application to the Eindhoven case study

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Title
Final report: Quantitative Risk Assessment models and application to the Eindhoven case study

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Summary

This report details the stochastic quantitative risk assessment methodology used in the PREPARED: Enabling change FP7 EU project (number 244232).

As cities around the world are becoming more prone to pluvial flooding (i.e. flooding from rainfall events, sometimes referred to as surface water flooding), it is becoming more important to understand the risk that these flooding events pose. As the urban population increases and cities expand on the surface, less water can infiltrate, leading to more water concentrating on the surface. In addition, surface expansion is not always met with complementary and suitable expansion of the drainage network. An increasing population also places greater stress on the drainage system by forcing it with greater volumes of water (waste and fresh). On top of these issues, climate change means that generally, rainfall events are becoming more frequent and more intense (another way of framing this is that the return period for a given rainfall profile is decreasing). Therefore, more properties are being flooded for a given rainfall event and properties that normally would not be affected are now being flooded. Properties are also being affected more frequently than before. This means that the risks to life, property, service and the economy are increasing. It is becoming ever more critical to quantify these risks and to understand at least some of the uncertainty involved in these estimations.

This report presents the results of the efforts in PREPARED Work Package 2.3. This was designed to identify, in partnership with the demonstration city, Eindhoven, the Netherlands, the major critical risks to quantify (Deliverable 2.3.1), a general methodology for deterministic quantitative risk assessment that was subsequently by applied to Eindhoven (Deliverable 2.3.2), and a general stochastic quantitative risk assessment that was applied to Eindhoven (Deliverable 2.3.3).

The deterministic and stochastic methodologies, along with their application to Eindhoven are briefly summarised. Work resulting from the application of the developed methodological framework indicates that, according to the constraints of the project, under the deterministic analysis, per-event pluvial flood damage could range between c. €12M to c. €156M depending on the scenario. EAD, a better measure of damage, ranges from € 16M to € 38M. Considerable per-event reductions are shown to be possible when the proposed risk-reduction measures are implemented. Our cost-benefit analysis is carried out over an analysis period of 50 years and includes the total damage to property and the cost of implementing the risk-reduction measures as the costs, and the total loss saved as a results of implementing the risk-reduction measures as the benefit. It is shown that, under the modelling assumptions, all risk-reduction measures for the deterministic case show net negative benefit, that is, they are not cost-effective over the 50-year analysis period.

Under the probabilistic analysis, we use the distribution of doorsteps in the nearby city of Rotterdam in order to assess the likelihood that a property will be affected in the event of pluvial flooding. This gives local city planners more information about the chance that a given value for damage will actually be attained in a flood event, and therefore they can plan defences and improvements more meaningfully. Under these simulations, the maximum per-event EAD value was more than double that found in the deterministic case. This is due to more buildings being affected at deeper water levels, as would be expected. However, it is also show that half this maximum value is attained at a depth of only c. 0.2m. For the same depth of flooding, this analysis suggests that more buildings are affected than in the deterministic case. Net-present costs when summed over the 50-year analysis period reach up to € 2.87bn, more than double those estimated for the fixed-threshold analysis. However, due to the probability functions, it is hypothesised that this value will rarely be reached. For the cost-benefit analysis, net-positive benefit was hinted at for one of the risk-reduction measures, suggesting cost-effectiveness over 50-years.

While these results and analysis represent a large step forward in the quantitative risk analysis of pluvial flooding, there are some limitations which mean that our results should be treated as 'worst case' numbers. In reality, it is likely that the risk-reduction measures proposed will actually have net-positive benefit over the next 50 years. This is due to a number of omissions from our analysis, which has the effect of reducing the damage costs, and therefore the overall benefit.

Firstly, our analysis only considers residential properties, and even here neglects cellars due to a lack of data. Costs for damages to industrial, commercial and municipal buildings were not included in the work. In addition, we only consider the direct cost to residential properties. Other direct costs, such as to city infrastructure including roads, power lines, damage to vehicles and telecommunications were not considered. Also, we neglected the financial impact of indirect losses. These can include things such as lost working hours, and the financial cost of stress-related illness as a result of the flooding.

In addition to the above, we also do not account for the impacts of climate change on pluvial flooding. It is anticipated that this will lead to more frequent pluvial flood events, and that rainfall will become more intense. This has the impact of, for a given rain event, reducing the return period of that event. So a 5-year return period event may gradually become a 3-year event. This increases the probability (the likelihood) of the event, which has direct consequences for damage assessments. Increased probability means higher EAD and damage costs for a given rainfall event. Higher damage costs lead to improved cost-benefit values. Therefore, the impacts of climate change will probably lead to risk-reductions measures gradually becoming better value-for-money as rainfall events becomes more frequent and more intense.

Despite these limitations, our work allows Eindhoven city planners to understand some of the uncertainty when carrying out cost-benefit analyses, and quantifies some of that uncertainty. Together with the spatial GIS analysis, it provides Eindhoven with a more robust quantitative risk assessment that will allow them to better consider future options for mitigating the potential impacts of climate and social change in the city. They can also further investigate and incorporate some of the factors we omitted in this analysis to improve upon this work.

Finally, the general methodological approach can be adapted and adopted by other PREPARED cities, and also by other cities globally. This could lead to better quantitative risk assessments generally, with more targeted use of resources, potentially offering considerable financial savings.

This report forms Deliverable 2.3.4 for the PREPARED: Enabling Change EC FP7 project.

Contents

1 Introduction

This document contributes to WA2 of the EC FP7 PREPARED: Enabling Change project, forming Deliverable 2.3.4. This report details the results of the application of the methodology for both the deterministic and stochastic elements of the quantitative risk assessment. The methodologies are applied to the Eindhoven demonstration city. The complete detailed methodology and application is reported in Deliverables 2.3.2 and 2.3.3. The aim of WP 2.3 is to develop quantitative models for the assessment of pluvial flood risk, applied specifically to Eindhoven. The specific objectives are (a) identifying the relevant risk categories for quantification, together with the associated critical risk event trees (Deliverable 2.3.1); (b) developing deterministic QRA models for these risk categories (Deliverable 2.3.2); (c) quantifying the uncertainty through the development of a robust stochastic QRA method (Deliverable 2.3.3); and (d) implementing experiences from testing in the PREPARED cities in the QRA models (this Deliverable).

This report provides detailed results from the implementation of the deterministic and stochastic quantitative risk assessment methods to Eindhoven. It uses previously published methods, combined with new data to build upon and improve on other pluvial flood risk assessments. By carrying out a probabilistic assessment based on the distribution of doorstep levels, we extend the current state-of-the-art. We use the new methodology to provide more robust quantitative risk assessment to Eindhoven, using financial loss as a result of pluvial flooding as the metric to quantify. Ultimately, this means that, although there is still further research to be carried out, Eindhoven are better positioned to make cost-benefit decisions regarding potential risk-reduction measures in the city.

This work forms part of the wider research carried out in Work Area 2 of PREPARED. The work in this report is also related to the research carried elsewhere in WA2 (for example see Deliverables 2.1.5, 2.2.4, 2.3.2, 2.3.3, 2.4.1, 2.4.2 and 2.4.3).

1.1 Report structure

The report begins with a brief summary of the deterministic and stochastic quantitative risk assessment methodologies that are described in full in Deliverables 2.3.2 and 2.3.3 respectively. This is followed by a description of the application of these methods to the case study.

Section 3 presents the detailed results of the study including the results from the GIS analysis and the per-event and long-term cost-benefit analyses for the deterministic and stochastic methodologies. The Appendix gives a detailed set of results.

Section 4 discusses the results and draws out some implications for Eindhoven and for the other PREPARED demonstration cities. It also details the potential for further work in order to improve our analysis. Section 5 concludes the report.

2 Brief summary of the pluvial flood risk assessment methodology applied to the Eindhoven case study

2.1 Summary of the deterministic methodology

The general methodological approach for the deterministic quantitative risk assessment in WP2.3 of PREPARED, and the subsequent detailed application of this methodology to the Eindhoven case study is reported in detail in Deliverable 2.3.2. Here, a brief summary of the method is presented.

In general, the method consists of four main stages:

- scenario definition including definition of the rainfall return-periods to analyse and which risk-reduction measures to investigate, the specific hydraulic model to be used, and specifically which risk to quantify.
- hydraulic modelling of the potential pluvial flood risk according to the scenarios as defined above.
- GIS analysis of the hydraulic model results in order to obtain all necessary flooding statistics (these should be defined with local partners)
- quantitative risk assessment based on the hydraulic modelling and GIs results. The exact method used here will vary according to the risk to be quantified.

This methodology should be tailored to each case study. The application for Eindhoven is set out in detail in Deliverable 2.3.2, and is summarised here in Section 2.3.

2.2 Summary of the stochastic methodology

As with the deterministic case, the stochastic quantitative risk assessment methodology to introduce a probabilistic element into the risk assessment in order to quantify some of the uncertainty, has been fully outlined in Deliverable 2.3.3. Here, a brief summary of the general approach is given, and the application to Eindhoven is summarised in Section 2.3 (full details are in Deliverable 2.3.3). Once deterministic modelling has been carried out, the steps are:

- define, with local stakeholders, the specific element in the risk analysis for which uncertainty will be better quantified. This could include for example uncertainty in the hydraulic model, in the damage approach considered, or in the rainfall return-period hyetograph characteristics.

This stage should also ensure that sufficient data are available in order to carry out a probabilistic assessment.

- create probability distributions for the element defined above, and apply these distributions to the quantitative element of the risk analysis. This results in probability curves for the quantified risk element (e.g. financial damage, flooding extents, etc.)
- re-analyse results, and frame in a manner suitable for non-specialists.

2.3 Application of the general methods to the Eindhoven case study

The detailed application is described in Deliverables 2.3.2 and 2.3.3. A summary of the application is described here. It is noted that all the scenarios, including the rainfall return periods to analyse, the pluvial flood risk-reduction measures to consider, the hydraulic mode to use and the specific risk to quantify were all defined by partners in Eindhoven. As a result, this work will have direct relevance for city planning decisions in the future.

- Nine scenarios, consisting of a combination of three rainfall return-periods (2, 5 and 10 years) and three risk-reduction plans, were defined (Table 1).
- The nine scenarios were modelled using the 1D hydraulic model Sobek (DeltaRes, 2013). Results were exported to GIS format for further analysis.
- Using GIS, the following values were obtained for each of the nine scenarios in 109 pre-defined zones in Eindhoven (Figure 1): maximum and average flooding depth; area flooded (in km2 and %); total number of properties flooded for all water depths; number and percent of properties flooded at depths > 0.1 m and; number and percent of properties flooded at depths > 0.2 m.

Table 1: Details of the nine risk assessment scenarios

Scenario ID	**Scenario description**
1a	Baseline t=2 simulation
1b	t=2 simulation with River Gender re-opened and separated sewer-stormwater network
1c	t=2 simulation with separated sewer-stormwater network only
2a	Baseline t=5 simulation
2b	t=5 simulation with River Gender re-opened and separated sewer-stormwater network
2c	t=5 simulation with separated sewer-stormwater network only
3a	Baseline t=10 simulation
3b	t=10 simulation with River Gender re-opened and separated sewer-stormwater network
3c	t=10 simulation with separated sewer-stormwater network only

For the deterministic quantitative risk assessment, all those properties identified as being affected by water greater than 0.1 and 0.2 m deep were assumed to be flooded. This means that for each of the nine scenarios, a fixed number of properties was analysed for each scenario in the next section of the analysis.

- Using the number of flooded properties, the per-event buildings, contents and total damage was calculated along with the EAD.
- Following this, a cost-benefit analysis for a 50-year analysis period was carried out. The net-present costs (for flooding events and for implementing the risk-reduction measures) were estimated accounting for inflation and applying a discount rate. Then the net-present benefit as a result of implementing the risk-reduction measures compared to the baseline scenario was estimated.
- Finally, the net-present value (benefit - cost) was estimated for every risk-reduction scenario.

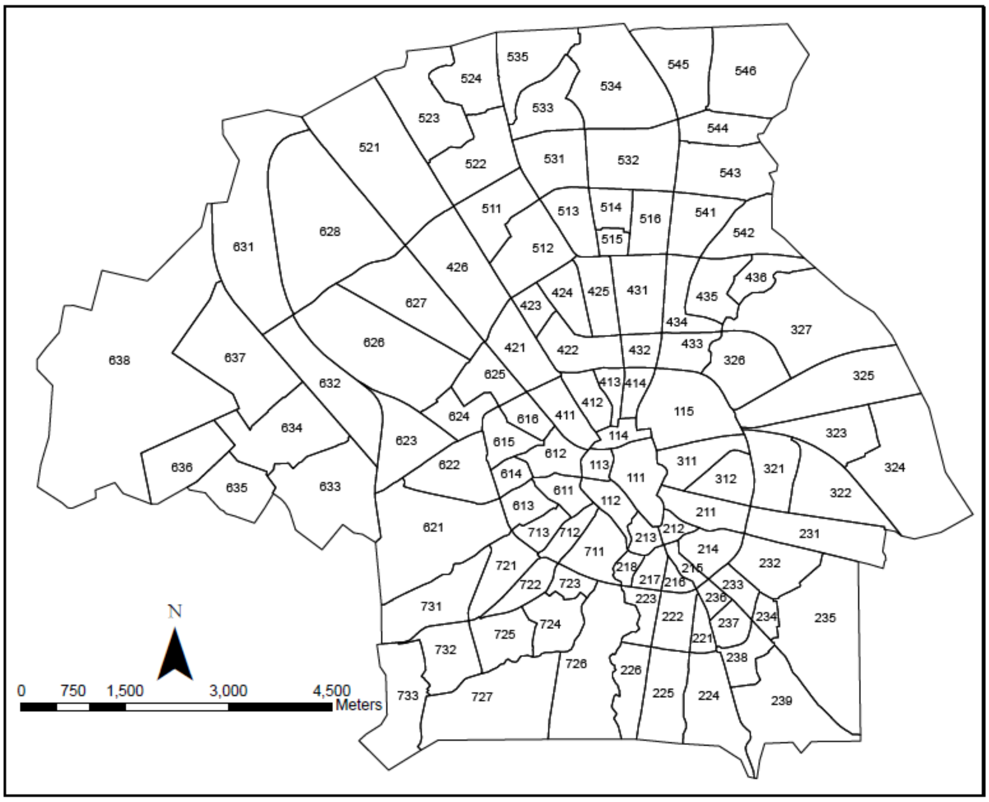


Figure 1: The 109 city zones in Eindhoven

Under the probabilistic approach, a different method was used.

- The number of properties intersecting all flooding depths were counted in the GIS analysis.
- Theses where subsequently scaled according to the probability that they would be flooded at any given water depth as determined by the probability and cumulative density functions produced from the results of 4664 doorstep height measurements in the nearby city of

Rotterdam. The likelihood that a property will be flooded for a given water depth is estimated at 2 cm intervals from 0 to 170 cm.

- For each scenario, a distribution of the number of properties affected depending on water depth is therefore produced.
- These distributions are then used to estimate the per-event damage and EAD. Instead of single values being produced for each scenario, a distribution of values is given, with damage and EAD varying according to water depth.
- Distributions for the net-present costs, benefit and net-present value are also given.
- 95% upper and lower intervals are placed on cumulative distributions. These reflect the confidence of the mean value for the net-present value for example. Narrower bands indicated a more confident estimate with lower variance.

3 Results of the quantitative risk assessment for Eindhoven

The results presented here as part of the PREPARED project are taken and adapted from Sušnik et al. (In Prep.).

3.1 GIS results

Tables 2 and 3 present summary results for: the total number of properties flooded over every flood-depth threshold (0, 0.1 and 0.2 m) for all scenarios and; the average flooded depth and percent area flooded in selected city zones respectively. Results for every scenario and city zone are presented in the Appendix. Figure 2 shows spatial results for the percent area flooded for Scenarios 1a-c and 3a-c.

Table 2: Number of properties flooded for each scenario and water depth threshold.

	Flooding depth		
Scenario number	**d>0m**	**d >0.1m**	**d >0.2m**
1a	22202	5338	1465
1b	21680	4969	1425
1c	21567	5020	1408
2a	62210	34202	12644
2b	61242	33512	12490
2c	61454	33582	12540
3a	88446	65673	37508
3b	87510	64873	36711
3c	87822	65219	37181
Total		**131588**	

Table 3: Selected results showing the average flooding depth and % area flooded for scenarios 1a, 3a and 3b (Table 1). The entire set of results can be found in the Appendix.

	1a scenario		3a scenario		3b scenario	
Zone number	**Average flooding depth (m)**	**% area flooded**	**Average flooding depth (m)**	**% area flooded**	**Average flooding depth (m)**	**% area flooded**
111	0.04	4	0.14	34	0.14	32
112	0.05	10	0.17	68	0.17	66
113	0	0	0.07	6	1.59	6
211	0.14	22	0.3	69	0.3	69
212	0	0	0.08	20	0.08	20
213	0	0	0.04	8	0.04	8
218	0.06	1	0.1	52	0.1	52
221	0.03	12	0.18	76	0.18	76
222	0.02	3	0.17	76	0.17	76
223	0.03	1	0.13	55	0.13	55
226	0.03	5	0.21	27	0.21	27

411	0.12	0	0.17	81	0.16	75
421	0.07	17	0.22	85	0.22	85
422	0.03	14	0.19	69	0.19	67
611	0.05	9	0.11	52	0.11	48
612	0.06	12	0.14	53	0.11	29
613	0.01	4	0.08	61	0.08	61
614	0.03	8	0.18	77	0.17	77
615	0.07	49	0.26	90	0.25	75
616	0.17	2	0.17	35	0.17	30
711	0.06	0	0.14	44	0.14	44
712	0.04	13	0.21	73	0.21	72
713	0	0	0.08	59	0.08	53

From Tables 2, 3, the Appendix and Figure 2, it is shown that generally there is negligible change to either the area flooded or the number of properties flooded for a given return period event and scenario, although between return periods there is significant change to both indicators. Most changes are in the order of a few percent. There are many zones with either no flooding for any scenario, or no flooded properties for any scenario.

However, there are some exceptions, 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 affected by flooding is reduced from 12% under the 1a scenario to 4% under the 1b and c scenarios, and from 53% under the 3a scenario to 29% under the 3b scenario (Table 3) and 32% under the 3c scenario. This reduction in flooded area means that throughout Eindhoven, fewer properties are flooded as a result (Table 2). Results indicate that while the largest reductions to flooded area and number of properties affected are in those zones that were specifically targeted by Eindhoven, the measures also have impacts in other zones throughout the city.

Figure 2: Spatial results showing the % of the area flooded in each city zone for scenario (a) 1a; (b) 1b; (c) 1c; (d) 3a; (e) 3b and; (f) 3c. See Table 1 for scenario definitions.

3.2 Deterministic QRA results

Per-event damage for the 0.1 and 0.2 m threshold values are shown in Table 3. Greater differences between scenarios are observed as the return period increases. Per-event damage is considerably greater at the 0.1 m doorstep threshold than at the 0.2 m doorstep threshold.

Table 3: Total per-event damage under the deterministic QRA for the 0.1 and 0.2 m doorstep thresholds for every scenario. See Table 1 for scenario definitions.

Scenario	Total per-event damage (€)	
	0.1 m threshold	0.2 m threshold
1a	12.7M	3.48M
1b	11.8M	3.39M
1c	11.9M	3.35M
2a	81.4M	30.82M
2b	79.7M	29.74M
2c	79.9M	29.86M
3a	156.3M	89.30M
3b	154.4M	87.40M
3c	155.2M	88.52M

When compared to the baseline, for the 'b' scenarios (Table 1) the financial damage reduction on a per-event basis is c. € 95,000 for t=2, € 1,081,000 for the t=5 and c. € 1,898,000 for the t=10 scenario. For the 'c' scenarios, when compared to the baseline, the damage reduction is c. € 136,000 for the t=2, € 962,000 for the t=5 and c. € 780,000 for the t=10 scenario.

In terms of the risk assessment, these results are reframed as an expected annual damage (EAD). For the baseline ('a') scenarios, the EAD is € 38.2M at the 0.1 m doorstep threshold and €16.8M at the 0.2 m doorstep threshold. For 'b' scenarios the EAD is € 37.3M at the 0.1 m threshold and € 16.3M at the 0.2 m threshold. For the 'c' scenarios the EAD is € 37.4M at the 0.1 m threshold and € 16.5M at the 0.2 m threshold. The EAD reduction when compared to the baseline for the separated sewer-stormwater network plus Gender re-opening scenario is c. € 454,000 and for the separated sewer-stormwater network scenario the reduction is c. € 338,000.

Using the method described in Deliverable 2.3.2, a cost-benefit analysis was carried. Here, only the discounted values are presented. Under the baseline scenario for the 0.1 m doorstep threshold, the total net-present cost when summed over the 50-year time horizon is c. € 1.425bn. For the separation plus Gender re-opening scenario, this is reduced to € 1.389bn, while under the separation-only risk-reduction scenario, the total damage cost is € 1.396bn. For the 0.2 m doorstep threshold, under the baseline scenario the total net-present damage cost is c. € 627M. When the separation plus Gender re-opening scenario was analysed, this was reduced to € 610M, while under the separation-only scenario, the total damage cost was € 614M.

With respect to implementing the risk-reduction measures over the 50-year time horizon, the separation plus Gender re-opening measures are estimated to cost c. € 56M, while the separation-only measure would cost c. € 46.5M under present values.

Implementing the separation plus Gender re-opening risk-reduction measures, the total saving (benefit) relative to the baseline over the 50-year time horizon under present values is c. € 35.7M under the 0.1 m doorstep threshold and € 29.1M under the 0.2 m doorstep threshold. For the separation-only scenario, the savings relative are c. € 16.9M under the 0.1 m doorstep threshold and € 12.6M under the 0.2 m doorstep threshold. Therefore, for the 0.1 m doorstep threshold and under the separation plus Gender re-opening scenario, the net present value of the risk-reduction measures is c. € -20.3M, while under the separation-only scenario, it is € -17.5M. Under the 0.2 m doorstep threshold, the net present value for the separation plus Gender re-opening scenario is c. € -39M, while under the separation-only scenario it is € -34M.

3.3 Probabilistic QRA results

In the fixed-threshold analyses, it was assumed that every building within the flooded zones was affected, yielding single values of present costs, benefits, and net-present values of the risk-reduction measures for each of the nine scenarios. With the data on doorstep distributions, we apply a probability of flooding to properties lying within the flooded zone - not every building is flooded immediately because of the doorstep height. The total number of buildings flooded is scaled by the cumulative distribution of doorstep levels derived from the measurements in Rotterdam (Figure 3) with subsequent analyses being affected. For example, under the 2 year return period baseline scenario, a total of 5338 properties are flooded with the 0.1 m fixed threshold. With the probabilistic methodology, the number of properties affected by pluvial flooding in Eindhoven is shown in Figure 4. The maximum number of flooded properties for the 1a scenario is 22202, but this is only reached at a water level equal to or greater than 106 cm (Figure 4). Below this, the number of properties varies according to the CDF (Figure 3). By way of comparison, at 0.1 m flood depth, 10952 properties were affected using the probabilistic analysis. This suggests that the fixed-threshold analysis may be underestimating damages, with consequences for the cost-benefit analyses.

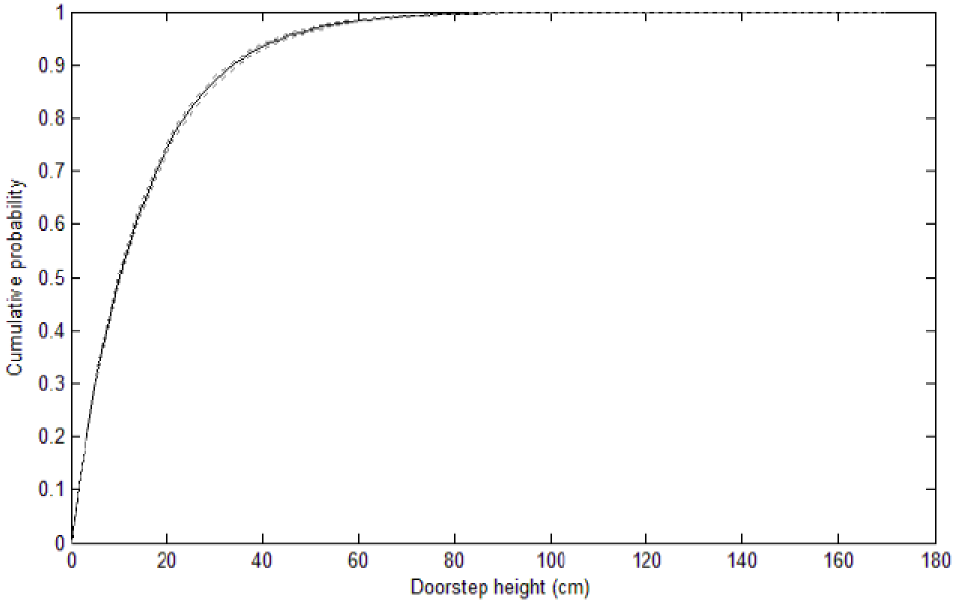


Figure 3: Cumulative probability function for the Rotterdam doorstep measurements.

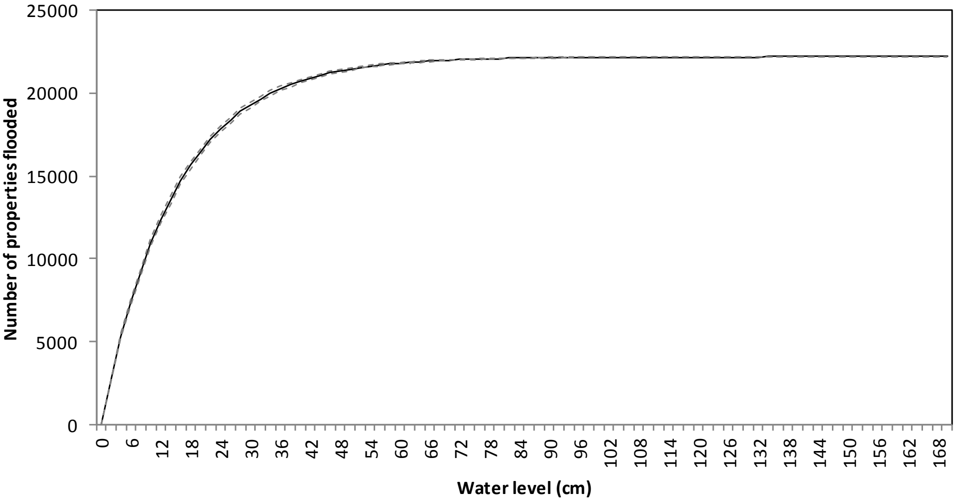
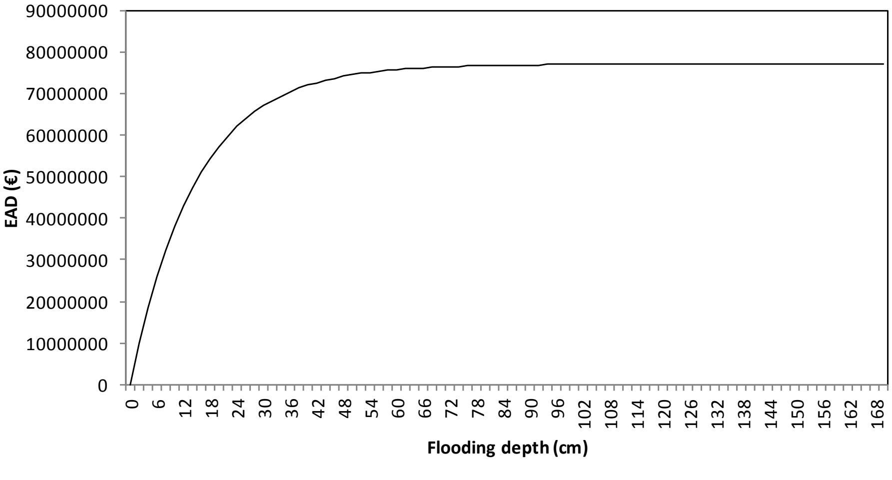


Figure 4: Number of properties flooded by flood depth for the 1a scenario. See Table 1 for scenario definitions.

Per-event EAD for the baseline and separation and Gender re-opening scenarios is shown in Figure 5. Half of the maximum EAD is reached with a flooding depth of c. 0.1 m. Maximum EAD is obtained at 1.06 m. The maximum EAD is considerably higher than that derived for the fixed-threshold analysis. For the baseline scenarios, the maximum EAD reached is over twice that estimated for the fixed-threshold analysis (€ 77.1M vs. € 38.2M in the 0.1 m fixed-threshold analysis). For the 'b' scenarios (Table 1), the maximum EAD reached is € 75.8M, while for the 'c' scenarios (Table 1) it is € 75.84M.

(a)



(b)

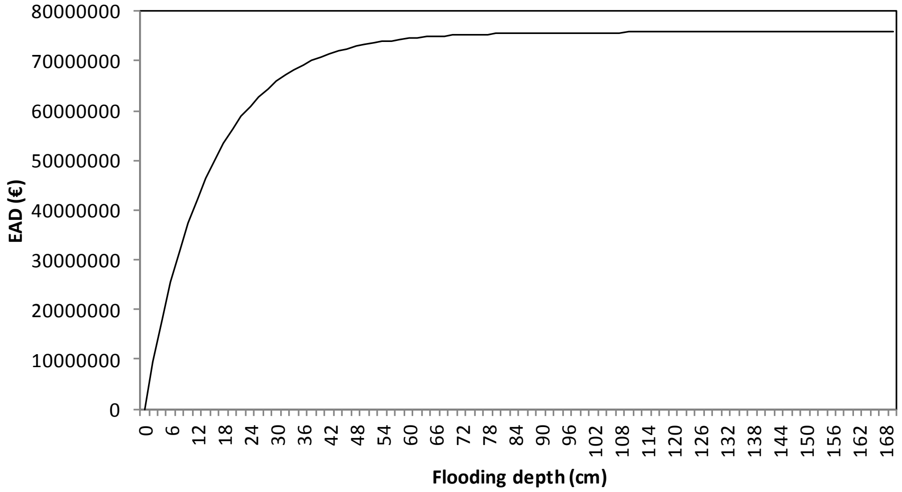
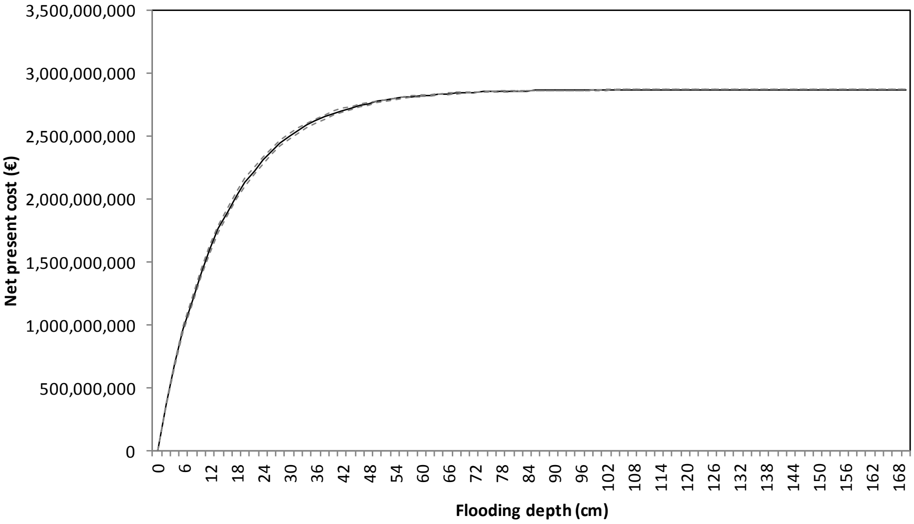


Figure 5: EAD distributions for (a) the 'a' scenarios and (b) the 'b' scenarios. See Table 1 for scenario definitions.

Net-presents costs for the 'a' and 'b' scenarios when summed over the 50-year analysis period are shown in Figure 6. The costs for implementing the two risk-reduction scenarios are the same as reported in Section 3.2. Total costs when summed over the 50-year analysis period are € 2.87bn for the 'a' scenarios and € 2.82bn for the 'b' and 'c' scenarios. As with the per-event EAD estimates, these maxima are more than double those estimated for the fixed-threshold analysis.

(a)



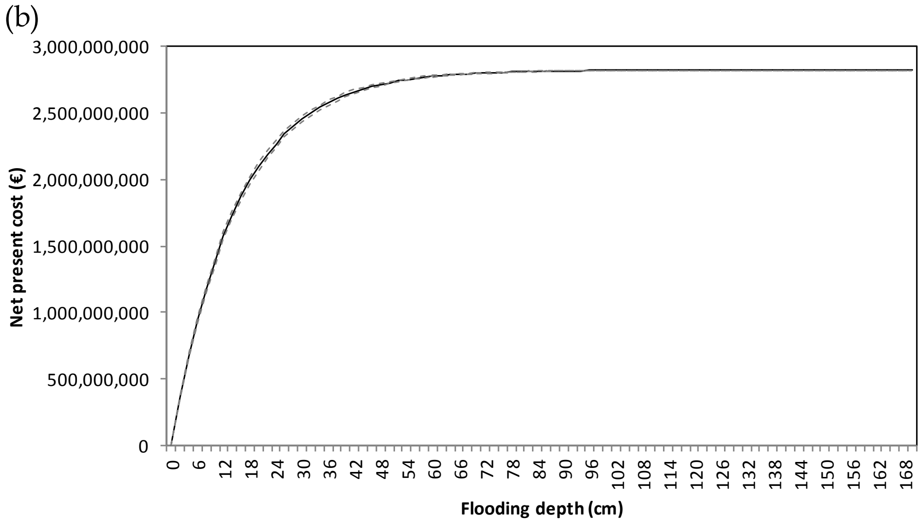


Figure 6: Net-present costs for (a) the 'a' scenarios and (b) the 'b' scenarios. Dashed lines indicate 95% confidence intervals. See Table 1 for scenario definitions.

Results of the net-present value calculations for the 'b' scenarios 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, this measure is suggested to be value-for-money over the 50-year analysis period. The separation and Gender re-opening does not attain positive net-present value, mainly because of the increased cost of including a second measure. The best net-present value figures are attained only at the deepest levels of flooding. At these depths, more buildings are affected, increasing the cost of flooding, and therefore improving the benefit of implemented measures. As the flooding depth decreases, the costs associated with the flooding decrease, as does the net-present value (Figure 7).

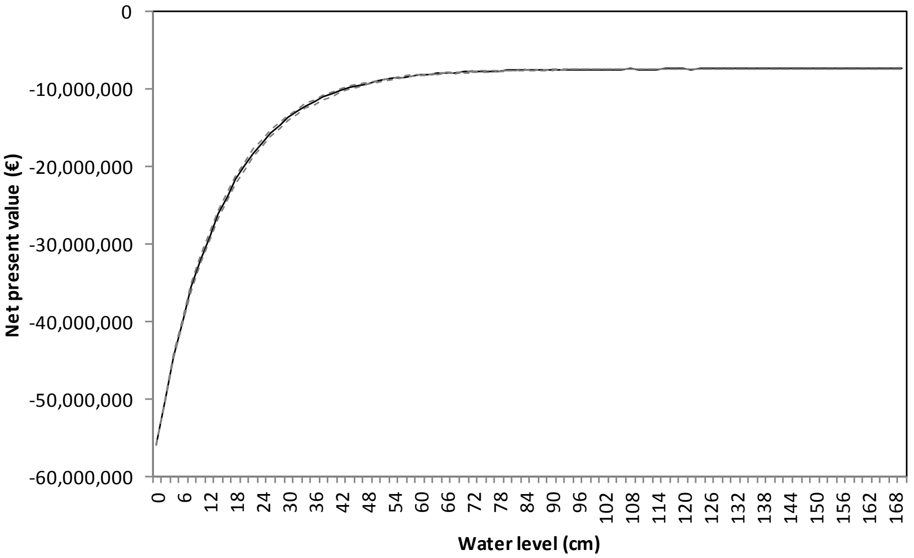


Figure 7: Net-present value for the 'b' scenarios. Dashed lines indicate 95% confidence intervals. See Table 1 for scenario definition.

4 Discussion and implications

Substantial per-event financial and EAD savings can be made through the implementation of the risk-reduction measures. Combing the separation of the sewer-stormwater networks with the re-opening of the River Gender was shown to offer the greatest potential for savings. However, implementing both risk-reduction measures decreases the net-present value as a result of the increased cost of both measures not outweighing the extra benefit.

For the fixed-value analysis, per-event EAD reaches €38.2 M, with per-event reductions of up to c. €450,000. Present-value costs when summed over the 50-year analysis period reach € 1.425bn with up to an additional € 56M required for the implementation of both risk-reduction measures. Net-present values for the risk-reduction measures are negative, implying that according to the analysis presented, they do not represent value-for-money. Comparison with the probabilistic assessment suggests that the number of properties and therefore the damage may be underestimated.

Probabilistic assessment gives EAD and net-present cost values that are over double those reported for the fixed-threshold assessment. Damage is shown to increase steeply with water depth. This difference in maximum damage values is due to the increased number of buildings flooded at high water levels in this analysis compared with the fixed-threshold analysis. However, when the probability distribution of doorsteps is considered, this level of damage would only occur under extreme circumstances. Because the damage values are greater, positive net-present values are indicated for the separation-only risk-reduction measure. When both measures are considered, the net-present value is negative, but not as much as for the fixed-threshold analysis. 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 still observed.

All our damage and net-present value estimations are underestimations. Apart from damage to buildings and contents, no further direct or indirect damages (e.g. traffic interruptions, business loss, disruption of electricity, lost working days due to stress, etc.) were estimated, only residential properties were considered, and cellars were not included. No estimation was included regarding damage to vehicles or to roads and pavements. The EAD estimations are underestimated values since rainfall events between the return periods 2, 5 and 10 as well as the events below the lowest return period (2) and above the highest return period (10) are not considered as we did not have access to hydraulic model simulation results for higher or lower return period rainfall events. The net-present value could become positive if we are able to accurately account for these other impacts in our work.

With respect to climate change, it is expected that the frequency of a given magnitude event will increase in the future. This change would subsequently impact on the EAD calculations, essentially making EAD larger. Assuming that investment and operational costs remain the same, then the net present value may become positive depending on the magnitude of climate change effects for a particular set of rainfall events.

Considering that climate change was not accounted for, that only current costs are considered, that indirect impacts of pluvial flood events were not accounted for, and that we restricted our analysis to residential properties only, our cost-benefit analysis should be viewed as a 'worst-case' conclusion. When other impacts and properties are considered together with the predictions of climate change, it is likely that the risk-reduction measures analysed here actually have a positive net-present value over the long-term, that is, that their financial benefits outweigh the costs.

4.1 Implications for Eindhoven

These results, based on an in-house hydraulic model developed by Eindhoven forced with Dutch national-standard rainfall profiles, mean that better, more reliable information regarding the effectiveness of risk-reduction measures in Eindhoven is available to city planners. This is especially applied to the domestic property sector. The results indicate that although for this analysis, positive net-present value for the risk-reduction measures was only observed for one set of analyses, due to the limited scope of the work, it is probable that in reality, the risk-reduction measures assessed here do actually have positive net-present value, although further work is required to confirm this.

By having better estimates for total per-event damage and EAD, by having mapping showing the spatial distribution of damage 'hot-spots', and by having a more robust probabilistic cost-benefit analysis, planners are in a better position to make more informed cost-benefit decisions regarding risk-reduction measures. They can also build on this work, incorporating other property, indirect impacts of pluvial flooding and/or the effects of climate change using the methodology we outline in Deliverables 2.3.2 and 2.3.3. The measure(s) most effective in offering financial risk reduction can be chosen with respect to the expected cost of implementing those measures. The measures can also be targeted to those areas that are most at risk of pluvial flooding, further increasing their effectiveness. Because project partners from Eindhoven were involved, and because the hydraulic model used was developed by staff in Eindhoven, the results and modelling assumptions will have more credibility to city planners, and are more likely to be taken up and further investigated.

5 Conclusions

Over two previous PREPARED Deliverables (D2.3.2 and D2.3.3), we outlined the general methodologies for deterministic and stochastic quantitative flood risk assessment. We also highlighted specifically how we would apply these general methods to the Eindhoven case study. This report has set out the results from that application, and briefly summarises the methodological approach adopted. In general, the deterministic method consists of four main stages:

- scenario definition including definition of the rainfall return-periods to analyse and which risk-reduction measures to investigate, the specific hydraulic model to be used, and specifically which risk to quantify.
- hydraulic modelling of the potential pluvial flood risk according to the scenarios as defined above.
- GIS analysis of the hydraulic model results in order to obtain all necessary flooding statistics (these should be defined with local partners)
- quantitative risk assessment based on the hydraulic modelling and GIs results. The exact method used here will vary according to the risk to be quantified.

Once deterministic modelling has been carried out, the general steps for the stochastic methodology are:

- define, with local stakeholders, the specific element in the risk analysis for which uncertainty will be better quantified. This could include for example uncertainty in the hydraulic model, in the damage approach considered, or in the rainfall return-period hyetograph characteristics. This stage should also ensure that sufficient data are available in order to carry out a probabilistic assessment.
- create probability distributions for the element defined above, and apply these distributions to the quantitative element of the risk analysis. This results in probability curves for the quantified risk element (e.g. financial damage, flooding extents, etc.)
- re-analyse results, and frame in a manner suitable for non-specialists.

For Eindhoven, the scenarios, hydraulic model, rainfall return-periods and specific risk to analyse were defined with stakeholders and local partners. Specific details of this application are not elaborated here, but can be found in Section 2 of this report and in Deliverables 2.3.2 and 2.3.3.

The results of the QRA to the Eindhoven demonstration city indicate that the methodology can be used to good effect in order to provide additional useful information to city planners and decisions makers, especially with relation to the potential efficacy of proposed risk-reduction measures. The analysis presented in this work can be expanded and improved as more data become available, providing a more comprehensive risk assessment to pluvial flooding than we were able to provide.

Under deterministic risk assessment, it is estimated that total per-event damage for the 0.1 m doorstep threshold may reach up to c. €155M under the 10-year return period baseline scenario while it is only c. €13M for the 2-year rainfall return period event. When framed more appropriately as an expected annual damage (EAD), values range from €16.3M to €38.2M depending on the scenario and doorstep threshold. EAD reductions of up to €445,000 were estimated as a result of the risk-reduction measures. For the cost-benefit analysis, covering a period of 50-years, the net-present costs have a maximum value of c. € 1.425bn under the 0.1 m doorstep threshold and c. €625M under the 0.2 m doorstep threshold. The risk reduction measures cost c. € 56M for the separation plus Gender re-opening measure, c. € 46.5M for the separation-only measure under present values. All net-present value figures were negative, indicating that the measures are not cost-effective over our analysis period.

Under the probabilistic assessment, EAD and net-present cost values that are estimated to be more than double those reported for the fixed-threshold assessment. Damage increases steeply with water depth. The differences in maximum damage values is due to the increased number of buildings flooded at high water levels in this analysis compared with the fixed-threshold analysis. When the probability distribution of doorsteps is considered, this level of damage would only be expected to occur under more extreme circumstances. Because the damage values are greater, positive net-present values are indicated for the separation-only risk-reduction measure. When both measures are considered, the net-present value is negative, but not as much as for the fixed-threshold analysis. 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 value are still observed.

All our damage and net-present value estimations are likely to be underestimations. Apart from damage to buildings and contents, no further direct or indirect damages were estimated. Only residential properties were considered, and cellars were not included. The EAD estimations neglected rainfall events between the return periods 2, 5 and 10 as well as the events below the lowest return period (2) and above the highest return period (10). It is expected that the frequency of a given magnitude event will increase in the future. This change would subsequently impact on the EAD calculations. Considering that climate change was not accounted for, that only current costs are considered, that indirect impacts of pluvial flood events were not accounted for, and that we restricted our analysis to residential properties only, our cost-benefit analysis should be viewed as a 'worst-case' conclusion.

Despite the limitations of the study, it represents a significant step forward to producing robust, probabilistic quantitative pluvial flood risk assessment for Eindhoven. It also demonstrates the applicability of our generic methodology.

By having a more robust risk assessment, and having mapping showing the spatial distribution of damage 'hot-spots', city planners are now in a better position to make more informed cost-benefit decisions regarding risk-reduction measures. They can also build on this work, incorporating other property, indirect impacts of pluvial flooding and/or the effects of climate change. Risk-reduction measures can be targeted to those areas that are most at risk of pluvial flooding, further increasing their effectiveness. Because project partners from Eindhoven were involved, and because the hydraulic model used was developed by staff in Eindhoven, the results and modelling assumptions will have more credibility to city planners, and are more likely to be taken up and further investigated. Finally, we believe that other PREPARED cities can take our generic method and apply it as required to their own individual set of circumstances to improve upon existing quantitative risk assessments.

6 Acknowledgements

We gratefully acknowledge all PREPARED project partners who contributed to this study, especially to partners in Eindhoven who dedicated valuable time, effort and resources to the work. We also gratefully acknowledge William Veerbeek for the contribution of the Rotterdam doorstep measurement data.

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APPENDIX

This Appendix shows the complete set of results for the GIS analysis. All scenarios and city zones are shown. For scenario definitions see Table 1. For further details, see Section 3.

Zone number	1a Scenario		1b Scenario		1c Scenario		2a Scenario		2b Scenario		2c Scenario		3a Scenario		3b Scenario		3c Scenario	
	Average depth (m)	Flooded area (%)	Average depth (m)	Flooded area (%)	Average depth (m)	Flooded area (%)	Average depth (m)	Flooded area (%)	Average depth (m)	Flooded area (%)	Average depth (m)	Flooded area (%)	Average depth (m)	Flooded area (%)	Average depth (m)	Flooded area (%)	Average depth (m)	Flooded area (%)
111	0.04	4.10	0.08	4	0.04	4	0.08	20	0.08	19	0.08	19	0.14	34	0.14	32	0.14	33
112	0.05	10.41	0.05	10	0.05	11	0.09	49	0.09	49	0.1	50	0.17	68	0.17	66	0.18	69
113	0	0.00	10.6	1	0	0	0.03	2	5.8	1	0.02	2	0.07	6	1.59	6	0.08	11
114	0.09	3.70	0.09	0	0.09	4	0.27	7	0.26	7	0.27	7	0.39	9	0.38	9	0.38	9
115	0.02	3.19	0.02	3	0.02	3	0.09	20	0.08	20	0.08	20	0.16	28	0.17	27	0.18	27
211	0.14	22.47	0.14	22	0.14	22	0.21	50	0.21	50	0.21	50	0.3	69	0.3	69	0.3	69
212	0	0.00	0	0	0	0	0.05	4	0.05	4	0.05	4	0.08	20	0.08	20	0.08	20
213	0	0.00	0	0	0	0	0.05	0	0.05	0	0.05	0	0.04	8	0.04	8	0.04	8
214	0.08	1.91	0.08	2	0.08	2	0.04	35	0.04	35	0.04	35	0.13	52	0.13	52	0.13	52
215	0	0.00	0	0	0	0	0.05	23	0.05	23	0.05	23	0.11	61	0.11	61	0.11	61
216	0.07	7.29	0.07	7	0.07	7	0.14	40	0.14	40	0.14	40	0.17	77	0.17	77	0.17	77
217	0.01	2.83	0.01	3	0.01	3	0.07	50	0.07	50	0.07	50	0.15	69	0.15	69	0.15	69
218	0.06	0.99	0.06	1	0.06	1	0.04	19	0.04	19	0.04	19	0.1	52	0.1	52	0.1	52
221	0.03	12.20	0.03	12	0.03	12	0.1	59	0.1	59	0.1	59	0.18	76	0.18	76	0.18	76
222	0.02	3.28	0.02	3	0.02	3	0.08	51	0.08	51	0.08	51	0.17	76	0.17	76	0.17	76
223	0.03	0.72	0.03	1	0.03	1	0.07	35	0.07	35	0.07	35	0.13	55	0.13	55	0.13	55
224	0.04	0.23	0.04	0	0.04	0	0.11	14	0.11	14	0.11	14	0.19	22	0.19	22	0.19	22
225	0.01	5.16	0.01	5	0.01	5	0.13	19	0.13	19	0.13	19	0.17	34	0.17	34	0.17	34
226	0.03	4.64	0.03	5	0.03	5	0.13	22	0.13	22	0.13	22	0.21	27	0.21	27	0.21	27
231	0.07	10.44	0.07	10	0.07	10	0.21	13	0.21	13	0.21	13	0.29	19	0.29	19	0.29	19
232	0.04	25.40	0.04	25	0.04	25	0.13	44	0.13	44	0.13	44	0.19	53	0.19	53	0.19	53
233	0.02	15.71	0.02	16	0.02	16	0.07	75	0.07	75	0.07	75	0.14	93	0.14	93	0.14	93
234	0.05	47.09	0.05	47	0.05	47	0.15	82	0.15	82	0.15	82	0.24	98	0.24	98	0.24	98
235	0.02	1.78	0.02	2	0.02	2	0.11	10	0.11	10	0.11	10	0.27	13	0.27	13	0.27	13
236	0.03	4.32	0.03	4	0.03	4	0.07	56	0.07	56	0.07	56	0.13	86	0.13	86	0.13	86
237	0.02	29.60	0.02	30	0.02	30	0.09	77	0.09	77	0.09	77	0.17	87	0.17	87	0.17	87

238	0.05	17.40	0.05	17	0.05	17	0.12	38	0.12	38	0.12	38	0.15	53	0.15	53	0.15	53
239	0.02	1.37	0.02	1	0.02	1	0.11	3	0.11	3	0.11	3	0.15	4	0.15	4	0.15	4
311	0.05	13.50	0.05	13	0.05	13	0.11	36	0.11	36	0.11	36	0.19	51	0.19	45	0.19	51
312	0.1	42.03	0.1	42	0.1	42	0.2	66	0.2	66	0.2	66	0.29	81	0.29	81	0.29	81
321	0.13	20.19	0.13	20	0.13	20	0.18	48	0.18	48	0.18	48	0.23	70	0.23	70	0.23	70
322	0.1	22.61	0.1	23	0.1	23	0.17	36	0.17	36	0.17	36	0.24	42	0.24	42	0.24	42
323	0.12	17.34	0.12	17	0.12	17	0.17	45	0.17	45	0.17	45	0.24	69	0.24	69	0.24	69
324	0.57	17.03	0.57	17	0.57	17	0.32	56	0.32	56	0.32	56	0.44	56	0.44	56	0.44	56
325	0.43	17.86	0.43	0	0.43	18	0.37	40	0.37	40	0.36	40	0.38	57	0.38	58	0.38	57
326	0	0.00	0	0	0	0	0.07	1	0.07	1	0.07	1	0.12	3	0.12	3	0.12	3
327	0	0.00	0	0	0	0	0.08	8	0.08	8	0.08	8	0.14	10	0.14	10	0.14	10
411	0.12	0.12	0.11	0	0.11	0	0.09	55	0.08	46	0.09	46	0.17	81	0.16	75	0.16	75
412	0.11	3.09	0.1	3	0.1	3	0.14	44	0.14	43	0.14	43	0.2	83	0.2	83	0.2	83
413	0	0.00	0	0	0	0	0.06	7	0.06	7	0.06	7	0.13	36	0.13	35	0.13	35
414	0	0.00	0	0	0	0	0	0	0	0	0	0	0.08	1	0.08	1	0.08	1
421	0.07	16.70	0.06	16	0.06	16	0.14	68	0.14	65	0.14	65	0.22	85	0.22	85	0.22	85
422	0.03	13.85	0.03	14	0.03	14	0.12	49	0.12	47	0.12	47	0.19	69	0.19	67	0.19	67
423	0.07	0.40	0.07	0	0.07	0	0.07	20	0.07	20	0.07	20	0.12	33	0.12	33	0.12	33
424	0	0.00	0	0	0	0	0.08	43	0.08	43	0.08	43	0.17	68	0.17	68	0.17	68
425	0	0.00	0	0	0	0	0.07	0	0.07	0	0.07	0	0.08	36	0.08	36	0.08	36
426	0.12	2.44	0.12	2	0.12	2	0.13	15	0.13	15	0.13	15	0.21	22	0.21	22	0.21	22
431	0.28	0.00	0.28	0	0.28	0	0.05	5	0.05	5	0.05	5	0.12	26	0.12	28	0.12	26
432	0	0.00	0	0	0	0	0.03	15	0.03	15	0.03	15	0.14	35	0.14	35	0.14	35
433	0.04	8.32	0.04	7	0.04	7	0.14	45	0.14	45	0.14	45	0.27	46	0.27	46	0.27	46
434	0.07	1.66	0.07	2	0.07	2	0.12	24	0.12	24	0.12	24	0.18	46	0.18	46	0.18	46
435	0.01	1.43	0.01	1	0.01	1	0.13	11	0.13	11	0.13	11	0.24	17	0.24	17	0.24	17
436	0	0.00	0	0	0	0	0	0	0	0	0	0	0.12	15	0.12	15	0.12	15
511	0.04	10.25	0.04	10	0.04	10	0.11	33	0.11	33	0.11	33	0.15	50	0.15	50	0.15	50
512	0.03	9.04	0.03	9	0.03	9	0.08	50	0.08	50	0.08	50	0.13	64	0.13	64	0.13	64

513	0.05	14.71	0.05	15	0.05	15	0.09	87	0.09	87	0.09	87	0.16	99	0.16	99	0.16	99
514	0.01	35.02	0.01	35	0.01	35	0.09	84	0.09	84	0.09	84	0.16	91	0.16	91	0.16	91
515	0	0.00	0.006	1	0	1	0.07	59	0.07	59	0.07	59	0.14	82	0.14	82	0.14	82
516	0.02	1.96	0.02	2	0.02	2	0.1	45	0.1	45	0.1	45	0.17	74	0.17	74	0.17	74
521	0.08	33.90	0.08	34	0.08	34	0.18	60	0.18	60	0.18	60	0.3	67	0.3	67	0.3	67
522	0.17	61.93	0.17	62	0.17	62	0.32	81	0.32	81	0.32	81	0.43	91	0.43	91	0.43	91
523	0.07	33.66	0.07	34	0.07	34	0.13	70	0.13	70	0.13	70	0.2	77	0.2	77	0.2	77
524	0.01	5.81	0.01	6	0.01	6	0.07	51	0.07	51	0.07	51	0.12	80	0.12	80	0.12	80
531	0.07	39.02	0.07	39	0.07	39	0.19	67	0.19	67	0.19	67	0.28	78	0.28	78	0.28	78
532	0.03	6.95	0.03	7	0.03	7	0.13	33	0.13	33	0.13	33	0.19	54	0.19	54	0.19	54
533	0.06	40.24	0.06	40	0.06	40	0.16	65	0.16	65	0.16	65	0.26	76	0.26	76	0.26	76
534	0.06	4.25	0.06	4	0.06	4	0.09	13	0.09	13	0.09	13	0.12	29	0.12	29	0.12	29
535	0.05	0.00	0.05	0	0.05	0	0.17	26	0.17	26	0.17	26	0.2	34	0.2	34	0.2	34
541	0.04	2.75	0.04	3	0.04	3	0.12	18	0.12	18	0.12	18	0.17	48	0.17	48	0.17	48
542	0	0.00	0	0	0	0	0.06	1	0.06	1	0.06	1	0.12	8	0.12	8	0.12	8
543	0.07	2.02	0.07	2	0.07	2	0.12	14	0.12	14	0.12	14	0.16	31	0.16	31	0.16	31
544	0.07	1.41	0.07	1	0.07	1	0.11	15	0.11	15	0.11	15	0.17	33	0.17	33	0.17	33
545	0.02	0.39	0.02	0	0.02	0	0.03	14	0.03	14	0.03	14	0.16	15	0.16	15	0.16	15
546	0	0.00	0	0	0	0	0.06	0	0.06	0	0.06	0	0.36	0	0.36	0	0.36	0
611	0.05	8.90	0.05	7	0.04	9	0.08	37	0.08	33	0.08	38	0.11	52	0.11	48	0.12	59
612	0.06	12.06	0.06	4	0.06	4	0.1	33	0.06	17	0.07	17	0.14	53	0.11	29	0.1	32
613	0.01	3.74	0.01	4	0.01	4	0.03	45	0.03	43	0.03	45	0.08	61	0.08	61	0.08	61
614	0.03	7.87	0.03	6	0.03	6	0.11	48	0.09	48	0.09	48	0.18	77	0.17	77	0.17	77
615	0.07	49.07	0.05	31	0.05	31	0.19	75	0.16	64	0.16	64	0.26	90	0.25	75	0.25	76
616	0.17	1.51	0.05	0	0.05	0	0.17	13	0.15	10	0.15	12	0.17	35	0.17	30	0.19	31
621	0.2	29.55	0.2	30	0.2	30	0.34	40	0.33	40	0.33	40	0.41	55	0.41	55	0.41	55
622	0.14	35.49	0.13	35	0.13	35	0.23	62	0.23	62	0.23	62	0.34	75	0.34	75	0.34	75
623	0.12	3.82	0.11	4	0.11	4	0.1	19	0.09	19	0.09	19	0.12	39	0.12	39	0.12	39
624	0.07	22.81	0.07	15	0.07	15	0.15	80	0.13	78	0.13	78	0.24	91	0.23	91	0.23	91

625	0.03	0.00	0	0	0	0	0.15	64	0.13	58	0.13	58	0.27	80	0.27	73	0.27	73
626	0.01	0.81	0.006	1	0	1	0.03	26	0.03	26	0.03	26	0.09	30	0.09	30	0.09	30
627	0	0.62	0.002	1	0	1	0.06	8	0.06	8	0.06	8	0.33	10	0.33	10	0.33	10
628	0.52	5.73	0.52	6	0.52	6	0.45	14	0.45	14	0.45	14	0.58	17	0.58	17	0.58	17
631	0	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
632	0	0.00	0	0	0	0	0.02	16	0.02	16	0.02	16	0.08	17	0.08	17	0.08	17
633	0	0.00	0	0	0	0	0.03	0	0.03	0	0.04	0	0.07	0	0.07	0	0.07	0
634	0	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
635	0	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
636	0	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
637	0	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
638	0	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
711	0.06	0.00	0.06	0	0.06	0	0.07	18	0.07	18	0.07	18	0.14	44	0.14	44	0.14	44
712	0.04	12.61	0.04	11	0.05	13	0.13	50	0.13	47	0.13	50	0.21	73	0.21	72	0.21	74
713	0	0.00	0	0	0	0	0.02	28	0.02	23	0.03	29	0.08	59	0.08	53	0.09	61
721	0.06	25.51	0.06	25	0.06	26	0.11	48	0.11	48	0.11	49	0.14	67	0.14	67	0.14	67
722	0.05	21.75	0.05	22	0.05	22	0.11	65	0.11	65	0.11	65	0.17	91	0.17	91	0.17	91
723	0.05	1.36	0.05	2	0.05	2	0.11	15	0.1	15	0.1	15	0.14	55	0.14	55	0.14	55
724	0.03	5.52	0.03	6	0.03	6	0.1	37	0.1	37	0.1	37	0.15	64	0.15	64	0.15	64
725	0.03	29.59	0.03	30	0.03	30	0.1	56	0.1	56	0.1	56	0.15	71	0.15	71	0.15	71
726	0.01	4.55	0.01	5	0.01	5	0.04	16	0.04	16	0.04	15	0.09	22	0.09	22	0.09	22
727	0.05	6.63	0.05	7	0.05	7	0.17	7	0.17	7	0.17	7	0.16	12	0.16	12	0.16	12
731	0.18	30.74	0.18	31	0.18	31	0.34	41	0.34	41	0.34	41	0.45	21	0.45	50	0.45	50
732	0.09	4.25	0.09	4	0.09	4	0.11	14	0.11	14	0.11	14	0.16	28	0.16	28	0.16	28
733	0.02	14.17	0.02	14	0.02	14	0.14	21	0.14	21	0.14	21	0.19	31	0.19	31	0.19	31