Journal of
Flood Risk Management

How the choice of flood damage metrics influences urban flood risk assessment

J.A.E. ten Veldhuis

Watermanagement, TU Delft, Delft, the Netherlands

Correspondence
J.A.E. ten Veldhuis, Watermanagement,
TU Delft, Delft, 2628CN, the Netherlands
Email: j.a.e.tenVeldhuis@tudelft.nl

DOI: 10.1111/j.1753-318X.2011.01112.x

Key words
Flood damage assessment; flood risk;
urban flooding.

Abstract

This study presents a first attempt to quantify tangible and intangible flood damage according to two different damage metrics: monetary values and number of people affected by flooding. Tangible damage includes material damage to buildings and infrastructure; intangible damage includes damages that are difficult to quantify exactly, such as stress and inconvenience. The data used are representative of lowland flooding incidents with return periods up to 10 years. The results show that monetarisation of damage prioritises damage to buildings in comparison with roads, cycle paths and footpaths. When, on the other hand, damage is expressed in terms of numbers of people affected by a flood, road flooding is the main contributor to total flood damage. The results also show that the cumulative damage of 10 years of successive flood events is almost equal to the damage of a singular event with a T = 125 years return period. Differentiation between urban functions and the use of different kinds of damage metrics to quantify flood risk provide the opportunity to weigh tangible and intangible damages from an economic and societal perspective.

Introduction

Previous studies have shown that direct tangible damage cannot sufficiently describe flood consequences and that intangible damage, particularly physical and mental health effects should be included in the appraisal of flood risk alleviation schemes (Ohl and Tapsell, 2000; Tapsell and Tunstall, 2003; Defra, 2004; Fewtrell and Kay, 2008). A proper aggregation of quantified flood risk is key to support decision making and can be accomplished by different flood damage metrics, monetary values being most commonly used (Dutta *et al.*, 2003; Jonkman *et al.*, 2003; Merz *et al.*, 2004; Thieken *et al.*, 2005). This is understandable from a decision-making point of view, as monetary values are most easily compared with capital investments. The question arises whether decisions based on monetarised flood risk sufficiently account for all types of urban flood damage, tangible as well as intangible, thus whether such decisions result in proper flood protection.

In low-lying countries urban pluvial floods are characterised by small depths and consequently small direct flood damage. For instance, in the Netherlands direct pluvial flood damage rarely exceeds €3500/household (Jak and Kok, 1999; van der Bolt and Kok, 2000; net present value 2009, for interest rate 4%). As a result, the relative importance of intangible damage like disturbance of traffic and inconvenience for pedestrians caused by pools on parking lots and sidewalks is high. On the contrary, damage characteristics of river floods and flash floods in hilly areas are entirely different. In this case, flooding spreads over large areas and may lead to evacuation of people and complete disruption of communities. Direct damage to buildings and infrastructure is large and cannot be compared with the costs of traffic delay or inconvenience (see, e.g. Penning-Rowsell *et al.*, 2005). The nature of intangible damage is different as well: severe floods may cause business interruption, supply-chain interruption and psychological stress following evacuation and insurance claim procedures. In lowland areas, pluvial flooding does not lead to evacuation; damage to buildings, if any, consists of cleaning costs and in some cases replacement of ground floor carpeting. Under these conditions, the contribution of traffic delay and inconvenience to flood damage becomes important.

Current standards for urban pluvial flooding are usually based on flooding frequencies and do not explicitly take flood damage into account. European standards recommend a flooding frequency depending on occupational land use: once in 10, 20, 30 or 50 years for rural, residential, commercial and city areas and underground railways and underpasses (CEN, 2008). In practice, these flooding standards are often interpreted as maximum sewer surcharge or maximum road flooding frequencies: hydrodynamic models are used to check compliance with the standards and these calculate

Table 1 Primary functions of urban drainage systems and damage classes used for municipal call classification. The numbers of calls in each class are given for the case of Haarlem city

