Quantitative risk analysis of urban flooding in lowland areas

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“Ουτος σοφωτατος εστι οστις εγνωκεν
οτι ουδενος αξιος εστι προς σοφιαν”

“Wisest is he who knows that he knows not”

Plato, Apology 23b,
cites Socrates

Summary

Over the last few decades, the interest in urban flood risk has been growing steadily worldwide, as the frequency of flooding and the damage caused by urban flood events have increased. Accelerated urbanisation has given rise to increased building in flood-prone areas and expansion of impervious areas, adding to the inflow into existing urban drainage systems and thus to the probability of flooding. In addition, climate change predictions increase concern over urban flood risk in cities around the world.

Analyses of urban flood risk require quantitative historical data on frequencies and consequences of flooding events to quantify risk. Such data are scarce: data collection takes place on an ad hoc basis and is usually restricted to severe events. The resulting data deficiency renders quantitative assessment of urban flood risks uncertain. The study reported in this thesis reviewed existing approaches to quantitative flood risk analysis and evaluation of urban flooding guidelines. It proceeded to explore historical data on flooding events from municipal call centres in two cities in the Netherlands with the final aim to quantitatively assess urban flood risk. Data from municipal call centres consist of texts describing citizens' observations of urban drainage problems. The texts provide information about causes, locations and consequences of flooding events. Flood risk analysis was applied according to a three steps approach: identification of causes of flooding, followed by a quantification of flood probabilities and a quantitative assessment of consequences of urban flooding.

Probabilistic fault tree analysis was applied to identify failure mechanisms of urban flooding based on call text information about flooding causes. Flood probabilities were quantified for each cause as well as contributions of individual causes to the overall flood probability. Fault tree analysis results showed that gully pot blockages stood out as the main cause of flooding; the contribution of heavy rainfall to the overall probability of flooding was small compared to that of blockages. This implies that component failures and human errors contribute more to flood probability than sewer overloading by heavy rainfall.

Call information on flooding consequences was used to draw risk curves for a range of flood damage classes: separate risk curves were drawn for consequences associated with human health, damage to private property and damage related to traffic disturbance. Risk curves for urban flooding depict flood damages on the horizontal axis and their associated exceedance probabilities on the vertical axis. The advantage of risk curves as opposed to a single expected value of risk as a summary value is that risk curves show the contributions of small and of large events to total risk. Call data per flooding event were used as a measure of event severity, based on the finding of a strong correlation between the amount of call data per event and rainfall volumes per event. The risk curves showed that total flood risk was mainly constituted by small events. Urban flood risk related to traffic disturbance was high compared to damage to private properties. Flood risk related to human health was small, according to call data information. Risk curves also showed that current flood protection strategy is risk averse: it provides higher protection from flood events with large consequences than from flood events with small consequences.

Flood waters that result form overloading of combined sewer systems are likely to be contaminated. A screening-level microbial risk assessment was conducted to estimate health risks to citizens associated with combined sewer flooding. The assessment was based on analyses of samples from flooding events and samples from combined sewers. The results indicated faecal contamination: faecal indicator organism concentrations in samples from flood waters were similar to those found in crude sewage under high flow conditions and *Campylobacter* was detected in all samples. Annual risk values were calculated for low and for high exposure scenarios: calculated annual infection risks vary from to $5x10^{-6}$ to 0.3; the minimum value is for *Cryptosporidium* and a low exposure scenario, while the maximum value is for *Campylobacter* based on high exposure scenario. The results showed that health risk associated with flood waters from overloaded combined sewers could be of the same order of magnitude as those associated with swimming in surface waters exposed to combined sewer overflows.

Risk assessment results based on call data information showed that urban flood risks in lowland areas are characterised by frequent flooding of roads and occasional flooding of buildings. Whether or not such flooding is acceptable for society depends on how flood risks can be compared to and balanced against investments to prevent or reduce flood risk. Such risk-based decision making requires risk outcomes that can be weighed against investments. To this end, risk values from call data analysis were translated into monetary values and into numbers of people affected by flooding. Translation into monetary terms resulted in high flood risk associated with flooding of buildings and low monetary flood risk associated with flooding of roads, cycle paths and footpaths. When expressed in terms of the number of people affected by flooding, the risk associated with flooding of buildings is low and the risk for flooding of roads is high. This implies that for lowland areas, risk-based decisions using monetarised values of flood damage put emphasis on flood risk for buildings. Conversely, if risk-based decisions focused on numbers of people affected by flooding, they would concentrate on damage associated with flooding of roads, cycle and footpaths. In risk-based decision making for urban flood protection, the choice what aspects to take into account and what level of flood protection is considered acceptable is typically a political one.

The effectiveness of existing strategies to cope with urban flooding was assessed based on a comparison of flood risk values associated with three failure mechanisms of urban flooding and associated coping strategies: gully pot blockage and cleaning, pipe blockage and cleaning and sewer overloading and capacity increase. The results were expressed as quantitative flood risk values in the form of a number of flooded locations per year per km sewer length, so that the results of two cases could be compared. It was shown that cleaning gully pots is a more efficient strategy to reduce flood risk than increasing sewer pipe capacity or sewer cleaning frequencies, for the investigated cases. Based on the same investment level, increasing gully pot frequencies was estimated to result in about 10% decrease in flood risk values, whereas increasing sewer cleaning or increasing sewer capacity resulted in less than 5% decrease.

Alternatively, flood risk can be reduced through reactive maintenance, by realising short reaction times to calls on flood events in order to limit flooding consequences. Call data showed that reactive handling is only efficient if the quality of call information is sufficient to discriminate between calls indicating large consequences that require immediate handling and those indicating small or irrelevant consequences.

Finally, the resulting risk values were used to evaluate current frequency-based guidelines for urban flooding. The results pointed out a number of shortcomings of frequency-based standards for urban flooding. First, all potential causes of flooding, including hydraulic overloading and asset failures should be taken into account to obtain a realistic flood risk estimate. Current focus on hydrodynamic model simulations to evaluate urban flooding tends to neglect the influence of asset failures. Second, flooding standards should specify to what spatial scale they apply to ensure proper evaluation. In current practice, flooding analysis is usually limited to a non-exceedance check of a given standard, while system functioning under exceedance conditions is not considered. If time-series are used to evaluate system functioning, including exceedance conditions, spatial scale becomes important to be able to decide whether what degree of exceedance is acceptable, by comparison to a generally applicable standard. Third, standards should take flooding consequences into account, because damage to society differs with various types and extents of consequences. The advantage or risk-based standards is that, unlike frequency-based standards, they incorporate flooding probabilities and consequences and that a risk-based approach looks at different kinds of failure mechanisms.

Quantification of urban flood risk based on historical series of call data is a first step towards quantitative risk assessment and risk-based evaluation of urban drainage systems. The advantage of call data is that they directly reflect citizens' experience with flooding; the disadvantage is that they represent only a part of all flooding events. This thesis concludes with recommendations on how to close existing knowledge gaps by improving existing call data collection

and storage. Suggestions are provided for additional data collection strategies and methods for urban flooding in order to facilitate complete and reliable quantitative urban flood risk analysis.

Samenvatting

De laatste tientallen jaren is de belangstelling voor stedelijke wateroverlastrisico's wereldwijd gestadig gegroeid, doordat de frequentie van wateroverlast en de schade veroorzaakt door wateroverlastgebeurtenissen zijn toegenomen. Versnelde urbanisatie heeft geleid tot toenemende bebouwing in overstromingsgevoelige gebieden en uitbreiding van verhard oppervlak, waardoor de instroming naar bestaande rioleringssystemen is gestegen en daarmee de kans op wateroverlast. Bovendien doen voorspellingen over klimaatverandering de angst voor wateroverlastrisico's in steden over de hele wereld toenemen. Analyses van stedelijke wateroverlastrisico's vereisen kwantitatieve historische gegevens over frequenties en gevolgen van wateroverlastgebeurtenissen om de risico's te kunnen kwantificeren. Zulke gegevens zijn schaars: gegevensverzameling vindt slechts op ad hoc basis plaats en blijft gewoonlijk beperkt tot ernstige gebeurtenissen. Het hieruit volgend gebrek aan gegevens maakt kwantitatieve berekeningen van wateroverlastrisico's onzeker. De studie waarvan dit proefschrift verslag is gestart met een evaluatie van bestaande benaderingen voor kwantitatieve risicoanalyse en bestaande richtlijnen voor stedelijke wateroverlast geëvalueerd. Vervolgens werden historische gegevens over wateroverlastgebeurtenissen afkomstig van gemeentelijke meldpunten in 2 Nederlandse steden geanalyseerd met het uiteindelijke doel om stedelijke wateroverlastrisico's te kwantificeren. Meldpuntgegevens bestaan uit teksten die waarnemingen van burgers van problemen in het stedelijk watersysteem beschrijven. De teksten bevatten informatie over oorzaken, locaties en gevolgen van wateroverlastgebeurtenissen. Bij de risicoanalyse werd een drie-stappen-benadering gevolgd: identificeren van oorzaken van wateroverlast, gevolgd door het kwantificeren van wateroverlastkansen en tenslotte van de gevolgen van stedelijke wateroverlast.

Voor het identificeren van de faalmechanismen voor stedelijke wateroverlast werd probabilistische foutenboomanalyse toegepast, op basis van informatie in de meldingenteksten over oorzaken van wateroverlast. Wateroverlastkansen

werden gekwantificeerd voor elke oorzaak apart evenals voor de bijdrage van elke oorzaak aan de totale kans op wateroverlast. Uit de resultaten van de foutenboomanalyse bleken verstopte kolken de belangrijkste oorzaak van wateroverlast; de bijdrage van hevige regenval aan de totale kans op wateroverlast was klein in vergelijking met die van verstoppingen. Dit betekent dat het falen van onderdelen en menselijke fouten meer bijdragen aan de kans op wateroverlast dan het overbelast raken van riolen bij hevige regenval.

Meldinginformatie over wateroverlastgevolgen werd gebruikt om risicografieken samen te stellen voor een serie schadeklassen van wateroverlast: aparte risicografieken werden getekend voor gevolgen voor de publieke gezondheid, voor schade aan private eigendommen en voor schade verbonden aan verkeershinder. De risicografieken voor stedelijke wateroverlast tonen een reeks toenemende wateroverlastschades met hun bijbehorende overschrijdingskansen. Het voordeel van een risicografiek ten opzichte van een samenvattende risico-uitkomst in de vorm van een gemiddelde is dat het aandeel van kleine gebeurtenissen ten opzichte van grote gebeurtenissen in het totale risico zichtbaar wordt. Het aantal meldingen per wateroverlastgebeurtenis is gebruikt als een maat voor de ernst van de gebeurtenis, op basis van de gevonden sterke correlatie tussen het aantal meldingen per gebeurtenis en het neerslagvolume. De risicografieken lieten zien dat het totale wateroverlastrisico met name werd bepaald door kleine gebeurtenissen. Stedelijke wateroverlastrisico's gerelateerd aan verkeershinder bleken groot in vergelijking met wateroverlastrisico's gerelateerd aan schade aan privaat eigendom, op basis van het aantal meldingen. Wateroverlastrisico's voor de publieke gezondheid waren klein volgens de meldingeninformatie. Tenslotte lieten de risicografieken zien dat de huidige beschermingsstrategie tegen stedelijke wateroverlast risicomijdend is: de bescherming tegen gebeurtenissen met grote gevolgen bleek hoger dan tegen gebeurtenissen met kleine gevolgen.

Water-op-straat dat een gevolg is van overbelasting van gemengde riolen is waarschijnlijk besmet met ziekteverwekkers. Een verkennende microbiologische risicoberekening is uitgevoerd om het gezondheidsrisico voor burgers verbonden aan het overlopen van gemengde riolen te bepalen. De berekening werd gebaseerd op analyses van monsters uit water-op-straatgebeurtenissen en uit gemengde riolen. De resultaten duidden op fecale verontreiniging: de concentraties fecale indicatororganismen aangetroffen in monsters uit water-op-straat zijn vergelijkbaar met de concentraties in gemengde riolen onder hoge-afvoercondities en *Campylobacter* werd in alle water-op-straatmonsters aangetroffen. Het jaarlijkse risico is bepaald voor een hoog en een laag blootstellingsscenario: het berekende jaarlijkse infectierisico varieerde van $5x10^{-6}$ to 0.3; de minimum waarde is voor *Cryptosporidium* en een hoog blootstellingsscenario, de maximum waarde is voor *Campylobacter* gebaseerd op een hoog blootstellingsscenario. De resultaten gaven aan dat gezondheidsrisico's verbonden aan water-op-straat afkomstig van overbelaste gemengde riolen van dezelfde grootte-orde zijn als de risico's verbonden aan zwemmen in oppervlaktewater waarop riooloverstortwater uitkomt.

De berekende risico's op basis van meldingeninformatie toonden aan dat stedelijke wateroverlastrisico's in laaggelegen gebieden worden gekenmerkt door frequente wateroverlast op straat en sporadische wateroverlast in gebouwen. Of dergelijke wateroverlast maatschappelijk acceptabel is hangt af van de manier waarop wateroverlastrisico's kunnen worden vergeleken met en afgewogen tegen investeringen om wateroverlast te voorkomen of te verminderen. Dergelijke risicogebaseerde besluitvorming vereist risico-uitkomsten die kunnen worden afgewogen tegen investeringen. Hiertoe werden de risico-uitkomsten uit de meldingenanalyse vertaald naar financiële termen en naar aantallen mensen die wateroverlast ondervinden. Vertaling naar financiële termen resulteerde in hoge risicowaarden voor wateroverlast in gebouwen en lage risicowaarden voor wateroverlast op wegen, fiets- en voetpaden. Wanneer risico werd uitgedrukt in aantallen mensen die wateroverlast ondervinden, resulteerde dit in lage risicowaarden voor wateroverlast in gebouwen en hoge risicowaarden voor wateroverlast op straat. Dit betekent dat voor laaggelegen gebieden, risicogebaseerde besluiten die uitgaan van risico's in financiële termen de nadruk leggen op wateroverlast in gebouwen. Risicogebaseerde besluiten op basis van het betrokken aantal mensen zouden zich juist concentreren op wateroverlast op wegen, fiets- en voetpaden. De keuze welke aspecten in beschouwing worden genomen bij risicogebaseerde besluitvorming en welk risiconiveau aanvaardbaar is, is naar de aard een politiek besluit.

De effectiviteit van bestaande strategieën om wateroverlast aan te pakken werden beoordeeld op basis van een vergelijking van de wateroverlastrisico's voor drie faalmechanismen en bijbehorende operationele maatregelen: verstopping van kolken en kolken zuigen, verstopping van rioolleidingen en rioolreiniging en overbelasting van riolering en capaciteitsuitbreiding. De analyse werd gebaseerd op risicowaarden uitgedrukt in de vorm van het aantal wateroverlastlocaties per jaar per kilometer rioolleiding, zodat de resultaten van de twee studiegebieden konden worden vergeleken. Op basis van de uitkomsten van meldingenanalyse bleek dat voor de onderzochte systemen het reinigen van kolken een efficiëntere strategie is om wateroverlast te verminderen dan het uitbreiden van rioleringscapaciteit of het reinigen van riolen. Bij hetzelfde investeringsniveau leverde het verhogen van kolkreinigingsfrequenties naar schatting 10% vermindering in het wateroverlastrisico, terwijl het verhogen van de rioolreinigingsfrequentie of het uitbreiden van rioleringscapaciteit minder dan 5% vermindering opleverde. In plaats van preventief, kan het overstromingsrisico reactief worden aangepakt, door korte reactietijden voor de meldingen na te streven teneinde de wateroverlastgevolgen te beperken. De meldingengegevens toonden aan dat reactief handelen alleen efficiënt is als de kwaliteit van meldinginformatie voldoende is om onderscheid te maken tussen meldingen die grote wateroverlast betreffen en direct handelen vereisen en meldingen die kleine wateroverlast of irrelevante problemen betreffen.

De risico-uitkomsten werden tenslotte gebruikt om bestaande richtlijnen die zijn gebaseerd op wateroverlastfrequenties te evalueren. De resultaten brachten een aantal beperkingen van frequentiegebaseerde normen voor wateroverlast aan het licht. Ten eerste zouden alle faalmechanismen, inclusief overbelasting en het falen van onderdelen in beschouwing moeten worden genomen om een realistische schatting van het wateroverlastrisico te verkrijgen. De bestaande nadruk op het gebruik van hydrodynamische modelsimulaties voor het evalueren van wateroverlast hebben de neiging de invloed van het falen van onderdelen te verwaarlozen. Ten tweede, zouden wateroverlastnormen specifiek moeten aangeven voor welke ruimtelijke schaal ze gelden om tot een juiste evaluatie te komen. In de huidige praktijk blijft wateroverlastanalyse doorgaans beperkt tot een niet-overschrijdingscontrole van een gegeven norm. Het functioneren van een systeem onder omstandigheden die de norm overschrijden wordt vaak niet geanalyseerd. Als daarentegen tijdseries worden gebruikt om systemen te evalueren, inclusief overschrijdingscondities, is de ruimtelijke schaal van belang om te kunnen bepalen of overschrijding aanvaardbaar is door deze af te wegen tegen een algemeen toepasbare norm. Ten derde zouden normen de gevolgen van wateroverlast in beschouwing moeten nemen, omdat de maatschappelijke schade afhangt van het type en de omvang van wateroverlastgevolgen. Het voordeel van risicogebaseerde normen is dat zij, in tegenstelling tot frequentiegebaseerde normen, zowel kansen als gevolgen in beschouwing nemen en dat een risico-benadering verschillende faalmechanismen bekijkt.

Het kwantificeren van stedelijke wateroverlast op basis van historische reeksen van meldinggegevens is een eerste stap op weg naar kwantitatieve berekening van stedelijke wateroverlastrisico's en risicogebaseerde evaluatie van rioleringssystemen. Het voordeel van meldinggegevens is dat ze direct weergeven hoe burgers wateroverlast ervaren; het nadeel is dat ze slechts een deel van alle gebeurtenissen bestrijken. Dit proefschrift sluit af met aanbevelingen hoe de bestaande kennishiaten te vullen door verbetering van de bestaande verzameling en opslag van meldinggegevens. Daarnaast worden suggesties gedaan voor aanvullende strategieën en methoden om gegevens over wateroverlast te verzamelen, teneinde tot complete en betrouwbare kwantitatieve risicoanalyse voor stedelijke wateroverlast te komen.

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6. Risk-based urban flood management: improving operational strategies

7. Discussion and recommendations

Chapter 1

Introduction and overview

1.1 Introduction

Research context

Over the last few decades, the interest in urban flood risk has been growing steadily worldwide, as the frequency of flooding and the damage caused by urban flood events have increased (e.g. Ashley et al., 2005; Schreider et al., 2005; Dutta et al., 2003). Accelerated urbanisation has given rise to increased building in flood-prone areas and expansion of impervious areas, adding to the inflow into existing urban drainage systems and thus to the probability of flooding. In addition, climate change predictions increase concern over urban flood risk in cities around the world (Wilby, 2007).

Urban flooding can be pluvial, fluvial or coastal flooding or a combination of these. Urban pluvial flooding occurs as a result of rainfall-generated overland flow ponding on the urban surface because it overwhelms urban underground sewerage/drainage systems and surface watercourses by its high intensity or is for some reason unable to enter drainage systems or water courses. Coastal flooding is caused by high sea water levels and waves overtopping protection structures; fluvial flooding is a result of overflowing of river banks. The focus of this thesis is on urban pluvial flooding.

Protection from urban pluvial flooding is provided by urban drainage systems. These are designed to function in accordance with prescribed flooding standards, mostly defined in terms of maximum flooding frequencies. Standards are set by local or regional authorities: cities, water boards or other governmental bodies responsible of water policy. Some differentiate between occupational land uses, like residential and commercial areas. By doing so, protection standards implicitly seek to establish a trade-off between investment costs for flood protection and expected damage from flooding: for higher expected damage, stricter flooding standards apply.

Problem

This trade-off is based on a qualitative assessment of expected flood damage; a lack of quantitative historical data on flooding incidents prevents quantitative assessment of urban pluvial flooding frequencies and damage. In the aftermath of recent flooding in England and Wales (Ashley et al. 2005), Germany (Thieken et al., 2005), USA (Hallegatte, 2008) and other areas, many more or less quantitative flooding analyses have been conducted, dedicated to individual, severe flood events. Flood risk analyses based on long data series comprising series of flood events are rare, since data collection takes place on an ad hoc basis and is usually restricted to severe events. This implies that compliance with flooding standards is not checked based on structural collection of event data to estimate return periods of flooding. Instead, compliance of systems with flooding standards is usually checked by hydrodynamic model calculations based on design storms with fixed return periods. Hydrodynamic models are subject to uncertainties associated with external model input, especially rainfall variability, errors in geometrical data and run-off catchment size, imperfect functioning of sewer components and a lack of data for calibration (e.g. Rauch et al., 2002; Pappenberger and Beven, 2006, Korving et al., 2009). As a result, the outcomes of urban drainage models are to a great extent uncertain. The use of flooding frequencies supplied by models to check compliance with flooding standards may lead to unreliable conclusions and possibly to unnecessary overdimensioning of drainage systems (Thorndahl et al., 2008).

In addition, hydrodynamic model calculations are sometimes used to prepare flood risk maps, count the number of properties at risk of flooding and to estimate flooding characteristics like flood depths and flow velocities. These outcomes serve to quantify flood damage and to decide whether investments should be made to reduce flood damage. Application of this approach for urban flooding results in large uncertainties since overland flow models used to calculate flood extents and flood depths are based on uncertain inputs from hydrodynamic models and suffer from a lack of input and calibration data. Additionally, establishment of depth-damage relations requires site-specific data on flood damages that are seldom available. These uncertainties must be addressed in order to improve quantitative assessment of urban flooding problems in order to provide a better foundation on which to base decisions to reduce flood risk,

Research aim

Current methods for urban pluvial flooding analysis are based on hydrodynamic models and damage assessments that are unreliable for various reasons, the main being a lack of data on flood occurrences. Investment decisions for urban flood protection require reliable estimation with known accuracy of flood frequencies and damage, whether derived from a combination of models or directly derived from event data. Data availability is central for either method chosen. The general problem statement addressed in this thesis is:

What new insights can risk analysis based on historical series of flood occurrence data provide with respect to characteristics of flood events in lowland areas?

The study reported in this thesis explores historical data on flooding incidents from municipal call centres in two cities in the Netherlands with the final aim to quantitatively assess urban pluvial flood risk. Municipal call centres receive calls from citizens about urban drainage problems and register information describing there observations. In the Netherlands, many municipalities have a call register: 109 out of 190 municipalities according to a recent inquiry (RIONED, 2007).

Flood risk is defined in this context as the product of flood probability and associated consequences. The study specifically addresses flooding incidents in lowland areas; these areas are characterised by a relatively high urban pluvial flooding frequency and small associated incident damage compared to hilly areas. As a result, questions as to what flooding standards to apply and how to balance investments and effects of flooding on the urban environment are different. Four research questions are derived from the main question to give further direction to this study:

1. What are the opportunities for using call centre data to identify causes that contribute to urban pluvial flood risk and how can occurrences of these causes be quantified?

Fault tree analysis is applied to identify possible causes of urban flooding and to quantify the contribution of different causes based on call centre data.

2. What consequences of urban pluvial flooding should be taken into account in a risk analysis and how can these be quantified?

Various kinds of consequences are compared, from potential microbial infection to material damage and intangible consequences of flooding.

3. Can the results of quantitative urban pluvial flood risk analysis based on historical data series from municipal call centres be used to support decisions on how to efficiently improve flood protection?

4. Can risk-based standards for urban pluvial flooding provide a more comprehensive basis to evaluate flood protection by urban drainage systems than current frequency-based standards?

The obtained quantitative results are used to evaluate current flood protection standards for two cities in the Netherlands and the efficiency of currently applied solutions to prevent or alleviate urban pluvial flood risk.

1.2 Urban flood risk literature

Urban flooding guidelines, design criteria and methods to evaluate compliance

Guidelines and design manuals for urban drainage systems have been developed in the last decades, for instance by EU (CEN, 2008), the US Federal Highway Administration (Brown et al., 2009) and in Australia (Pilgrim, 2001) that contain prescriptions or recommendation for protection from pluvial flooding. Most refer to maximum flooding frequencies and differentiate between occupational functions, applying lower frequencies to more vulnerable or economically valuable areas. This implies that flood protection levels are based on the concept of risk, combining frequency and expected damage. While is frequencies are defined quantitatively, the damage or vulnerability component is described in a qualitative way. The European Guideline EN752 (CEN 2008) for drains and sewer systems outside buildings contains the following requirement for protection against flooding: “Flooding shall be limited to nationally or locally prescribed frequencies taking into account the health and safety effects, costs, extent to which any surface flooding can be controlled without causing damage and whether it is likely to lead to flooding of basements.” The guideline also states that “It is usually impracticable to avoid flooding from very severe storms. A balance therefore has to be drawn between cost and the political choice of the level of protection provided. The level of protection should be based on a risk assessment of the impact of flooding to persons and property.” Directive 2007/60/EC on the assessment and management of flood risks (EU, 2007) defines ‘flood risk’ as the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event. The directive applies to coastal and river flooding; its application “may exclude floods from sewerage systems”. It is interesting to note that both guidelines centre around the concept of risk, which requires an analysis of flooding frequencies and expected damage.

This thesis focuses on flooding problems in lowland areas based on case studies in the Netherlands; the EN752 is the relevant guideline for this area. The EN752 guideline translates requirements for flood protection into two types of design criteria, depending on the complexity of the design method applied. Simple design methods are to be applied only to small schemes. Design criteria for simple design methods are based on design storms that should not lead to sewer system surcharge. Those for complex methods are based on hydrodynamic model calculations for time-dependent design rainfall. The design storms have a recommended return period of 1, 2, 5 or 10 years for rural, residential, commercial and city centre areas and underground railways and underpasses respectively. The design criteria for complex design methods refer to flooding frequencies that are to be calculated using a time-dependent rainfall input. The recommended design criteria for flooding frequencies are 1 in 10, 20, 30 or 50 years for rural, residential, commercial and city areas and underground railway and underpasses respectively.

In practice, design storms are traditionally used to evaluate the capacity of small and large sewer systems, because calculations for time-dependent rainfall series require long calculation times (Thorndahl et al., 2008). The European guideline applies a 5 to 10 fold higher return period for flooding frequencies based on time-dependent rainfall than for design storms leading to surcharge. Thus, it implicitly assumes that the return period of surcharge based on design storms corresponds with a 5 to 10 times longer return period of flooding. In reality, this relation depends on specific urban drainage systems characteristics like transport distances, invert levels, ground level variations, bottle neck connections, storage capacity etc. When compliance with urban flooding standards is based on design storm calculations, an unknown uncertainty is introduced due to the unknown relation between return periods of design storms and return periods of flooding. Additionally, surcharge and flooding frequencies provide no information on flood damage so that separate analyses should be conducted to assess expected damage.

In the Netherlands, local authorities decide upon the protection level against flooding that sewer systems should provide. Commonly, the guideline for flood protection is defined in terms of a maximum expected street flooding frequency of once per year or once per two years (van Mameren and Clemens, 1997). In many cases, the guideline does not specify to what area size this frequency applies and how the guideline should be evaluated. In practice, flooding of sewer systems is evaluated by hydrodynamic model calculations for a sewer subcatchment or for a sewer system in a city as a whole. Thus, the area the guideline is applied to depends on the boundaries of the available hydrodynamic model. Design storms with return periods of one or two years are applied to check system performance against the flooding guideline. Unlike the approach in the European guideline, design storms are directly used to evaluate street flooding and the return period of street flooding is assumed to be equal to the return period of flooding as a result of time-dependent rainfall. To account for uncertainty associated with the latter assumption, design storms of a higher return period than the required return period of flooding are sometimes used or surcharge to a certain level below ground level is taken as maximum acceptable water level for a design storm instead of the rise of water levels up to ground level.

Flood risk instead of flood frequencies

Required protection levels against flooding are mostly expressed in terms of a maximum flooding frequency or, inversely, a minimum return period of flooding. They do not provide sufficient information to support investment decisions for flood reduction since they do not include flood damage. If investment costs are to be balanced against the level of protection provided, the level of protection should be based on a risk assessment of the impact of flooding to persons and property (EN 752, 2008).

The word 'risk' is used and interpreted in many ways. A committee established by the Society for Risk Analysis concluded after 4 years of deliberation that no common definition for the word risk could be found and concluded that it would be better to let each author define it in his own way explaining clearly what way that is (Kaplan, 1997). A number of common concepts are generally agreed upon in risk theory. The basic concept is that risk incorporates some probability of unwanted events and consequences following that event. Kaplan and Garrick (1981) in their article in the 1st issue of the journal of the Society of Risk Analysis argue that the question "What is risk" really includes 3 questions:

1. What can go wrong?
2. How likely is it to happen?
3. If it does happen, what are the consequences?

The answer to the first question can be considered as a scenario; e.g. overtopping of a river dike and collapse of a river dike are different scenarios for flooding. Several qualitative and quantitative methods are available to find scenarios for unwanted events, see e.g. the fault tree handbook issued by NASA (Vesely et al. 2002). The answer to the second question addresses uncertainty about the occurrence of hazardous events or scenarios. The answer takes the form of a frequency or probability. The answer to the 3rd question refers to a damage index, resulting from an unwanted event.

The advantage of risk over frequency is that the concept of risk incorporates both the frequency of events, mostly translated into a probability, and the associated damage. By differentiating between occupational uses, current flooding standards incorporate prioritisation according to the potential damage of flooding to some extent. Risk-based standards do this in a more explicit and quantitative way.

The philosophy of risk analysis is relatively recent; it was first applied in the 1960's in the nuclear, aeronautic and chemical process sectors, where great hazards and financial losses are involved upon occurrence of unwanted events (Bernstein, 1996). Risk-based policies that regulate hazardous activities and installations usually focus on potential casualties or fatalities. An example of a quantitative risk measure is societal risk: the frequency of having an accident e.g. in an industrial plant with at least a certain number of people being killed simultaneously (e.g. VROM, 2005; HSE, 1989). Loss of life as a result of urban flooding may occur in cities in developing regions of the world, e.g. in South/ South-East Asia (Mark et al, 2004). In most modern cities in the industrialized part of the world urban flooding rarely causes casualties; flooding consequences mainly consist of damage to properties and interruption of industrial and social processes. (e.g. Apel et al., 2008).

Besides the danger of loss of life due to certain activities, risk can be expressed in economic terms, in a cost-benefit analysis. This allows for an evaluation of cost-effectiveness of mitigation measures and thus to optimise investments (Dutta et al., 2003; Nussbaum, 2006; Olsen et al. 1998). For instance, the expected value of economic damage is used as part of cost benefit analyses for flood prevention measures in the UK and in The Netherlands (Jonkman et al., 2003). In both approaches the benefits of a measure are determined by calculating the expected value of the economic damage before and after implementation of the measure. The difference between these two values is the benefit, which can be weighed against the costs of the measures. Cost-benefit analysis has several important drawbacks: translation of benefits of flood risk reduction into monetary terms requires many assumptions that are subject to uncertainty and the translation of all costs and benefits as a result of the investment to monetary values for the year the investment is to be made, introduces additional uncertainty (Graham, 1981).

Urban flood modelling

In current urban drainage practice, hydrodynamic models are commonly applied to check compliance with urban flooding standards, because local data on flood events are unavailable or incomplete. The use of hydrodynamic models has a drawback: because modelling results are subject to uncertainty, they can be used for comparison between design options, but are usually too inaccurate for quantitative evaluation of historical events. If model outcomes are to be used in an absolute sense, to evaluate compliance with standards, models should be calibrated and verified and uncertainty in model outcomes must be quantified. Beven and Binley (1992), Pappenberger and Beven (2006), Mannina et al. (2006), Thorndahl et al. (2008) and many others have drawn attention to the importance of uncertainty analysis in hydrological and urban drainage modelling and have demonstrated the impact of uncertainties on model outcomes. Using a calibration of runoff volumes, Schaarup-Jensen et al. (2005) showed a remarkable difference between an uncalibrated (using default model values) and a calibrated urban drainage model, in predicted flooding frequencies.

Even if data are available for model calibration, uncertainties in model structure, model parameter assumptions and inherent uncertainty in rainfall and run-off characteristics lead to uncertainty in model outcomes. In addition, degradation processes like sedimentation and pipe corrosion lead to development of further discrepancies between the real system and theoretical model conditions. Thorndahl et al. (2008) investigated different types of uncertainties in drainage models, e.g. uncertainties in inputs (boundary conditions), parameters, model structure, and conceptual uncertainties. They show that even for calibrated models predicted values can deviate quite markedly from observed values. In particular, the models tested perform somewhat poorly in predicting peaks and tails of flow rates, peaks being of particular importance for correct prediction of flooding. This implies that a comparison of model-predicted flooding frequencies to flooding standards to check compliance may easily lead to erroneous conclusions.

Information on frequencies of flooding from manholes is not sufficient to perform a flood risk analysis: models should provide additional information on flood depths and flooding characteristics in order to be able to asses flood damage. Hydrodynamic sewer models can simulate the flow in pipe networks and the rise of water levels at manholes up to ground level. Sewer models are not adequate to simulate surface flooding (Schmitt et al., 2004), since they are unable to simulate the transition from pressurised pipe flow to surface flooding.

In order to simulate flooding in a realistic manner, urban flood models need to couple the underground and above-ground systems in what is referred to as the dual drainage concept (Djordjevic et al., 2005). Mark et al. (2004) provide an example of one-dimensional overland flow modelling for flooding simulation. The greatest inaccuracy of this approach lies in the approximation of flooding in streets by one-dimensional flow paths. One-dimensional models are seen as a good approximation as long as the water remains within the street profile and flow paths can be well identified. Still, the outcomes of one-dimensional flow models are sensitive to the assumptions necessarily made to translate two-dimensional flow processes into a one-dimensional flow. Two-dimensional flow models are able to capture the reality of two-dimensional overland flow to a greater extent. The downside of these models is a large data requirement, in particular with respect to digital terrain information, and large computational efforts. Even though more examples of coupled one-dimensional/two-dimensional flow models have recently become available (e.g. