

Article

Comparing Methods of Calculating Expected Annual Damage in Urban Pluvial Flood Risk Assessments

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Abstract: Estimating the expected annual damage (EAD) due to flooding in an urban area is of great interest for urban water managers and other stakeholders. It is a strong indicator for a given area showing how vulnerable it is to flood risk and how much can be gained by implementing e.g., climate change adaptation measures. This study identifies and compares three different methods for estimating the EAD based on unit costs of flooding of urban assets. One of these methods was used in previous studies and calculates the EAD based on a few extreme events by assuming a log-linear relationship between cost of an event and the corresponding return period. This method is compared to methods that are either more complicated or require more calculations. The choice of method by which the EAD is calculated appears to be of minor importance. At all three case study areas it seems more important that there is a shift in the damage costs as a function of the return period. The shift occurs approximately at the 10 year return period and can perhaps be related to the design criteria for sewer systems. Further, it was tested if the EAD estimation could be simplified by assuming a single unit cost per flooded area. The results indicate that within each catchment this may be a feasible approach. However the unit costs varies substantially between different case study areas. Hence it is not feasible to develop unit

costs that can be used to calculate EAD, most likely because the urban landscape is too heterogeneous.

Keywords: climate change adaptation; damage cost estimation; expected annual damage; integrated risk analysis; urban flood risk

1. Introduction

Recent extreme precipitation events in Denmark have created awareness amongst the general public about the challenges faced by urban societies in order to adapt to future climate conditions. With an expected increase in high intensity precipitation patterns and with urban areas growing and becoming denser the need for adapting has become greater than ever [1,2]. On top of all of this the long technical lifetime of urban drainage systems makes it important to take the impacts of climate change into account when designing new systems or renovating existing ones [3]. The costs of flooding in urban areas are high compared to rural areas as there is a high concentration of value in cities meaning that potentially small floods result in large damage [4].

Assessing adaptation measures based on their costs and benefits also lag behind especially in large urban areas with a complex drainage network and urban context [5,6]. As research advances it appears that there is no simple solution to the adaptation challenge and strategies are often specific to the location [7]. The rise of more detailed hydraulic models and more computational power has given urban water managers a better opportunity for describing the propagation of floods by combining 1D sewer models and 2D surface flow models [8,9]. These new tools also allow for the possibility of flood damage costs to be estimated differently. With higher spatial resolution and a better description of flow processes it is now possible to try and describe the very heterogeneous patterns seen in urban areas both with regard to the extent of flooding, and the distribution of assets.

Zhou *et al.* [6] described a framework for identifying climate change adaptation options to pluvial flood risk which will be adopted in the present study. A key element in the framework is to calculate the Expected Annual Damage (EAD) given information on current and future extreme precipitation. The calculation of the EAD is associated with some assumptions and this study aimed at investigating some of these assumptions to improve the calculation of the EAD or possibly validate the existing methods. In particular the focus is on assumptions related to costing of damage with the aim of minimizing the need for hazard calculations, since these are very time consuming. Two study areas, both located in Denmark, formed the basis of the calculations carried out in this study. These results were subsequently compared to a later study by Hede & Kolby [10] in which a location from central Copenhagen was analyzed.

2. Materials and Methods

2.1. Flood Risk Assessment Framework

The framework for economic flood risk assessment consists of two main components: a flood hazard assessment and a flood vulnerability assessment. Combining the knowledge of the hazard, or

probability, with the vulnerability gives an assessment of the risk. This is done through a GIS (Geographic Information System)-based risk model which gives an instant picture of the risk at a certain point in time. An overview of the framework can be seen in Figure 1.

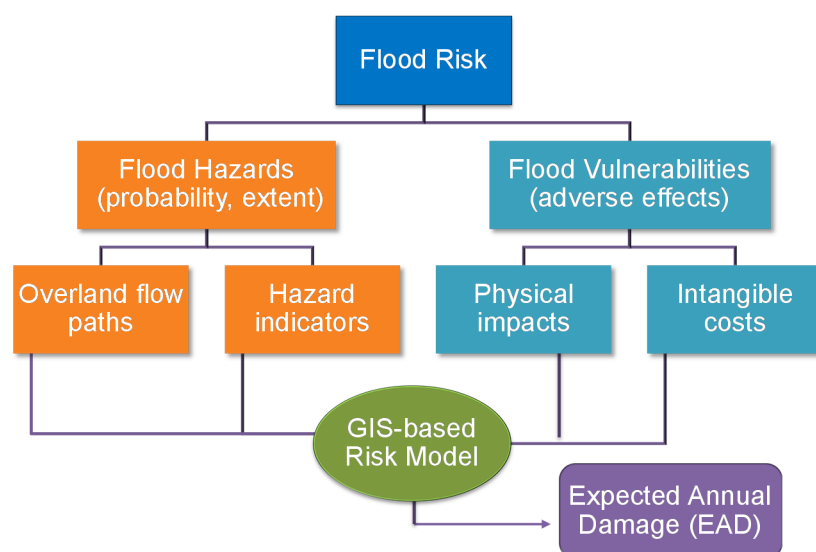


Figure 1. Framework for assessing economic pluvial flood risk [6].

2.1.1. Flood Hazard Assessment

The flood hazards are computed using a coupled 1D–2D hydraulic model which is subjected to an extreme external loading in the form of precipitation with a given return period [6]. Given the external loading, rainfall-runoff relationship, sewer system hydraulics and terrain it is possible to calculate the extent and depth of the flooding in the urban setting. The result of the flood hazard assessment is a snap-shot of the maximum water depth computed for the input external loading at a given point in time. For an event with a return period of 100 years an example of a flood hazard assessment can be seen in Figure 2. To represent the external loading corresponding to a 100 year event for all locations in the catchment with only one simulation a Chicago Design Storm is constructed based on a regional Intensity-Duration-Frequency (IDF)-curve in accordance with current design practices for Denmark [2]. Other ways to construct design storms can be applied as described in [11].

The calculation for the flood hazard assessment was done using the software from DHI (Hørsholm, Denmark) with MIKE URBAN calculating the 1D hydraulics of the sewer system and MIKE FLOOD for the overland flow computations [8,9].

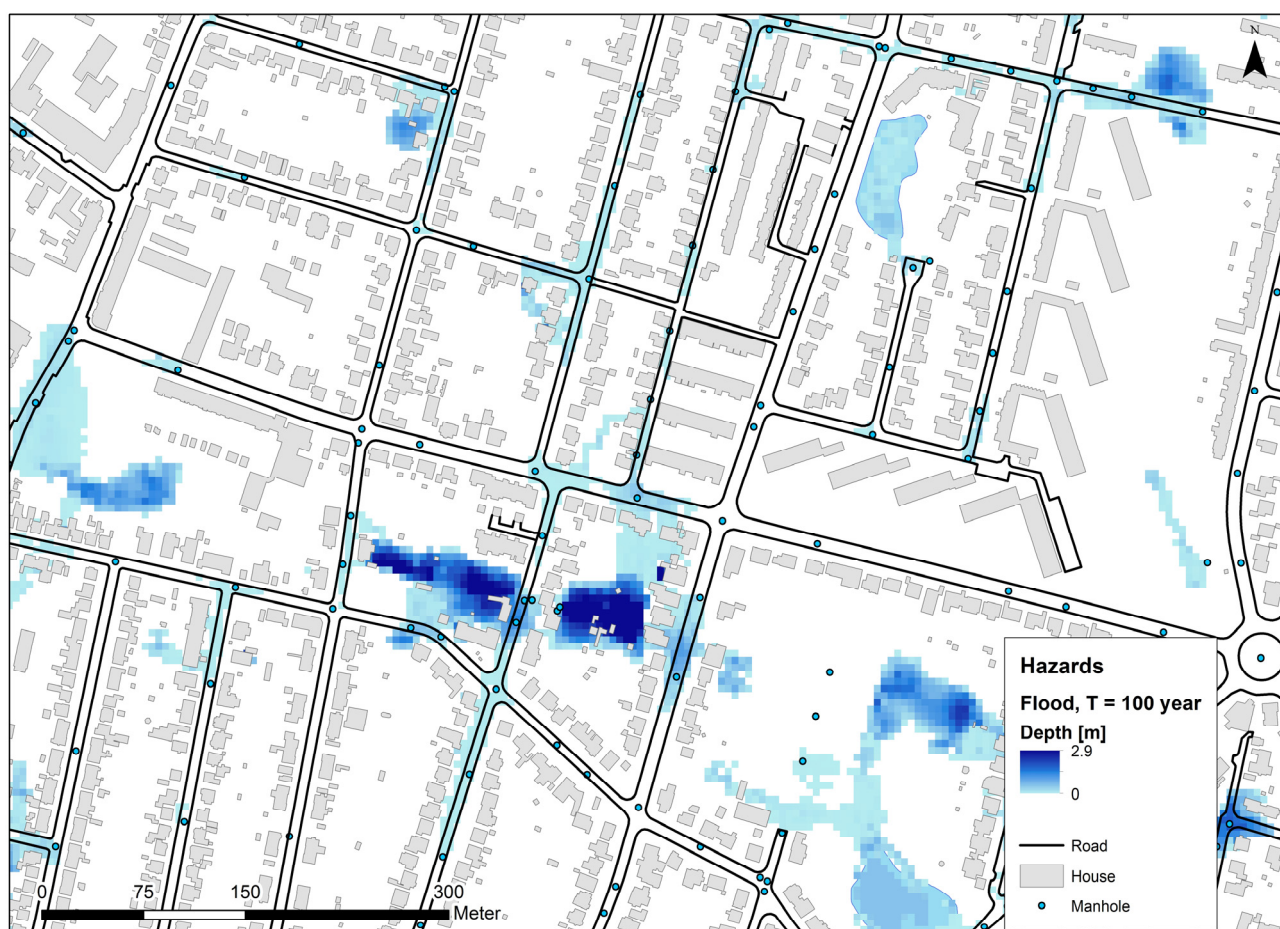


Figure 2. The result of the flood hazard assessment shows both the extent and the depth of the flooding for a given return period. Here the hazard assessment for a subcatchment in the city of Odense for a 100 year return period is shown.

2.1.2. Vulnerability Assessment

Knowing the extent and depth of a flooding it is also necessary to assess how vulnerable an urban area is to such hazards. The framework distinguishes between physical damage and intangible losses [2]. Physical damage refers to the damage done to buildings and infrastructure as a direct result of the flooding. The intangible losses are the loss of recreational value, damage to health and other inconveniences like traffic delays *etc.* [12]. In some cases costing of flooding is based on stage-damage curves, *i.e.*, a function relating damage to inundation depth and extend [4,13]. Because of the highly heterogeneous urban fabric, costing in cities is often based on unit costs of flooding of specific types of assets [6,14,15]. An example of such a vulnerability assessment can be seen in Figure 3.

For a given external loading the vulnerability of an area can be estimated through a GIS-software where the identification of flooded properties can be estimated by formulating certain threshold values for each damage class. The GIS-based risk model contains information on the location of houses, roads, recreational areas (lakes) and other damage classes. Combining this with the extent and depth of the flooding (obtained from the hazard assessment) provides damage cost estimation for a specific return period. To estimate the damage cost in each of the study areas the damage classes and unit costs shown in Table 1 were used for all case studies.

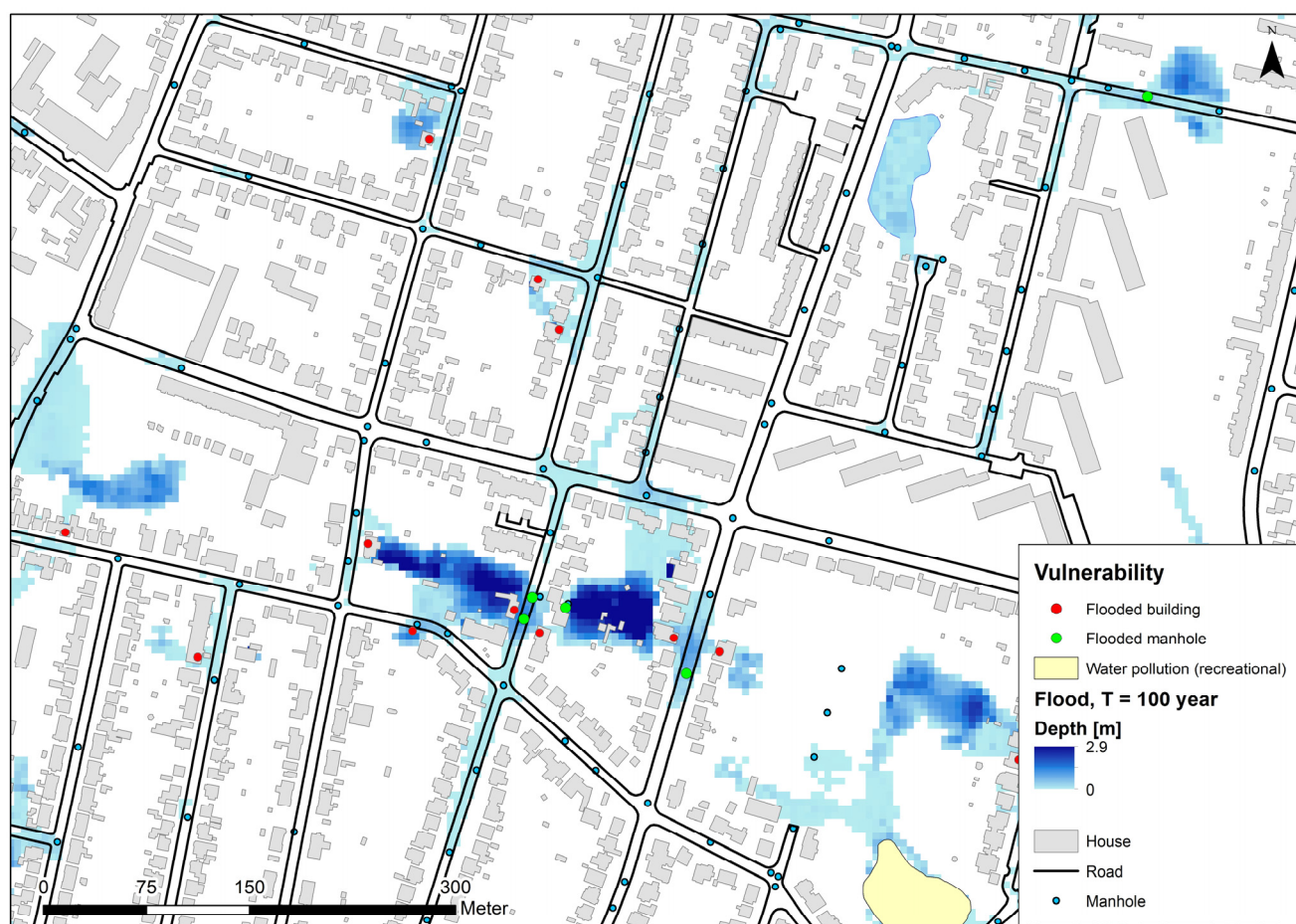


Figure 3. Vulnerability of the urban area in the city of Odense to the hazard illustrated in Figure 2.

Table 1. Overview of the damage classes and unit costs used in the flood risk assessment framework. The unit cost is incurred if (some part) of the damage class is exposed to a flood depth higher than the threshold value.

Damage Class	Flood Depth Threshold (m)	Unit Cost (EURO)
Residential	0.10	13,500
Commercial	0.10	71,150
Public Institution	0.10	62,150
Road	0.30	6,750
Manhole	0.10	1,350
Water pollution (recreational)	0.15	67,400

Not all damage classes are present in all case studies. The unit cost for pollution of a recreational area is taken from Arnbjerg-Nielsen and Fleischer [16]. The other unit costs are derived from insurance payouts after a particularly severe rain event which struck Copenhagen on the 2nd July 2011 [10]. It had an estimated cost of around 800 million EURO and according to the Swiss reinsurance company Swiss Re it was the largest damage costs due to a weather event in Europe in 2011 [17].

2.1.3. Risk Model

Carrying out the hazard and vulnerability assessment gives a flood cost related to a certain external loading in the form of the return period of the simulated event. It is necessary to carry out multiple simulations using events covering a large range of return periods, see Figure 4. For a given return period the resulting damage costs have to be compared to the probability of such an event occurring. Large events that normally cause substantial damage may not contribute a great deal to the average annual costs due to their low probability. Combining a series of events with corresponding return periods yields a curve we denote as the flood risk density curve (RDC). An example of this can be seen in Figure 5.

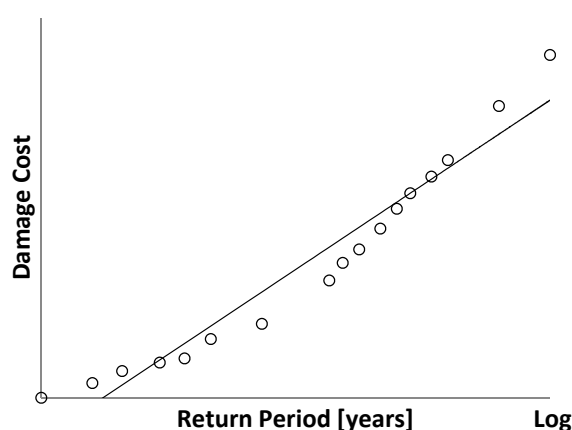


Figure 4. For increasing return periods the damage cost for the individual event will also increase. The relation can be depicted as a log-linear relation between the return period and the damage costs which allows for the extrapolation of the damage cost for the interlying return periods.

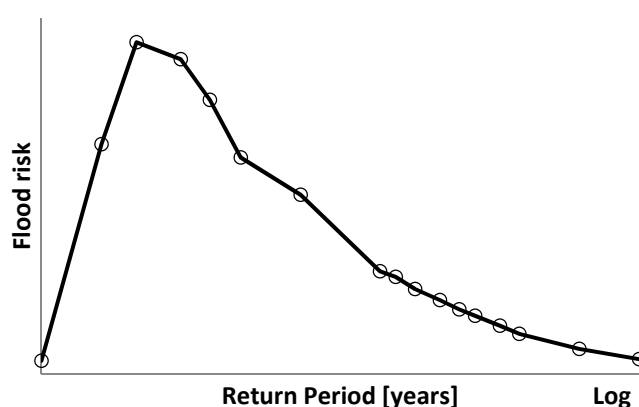


Figure 5. Flood risk density curve (RDC). Increasing return periods also means an increase in the damage costs, however also a lower probability of occurring, yielding the relation seen in this figure between the flood risk and the return period. The log-linear relation established in Figure 4 is used for construction of the RDC.

The relation between flood risk and return period displayed in Figure 5 is based on a range of different return periods used as extreme external loadings in a hydrodynamic model. The risk density curve gives a clear description of the relative contributions of the return periods to flood risk. The flood risk approaches zero for the larger events as a result of their low probability of occurrence even though the cost of such an event is large [18].

2.1.4. Expected Annual Damage (EAD)

The expected annual damage (EAD) of any given year is the integration of the flood risk density curve over all probabilities. Denoted by $D(p)$ the damage which occurs at the event with probability p (the inverse of the return period) in the catchment with area A . The EAD can then be expressed as [6]:

$$\text{EAD} = \iint_{A,p} D(p) dp dA \quad (1)$$

The integral is solved for the return period of $T_{D(p)} = 0$ (where no damage occurs at this event and with a probability of $p_{D(p)} = 0$) to the infinitely large event (probability of 0). In many cases, $T_{D(p)} = 0$ represents the actual service level of an existing drainage system, *i.e.*, the return period where damage starts to occur in the catchment. Of course it is not possible to simulate the damage cost for all events between $T_{D(p)} = 0$ and $T = \infty$. Therefore some approximation must be done in order to calculate the EAD.

The framework presented by [6] recommends the use of a log-linear relation between the return period and the damage costs which enable only very few simulations of the hazards and corresponding costs to be carried out, based on the analysis in accordance with Arnbjerg-Nielsen and Fleischer [13]. Using a log-linear model to represent exceedance series is frequently used in hydrology [14], and hence such an approximation seems reasonable.

There are other ways for calculating the EAD, *i.e.*, solving the integral in Equation (1). In this study we investigated and compared three methods, which are a simulated time series of costs, a numerical integration of all probable return periods, and an analytical solution, respectively.

(a). Generating a Long Time Series with the Same Statistical Properties as the Damage-Cost Return Period Curve.

Using a simulated time series to calculate the EAD has been used in previous studies [6,16]. It is based on calculating the expected events and associated costs that on average will occur within a prescribed observation period. In such a time series each of the events associated with damage will have precisely the return period corresponding to one of the plotting positions of the exceedance series of damage costs during that observation period [19]. In the present context a distribution free plotting position is favored, *i.e.*, the median plotting position [20]:

$$T = \frac{1}{p} = \frac{n + 0.4}{m - 0.3} \quad (2)$$

where p is the exceedance probability, n is the length of the simulated time series period and m is the rank of the event within the observation period. In other words, when simulating an observation period of 100 years the largest event (rank 1) is the event corresponding to a return period of 143 years. Similarly the second highest expected cost corresponds to the cost of a 59 year event, and so forth. The

EAD can then be calculated as the sum of all damage costs of the different return periods divided by the length of the observation period as illustrated in Table 2. The method is described in more detail in Arnbjerg-Nielsen and Fleischer [16] where it is also demonstrated how to apply the method using only two flood simulations using the log-linear model shown in Figure 4.

Table 2. Overview of calculation of expected annual damage (EAD) (using method (a)).

Rank	Return Period	Damage Cost for Event
1	T_1	C_1
2	T_2	C_2
3	T_3	C_3
...	...	...
m	T_m	C_m
Total cost	-	$\sum_{i=1}^m C_i, \text{ for } C_i > 0$
EAD	-	Sum/ n

(b). Estimating EAD Using Numerical Integration

As mentioned previously the EAD can be calculated by integrating flood damage over all probabilities. This is done by calculating the cost for n return periods where both hazards and vulnerabilities have been calculated. Several different methods for numerical integration exist; however, the trapezoidal rule is often used, leading to the following equation:

$$\text{EAD} = \frac{1}{2} \sum_{i=1}^n \left(\frac{1}{T_i} - \frac{1}{T_{i+1}} \right) (D_i + D_{i+1}) \quad (3)$$

where n is chosen so that all relevant return periods are covered from negligible cost of quite frequent events to very rare events.

(c). An Analytical Solution for EAD Estimation

Using the log-linear relation in approach a) it is also possible to assess the EAD through analytical integration. Assuming that the damage cost for a the return period T can be expressed as: $D(T) = a + b \times \ln(T)$. The EAD can then be calculated analytically as:

$$\text{EAD} = \int_0^{\exp(\frac{a}{b})} (a - b \ln(p)) dp = [p(a - b \log(p) + b)]_0^{\exp(\frac{a}{b})} = b \exp(\frac{a}{b}) \quad (4)$$

The integration is performed from a probability of 0 ($T = \infty$) to the point where the log-linear function intersects with the x-axis implying the case with the flood damage no longer occurs.

2.2. Hypotheses to Be Tested

In principle the three methods should yield similar results under the assumption that the postulated log-linear relationship is reasonable. However, the amount of required hazard calculations differs substantially. Hence the main hypothesis to be tested is that the log-linear relationship is reasonable.

A second hypothesis is to see if the heterogeneity of the urban layout prohibits the use of a single unit cost per flooded area.

3. Study Areas

Two areas located in the cities of Odense and Aarhus, respectively, are used for testing the methods for calculating the EAD, see Figures 6 and 7. Both of the areas are located in close proximity to the sea which serves as the receiving water body for the storm water. Both of these systems can be described as fully developed low density residential areas. The study area used by Hede & Kolby [10] covers part of central Copenhagen. It consists of a combined system that discharges its excess storm water to the harbor through a series of combined sewer overflows (CSO). A layout of the area can be seen in Figure 8. It is larger and more complex than the other two catchments in the sense that it contains part of Central Copenhagen as well as densely developed urban areas. Adding this catchment to the study gives an indication of whether the findings may be scaled to larger catchments. A summary of the catchment characteristics are given in Table 3.

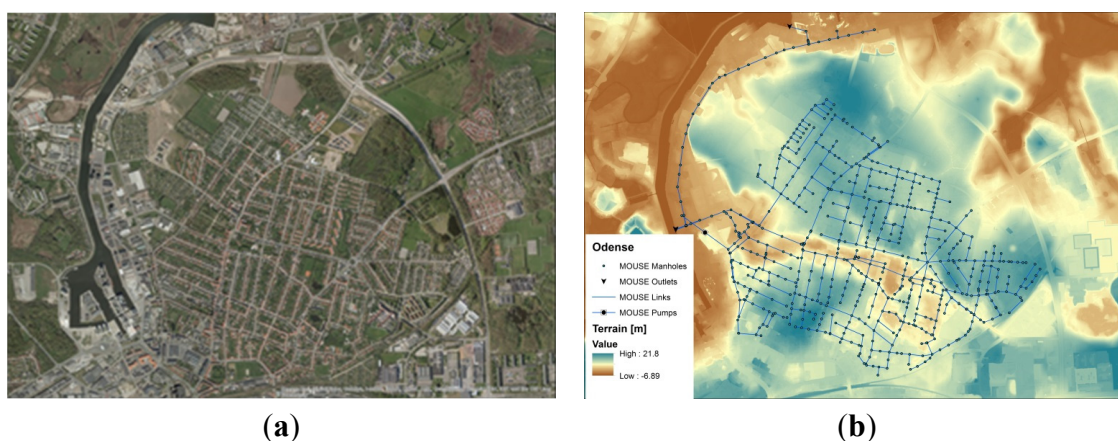


Figure 6. Study area located in Odense, Denmark. The area is a fully developed residential area with a combined sewer system. (a) shows an orthophoto while (b) shows the digital surface terrain as well as the sewer layout.



Figure 7. Study area located in Aarhus, Denmark. The area is a fully developed residential area with a combined sewer system. (a) shows an orthophoto while (b) shows the digital surface terrain as well as the sewer layout.

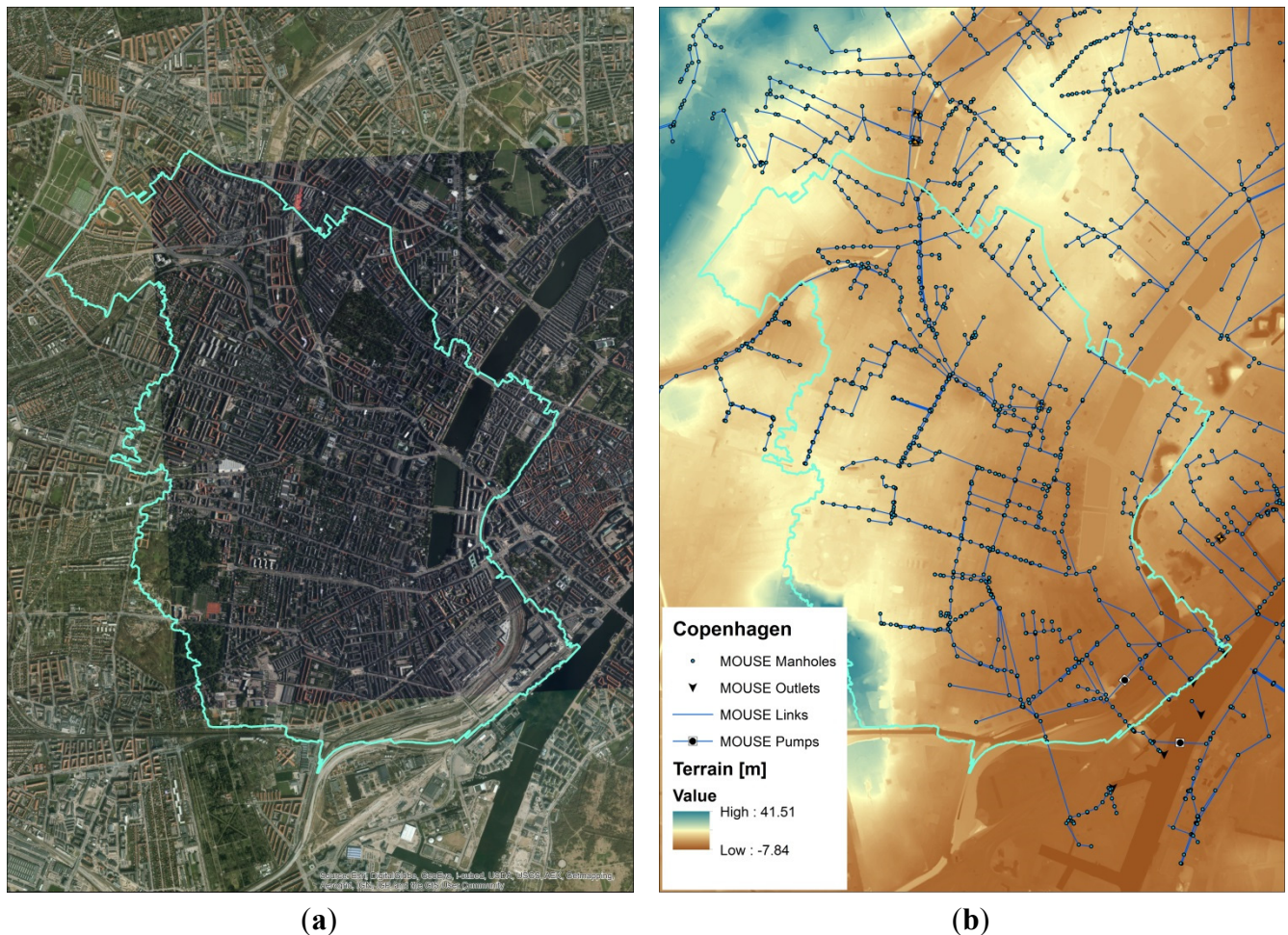


Figure 8. The study area used by Hede& Kolby [10] is located in central Copenhagen and is a dense urban area with combined sewer overflows (CSOs) located in the southern part of the area which discharges to the harbor when the system capacity is exceeded. (a) shows an orthophoto while (b) shows the digital surface terrain as well as the sewer layout.

Table 3. Main characteristics of the case study areas.

Area	Type	Sewer System	Size (ha)	Degree of Paved Area
Odense (Skibhus)	Residential	Combined	389	0.33
Aarhus (Risskov)	Residential	Combined	377	0.17
Copenhagen (Nørrebro)	Residential/Commercial	Combined	1080	0.55

4. Results and Discussion

The three methods for calculating the EAD were tested on the catchments in Odense and Aarhus. Carrying out a larger number of simulations enables a better examination of the relationship between the damage cost and the return period. For the two initial study areas the results for the damage cost calculations are shown in Figures 9 and 10.

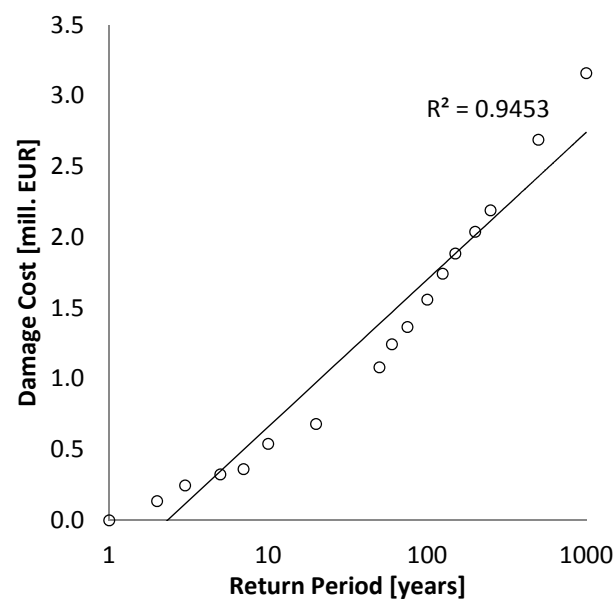


Figure 9. Log-linear relation between damage costs and the return period for the study area in Odense.

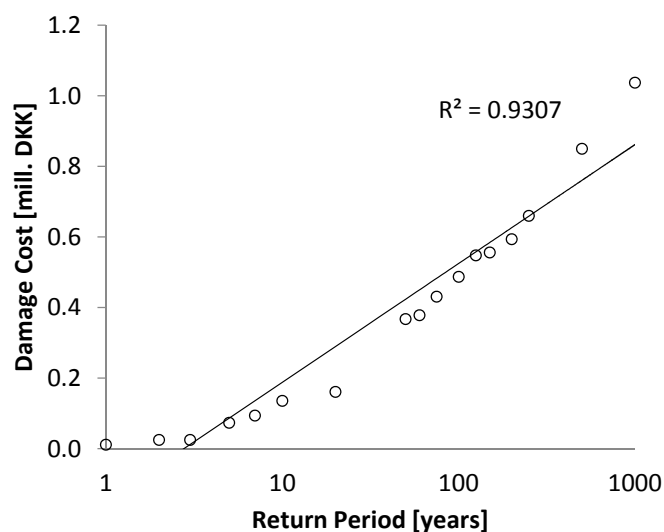


Figure 10. Log-linear relation for the study area located in the city of Aarhus. Note that this area has lower damage costs than the area located in Odense.

From Figures 9 and 10 it can be seen that the relation between the damage costs and the return period develops smoothly. However, a shift seems to be evident in the sense that the smaller events (below a return period of approximately 20 years) follow one log-linear relation and the larger events follow a different relation. Accounting for this shift in the log-linear relation yields the results seen in Figures 11 and 12. This shift in the relationship occurs for both systems and at the same return period and is also present in the third catchment (not shown). As indicated in Figures 11 and 12 the log-linear relationship for high return periods crosses the x-axis at a return period of 10 years which corresponds to the design criteria with which the sewer systems were originally designed [21]. Shifts in the cost function because of design criteria are possible, as discussed by e.g., Ward *et al.* [18]. Hence it is likely

that this shift is due to redevelopment in the area after the sewer system was designed. However, further testing of this hypothesis would require calculation of more catchments and/or information about the precise history of the development of the catchments. This is not available for the present study. Regardless of the reason it is clear that the model accounting for the shift in the log-linear relation has a higher ability to describe the costs and hence gives a better representation of the total flood risk for the catchments.

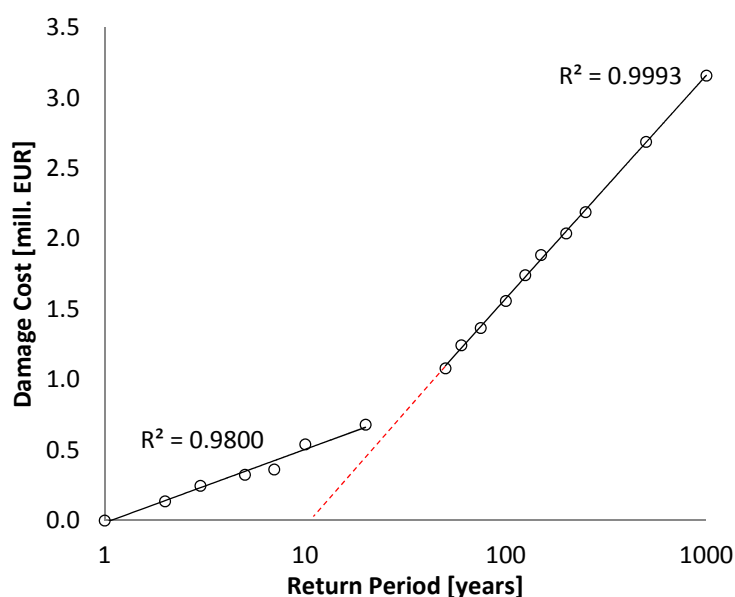


Figure 11. Accounting for the shift in the log-linear relation for the study area in Odense.

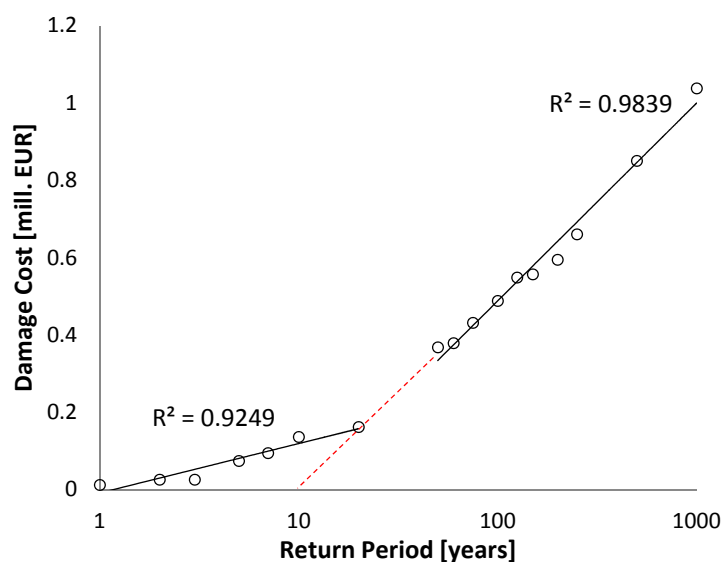


Figure 12. Accounting for the shift in the log-linear relation for the study area in Aarhus.

As shown in Table 4 there are only relatively small differences between the three methods to calculate EAD. The three different solutions tested for the EAD all give values between 179,000 and 227,000 EUR/year for the Odense study area and 47,900 and 54,700 EUR/year for the Aarhus study area. The values for the EAD are systematically higher for both study areas when the log-linear shift is accounted for, while no other tendencies can be identified. This indicates that probably the shift around the design level is the most important factor to take into account, if more detailed analyses are needed. Based on the analysis of the two catchments it seems that the analytical solution assuming a single log-linear relationship is sufficient. Hence this is favorable since it requires the least amount of hazard calculations even though it gives the highest value of EAD of the three methods. When using the EAD for cost-benefit analysis (CBA) the input is the reduction EAD before and after risk reduction measures. Hence a slight overestimation of EAD both before and after will tend to cancel out and the net result in a CBA will be negligible.

Table 4. Overview of the resulting EAD based on the calculation method used.

Method	Accounting for Log-Linear Shift	EAD [1000 EUR/Year]	
		Odense	Aarhus
(a) Simulated time series	No	189	51.0
	Yes	220	52.5
(b) Numerical solution	No	179	47.9
	Yes	210	49.4
(c) Analytical solution	No	194	52.8
	Yes	227	54.7
Average	-	203	51.4

One of the disadvantages with the EAD calculations described and tested in the previous study is that they can be quite time consuming and require access to the relevant GIS-information on the different damage classes. Hence it needs to be tested whether an average damage cost per flooded area is sufficient to describe the calculated costs. A simple way to test this hypothesis is to plot the calculated cost per area *versus* the return period as shown in Figure 13. The calculated damage cost per area is obtained by dividing the calculated costs for a given return period by the area that is flooded by more than a threshold value. The result is shown for two threshold values, 10 and 20 cm, respectively. For comparison the same unit cost is shown for Copenhagen for a threshold value of 10 cm.

Based on the results from the case study areas it seems that the hypothesis is reasonable for return periods higher than 10 years, but that the unit cost varies substantially between catchments. In particular the Copenhagen area has a different unit cost, which may be due to the different land use compared to the other areas. However, even the differences between Odense and Aarhus are quite large. Hence it may be reasonable to use the amount of flooded land as an indicator for vulnerability, but it is not reasonable to convert this indicator to a calculation of EAD. Hence it is confirmed that the vulnerability assessment in urban areas should be based on a rather detailed assessment of land use, if possible. This is also the suggested approach in other papers, e.g., [18,22].

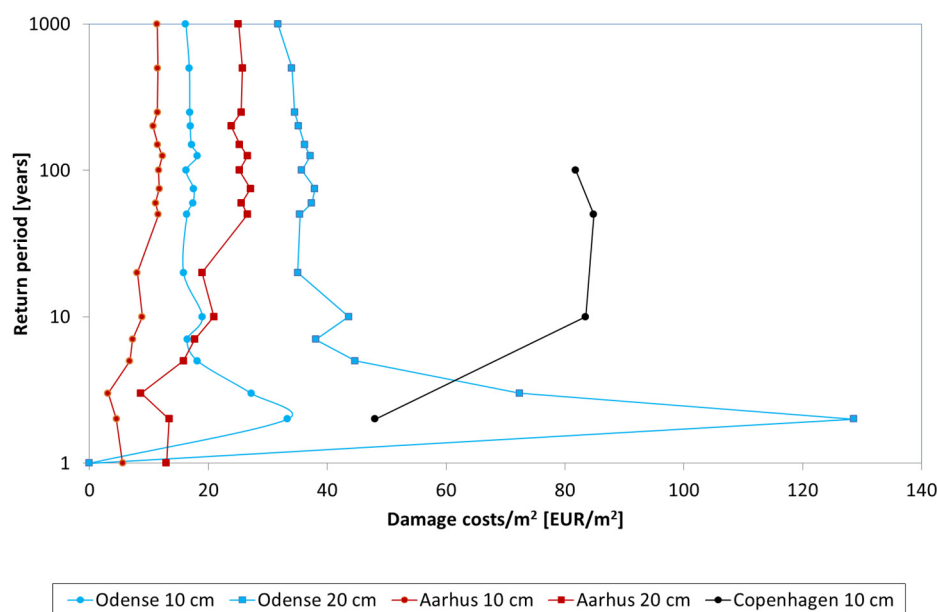


Figure 13. Damage costs/m² for the two areas in Aarhus and Odense compared to the cost in Copenhagen. Each point on the line represent a specific return period from $T = 1$ to $T = 1000$ years.

5. Conclusions

In this study three different methods were tested for calculating the Expected Annual Damage (EAD), all based on the log-linear relation between the damage cost and the return period. By carrying out multiple simulations for varying return periods it is possible to better describe the relationship between return periods and calculated costs, but the improvement is small. For both case studies a shift in the costs was identified around a return period of 10 years. This corresponds to the Danish design guidelines for urban drainage systems and hence the shift may be due to city development occurring after the sewer system has been constructed. The three calculation methods of the EAD were tested with and without considering the log-linear shift. The results indicate that the three methods yield very similar results. The identified shift in costs occurring at the design return period was more important than the method to calculate the EAD.

Using the amount of flooded area as an indicator for vulnerability seemed a feasible approach, especially for larger return periods. However, for small return periods the method was not suitable, and variations in vulnerability between catchments and choice of flood threshold is large. Hence it seems that cities are too heterogeneous to allow calculation of the EAD based on this approach.

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Author Contributions

The study was scoped by Karsten Arnbjerg-Nielsen and Jens Jørgen Linde. They also assisted with developing the approach as well as providing the data. The simulations of the catchments in Odense and Aarhus were carried out by Anders Olsen under close supervision of Qianqian Zhou. The bulk part of the text was written by Anders Olsen and Karsten Arnbjerg-Nielsen with frequent and substantial input to the writing process from all co-authors in the form of feedback and suggestions for improvement.

Conflicts of Interest

The authors declare no conflict of interest.

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