Primary functions		Damage classes	No. of calls
Protection of human health: physical harm or infection	C1	Flooding with wastewater (toilet paper/excreta)	20
	C2	Manhole lid removed	4
Protection of buildings and infrastructure against flooding: damage to public and private properties	C3	Flooding in residential building (house/flat/garage/shed)	78
	C4	Flooding in commercial building (shop/restaurant/storage hall)	26
Prevention of road flooding: traffic disruption	C5	Flooding on residential/main road	596
	C6	Flooding of sidewalk/cycle path	344
	C7	Flooding at bus stop/taxi stand/bus or train station	18
	C8	Flooding in shopping street/commercial centre	155

sewer surcharge and manhole flooding. Implicit in this method of evaluation of flooding standards is the assumption that most buildings are located above road level and that by protecting roads, buildings are protected, too. In current practice, this assumption is not verified. Recent developments in two-dimensional overland flow modelling should enable flooding calculations at building level in the future.

Climate change projections have triggered a debate among urban drainage professionals in the Netherlands whether current standards should be applied to roads and buildings alike or whether temporary flooding of roads and public spaces can be accepted and only buildings should be protected under a given standard. In the light of this discussion flood damage estimation methods should be available that adequately represent tangible and intangible damages associated with flooding of buildings, roads and other infrastructure.

The aim of this paper is to compare two types of metrics for urban pluvial flood damage estimation incorporating tangible and intangible damage to buildings, roads and other urban infrastructures: monetary values based on stage-damage functions and the number of people affected by flooding based on municipal call centre statistics. Tangible damage refers to material damage to structures, whereas intangible damage refers to damages that cannot be quantified exactly, such as stress and inconvenience. The results are used to quantify urban pluvial flood risk for a case study and to evaluate how the choice of metrics influences the outcomes and, consequently, investment decisions based on these outcomes.

Materials and methods

The primary data used in this study consist of data from municipal call centres that register information on urban drainage problems observed by citizens. Call data are available for a period 10 years for Haarlem, a city of 147 000 inhabitants. Most calls refer to problems of local flooding, ranging from local flooding of a road or parking lot to flooding inside residential and commercial buildings. Call texts describing citizens' observations constitute a series of detailed event data, as they provide information on time, location and characteristics of flooding. A damage classification for urban flood-related calls was developed for this study, based on the primary functions of urban drainage systems (Butler and Davies, 2004). Table 1 gives a summary of primary functions and damage classes that were used for call classification. For illustration, the numbers of calls in each class for the case of Haarlem are added.

The assignment of classified calls to independent flooding incidents results in a list of incidents and numbers of calls per damage class per incident. These results are translated into damage estimates per incident per damage class by multiplication of the number of calls per incident per class and estimated damage per call for that particular class. Integration of damages over all incidents per class results in total damage estimates per damage class.

Translations of call numbers to damage estimates are based on a number of assumptions with respect to the amount of damage and the number of affected people per call for each damage class. Uncertainty introduced through these assumptions is incorporated in damage calculations by assuming that each damage estimate has a uniform probability distribution: it varies between a minimum and a maximum estimate and all values in between have an equal probability.

Assumptions for translation of flood damage into monetary values: stage damage curves

Stage-damage curves are usually based on information about depth, velocity and other characteristics of flood waters. If call texts are to be used as input for stage-damage curves, a

Table 2 Assumptions damage metrics for flood risk assessment

	Damage classes	Monetary damage		Remarks
		Min (€)	Max (€)	
C1	Flooding with wastewater	0	220	Max: WTP to prevent health effects of flooding
C2	Manhole lid removed	0	220	Idem C1
C3	Flooding in residential building	1000	30 000	Min: cleaning costs only; max: flood depth 10 cm, medium building value
C4	Flooding in commercial building	2000	30 000	Idem C3; min cleaning costs for larger building surface
C5	Flooding on residential/main road	10	700	10–700 vehicles; 5 min delay/vehicle; €12.5/hr
C6	Flooding of foot//cycle path	0	220	Idem C1
C7	Flooding at bus stop/taxi/train station	0	220	Idem C1

flood depth must be derived from the call text. Call texts do not specify flood depths; they repeatedly mention that 'water comes flowing into the house' or similar statements. Call texts indicate that floors and carpets are often wetted, yet water depths are unlikely to exceed 10 cm: none of the calls mention high water levels or high velocity flows. Because flood depths are small, only the low ranges of stage-damage functions are applicable.

In this study, stage-damage information from studies in Germany (Apel *et al*., 2008; 2009) and the Netherlands (Gersonius *et al*., 2006) is used. As a first approximation, a flood depth of 10 cm was assumed for all calls in classes concerning flooding of buildings. Related damage according to stage-damage functions varies from €10 000 to €30 000 for residential buildings. A minimum of €1000 was assumed here to account for cleaning costs. None of the call texts related to flooding of commercial buildings report damage to inventories, one call mentions that customers tend to leave as water flows in. As available information does not suggest principle differences in costs, the same stage-damage functions were used for residential and commercial buildings. Yet for commercial buildings a higher minimum of €2000 per flooded building was assumed to account for higher cleaning costs.

Assumptions for translation of flood damage into monetary values: traffic delay costs and inconvenience

No references of stage-damage curves for traffic losses caused by urban flooding have been found. Traffic losses mainly relate to the costs of traffic delay, which have been quantified in congestion cost studies. Most of these studies relate to highways, few relate to traffic in urban areas. Bilbao-Ubillos (2008) quantified congestion costs in urban areas at €12.50 per hour of delay.Based on traffic counts for main roads in Haarlem (Gemeente Haarlem, 2008) a minimum and a maximum amount of vehicles were estimated for residential roads. A traffic delay of 5 min per vehicle was assumed for pools on residential roads, equal to a delay of one cycle at traffic lights.

Flooding of cycle paths, sidewalks, bus stops, etc. merely causes inconvenienceto cyclists and pedestrians. A study in the UK (Defra, 2004) quantified the willingness-to-pay to avoid health impacts associated with flooding. Health impacts included physical and psychological effects of homes being flooded. Although these effects refer to a more serious type of flooding experience, the willingness-to-pay (WTP) value from this study was taken as an upper boundary: €220. The lower boundary was set at €0.

Assumptions for translation of call data into monetary damage are summarised in Table 2, for all classes.

Assumptions for translation of flood damage into numbers of affected people

Table 3 summarises assumptions used in this study for numbers of affected people per call in every damage class. Assumptions for car and cycle traffic were based on traffic density figures from the yearly statistics report for the city of Haarlem, year 2007 (Gemeente Haarlem, 2008). Assumptions on pedestrian traffic and sizes of households and commercial personnel are based on oral communications with experts.

Results and discussion

Figure 1 gives a graphical presentation of expected values and standard deviations per consequence class. It shows that cumulative monetary damage to residential buildings (class C3) is significantly larger than monetary damage to commercial buildings (C4) and monetary damage caused by flooding of roads (C5), of sidewalks and cycle paths (C6) and of bus stops (C7). Monetary damage to commercial buildings is of the same order of magnitude as monetary damage caused by flooding of roads; commercial buildings is associated a low incidence of flooding and large damage per incident, whereas road flooding has a high incidence and small damage per incident. The number of people affected by road flooding is larger than for all other classes. The expected values of numbers of people affected for classes C1 to C4 and

Table 3 Assumptions for numbers of affected people per call in damage class

	Damage classes	No. of affected people Min	Max	Remarks
C1	Flooding with wastewater	10	100	10–100 pedestrians or cyclists on cycle or footpath
C2	Manhole lid removed	5	500	5–500 cyclists or cars on road or cycle path*
C3	Flooding in residential building	2	5	Size of household
C4	Flooding in commercial building	2	10	Owner, personnel and customers
C5	Flooding on residential/main road	30	500	30–500 vehicles per 15 min*
C6	Flooding of foot/cycle path	5	115	5–115 cyclists per 15 min*
C7	Flooding at bus stop/taxi/train station	10	20	10–20 travellers waiting at bus stop/station

**Source*: Gemeente Haarlem, 2008. Yearly statistics 2007.

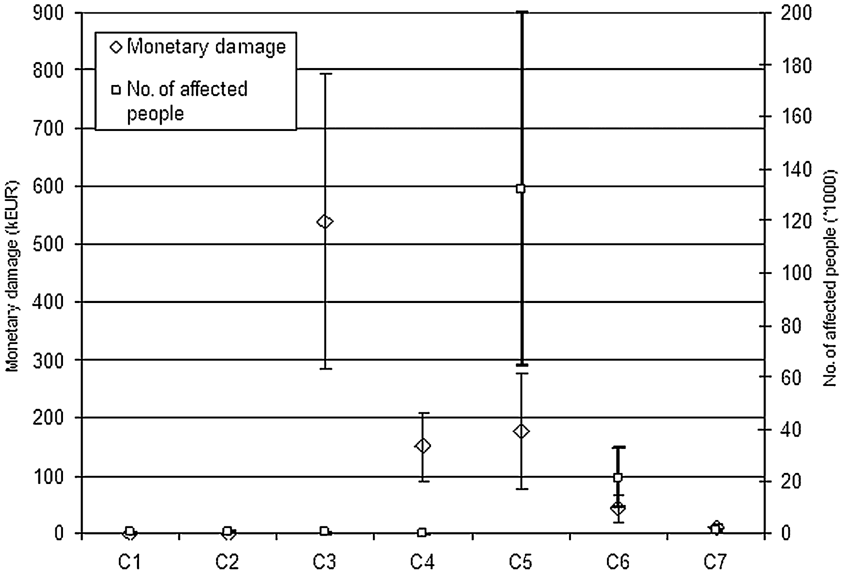

Figure 1 Total urban flood damage for damage classes C1 to C7 for the city of Haarlem, period 1997–2007. Data points show mean values of monetary damage and number of affected people per class, error bars show standard deviations from the mean.

C7 are less than 1% of the expected value of the number of people affected for class C5. Figure 1 shows that even if damage estimates are subject to large uncertainty as a result of assumptions underlying cost calculations, discrepancies between damages in most classes are significant.

Figure 2 shows minimum and maximum values monetary damage and numbers of affected people in terms of damage per kilometre sewer length per year. This representation allows comparison with other cities of different size and total sewer length (ten Veldhuis, 2010). Figure 2 shows that threats to human health caused by wastewater flooding and uplifted manholes are almost negligible, as a result of low occurrence and low damage values. Monetarised damage to buildings exceeds other kinds of monetarised damage, yet the number people affected by building flooding is low. Flooding of roads, cycle paths and foot paths results in low monetary damage, yet affects large numbers of people.

The results show that flooding of buildings contributes most to flood damage expressed in monetary values, whereas road flooding affects the largest number of people. The results presented in ten Veldhuis (2010, Chapter 4) show that the same result applies to two different case studies in lowland areas, Haarlem and Breda. Therefore, the results shown in Figure 2 are likely to be representative of flooding incidents with return periods of less than 10 years in medium size cities in lowland areas. The question to what extent results of the two case studies can be generalised to other cities in lowland areas is discussed in ten Veldhuis (2010).

For comparison, the cumulative costs of building flooding as a result of small flood events, as calculated in this study, is compared with the costs of building flooding as a result of a singular rare event. The cumulative costs for small events are derived based on the assumptions presented in Tables 2 and 3; rare event damage data are derived from Van der Bolt and Kok (2000). Their data concern a pluvial flood event in 1998 with an estimated return period of 125 years. This event was classified as a national disaster and fell under the Dutch

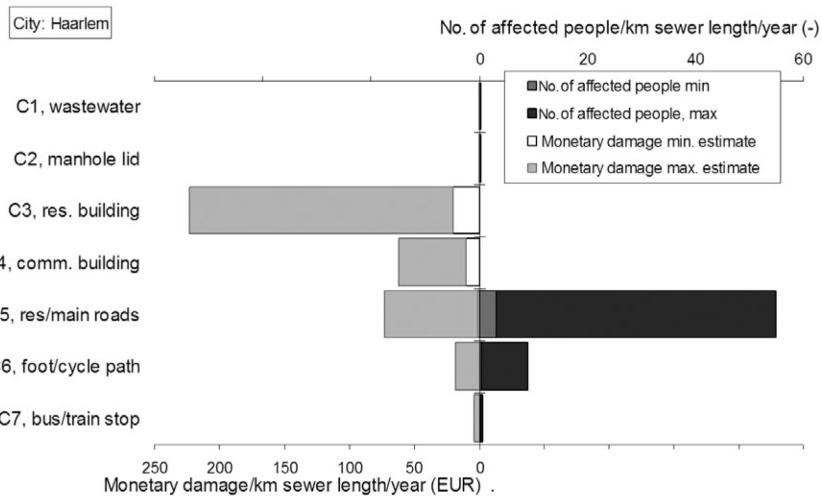

Figure 2 Monetary flood damage in EUR per kilometre sewer length per year and number of people affected by flooding per kilometre sewer length per year for damage classes C1 to C7, case of Haarlem.

Table 4 Cumulative flood damage to buildings and roads for 10 years of successive events versus singular event damage to buildings for a rare event

Flooding of buildings	Monetary costs (*1000 €)	Number of people affected	Monetary costs/affected person (€)	Monetary costs/affected person/year (€)[¶]
Flooding of buildings (tangible damage)				
Expected value of cumulative costs of small events, 10 years	689	490	1400	140
Costs of T = 125 years event	3 255[†]	2 400[‡]	1360	55[¶]
Flooding of roads, cycle paths etc. (intangible damage)				
Expected value of cumulative costs of small events, 10 years	230	155 000	1.5	0.14
Sewer tax (partially spent on flood protection)				
Cumulative sewer taxes, 10 years	68 000[§]	147 000	450	45

[†] 2009 value, based on1999 value €2000/house and interest rate 4%; 1050 houses. [‡] 1050 houses, average household size 2.3 (CBS, 2009). [§] Average sewer tax 1997–2007: €90/year; 76 000 households. [¶] Net present values of yearly expected damage, based on 4% interest rate.

Compensation Act. Table 4 presents a summary of the cumulative costs of successive events over a 10-year period versus the costs of the T = 125 years event. The first row gives the expected values for cumulative costs and cumulative number of affected people of small events over a period of 10 years: it shows expected values of monetary costs and of the number of affected people in total (first two columns), per person (third column) and per person per year (last column). The second row gives the damage of the T = 125 year event, in total for 1050 houses, per person and the equivalent annual damage per person per year. The latter value is calculated as the yearly value that would be paid to repay the damage over a period of 125 years, at a 4% interest rate (Eqn 1). In this case it is assumed that the damage would occur at the beginning of the 125-year period and subsequently be repaid.

$$EqAD_{125} = P * \frac{i * (1+i)^{T}}{(1+i)^{T} - 1} \tag{1}$$

where $EqAD_{125}$ is the equivalent annual damage of T = 125 year event; P is the amount of damage on which interest is calculated for repayment i, which is the interest rate, and T is the length of repayment period.

Alternatively, the contribution of $T = 125$ years and rarer events could be calculated as the area under the cumulative damage graph, according to:

$$EAD_{125+} = P * \lim_{n \to \infty} \frac{1}{T} - \frac{1}{n} \tag{2}$$

where EAD_{125+}, contribution of events with return period and $T = 125$ years and larger to the expected annual damage.

This results in a value of €11 instead of €55; note that in the latter case no interest rate is taken into account. The values in Table 4 show that the cumulative monetary damage to buildings per affected person over a period of 10 years is of the same order of magnitude as the damage per person for a T = 125 years event.

Although the severe event damage was considered eligible for compensation by the national government, cumulative damage of small events is not compensated; the responsibility is left with private owners to seek insurance against pluvial flood damage.

This outcome confirms a risk-averse attitude (Vrijling, 2001): even though the yearly expected damage of small events if of the same order of magnitude as annual expected damage related to a T = 125 years event (according to the last column of Table 4), the latter is compensated for by government authorities and the former is not. This suggestssmall accidents are more easily accepted than one single rare accident with large consequences, even though the annual expected damage is similar in both cases The results also show that for people affected by flooding of buildings, the yearly damage is likely to exceed the amount of yearly sewer tax paid. Sewer tax budgets are partially spent on flood prevention, thus the annual investment in flood prevention per person is lower than the annual expected flood damage per person for small events, paid by individuals affected by flooding or by insurance companies if applicable. The annual budget spent on flood prevention is lower than the equivalent annual damage of severe events compensated by government. The explicit quantification of these values helps to better support decisions on the distribution of flooding costs over government and citizens' budgets.

In an economic evaluation, the question is whether more efficient flood protection could be achieved by investments to reduce flood risk through preventive measures and if so, whether it is more efficient to reduce the probability or the consequences component of flood risk. Given the uncertainties in the current study, the outcome of such evaluations is inevitably uncertain. A comprehensive evaluation of investments versus reduction of flood risk requires additional knowledge on the costs and effects of maintenance strategies, for gully pot cleaning, sewer cleaning, repair of manifolds, etc., which can be obtained from experiments, preferably on real-world scale.

Conclusion

This study is a first attempt to gain insight into different kinds of flood damage and to find quantitative measures for comparison of direct damage and indirect, intangible damage. Flood quantification studies tend to be based on monetarisation of damage, which leads to a prioritisation of tangible damage to buildings over intangible damage associated with flooding of roads, cycle and footpaths. Application of different kinds of damage metrics provides the opportunity to weigh tangible and intangible damages in various ways and to evaluate flood damage in a more balanced way.

The results show that flood protection for the investigated case is risk-averse: protection from small events is low compared with larger events. The results also show that the number of people affected by tangible damage is small compared with those affected by intangible damage. Based on the available data it cannot be concluded whether the current protection level is an economic optimum: the effect of investments to reduce flood risk, especially those related to increased maintenance, are too uncertain. Another question to be answered is whether the distribution of damage over small and large events and over tangible and intangible damage correctly reflects a safety level that is considered acceptable by society. The large difference in outcomes based on different metrics, as highlighted in this study, suggests that investment decisions for flood risk reduction should not be based on a traditional benefit cost analysis only: intangible damage is better captured by metrics that relate directly to the damage type, for instance number of people affected by flooding of buildings, roads and pavements, number of vehicles or traffic delay for road flooding.

The outcomes of this study show large differences between tangible and intangible flood damages for flooding of buildings and roads; this implies that flood protection is better represented by separate flooding standards expressed in multiple metrics relating to tangible and intangible damage and for different urban functions, such as residential buildings, commercial buildings, critical infrastructure (e.g. power supply and distribution stations), main traffic arteries and residential roads. The protection level that is to be provided for different urban functions is in essence a political decision, because the valuation of flood protection contains aspects that may be valued differently by different stakeholders.

If flooding standards and investments prioritisation are to be based on a risk approach, data and model predictions must be able to discriminate between different kinds of flood damage and flooding causes to support policy development and decision making. This implies that data on intangible damage as well as on tangible damage should be collected on a structural basis. Call data, complemented with other flood incident observations are a valuable data source in this respect. Call data could be improved by recording additional information on flood event details from citizen, preferably on a preset collection of flood event characteristics that support further analysis. Recent development of two-dimensional overland flow models can help to make a distinction between flooding consequences related to roads and buildings, if they can be properly calibrated, which again requires systematic recording of flood event details.

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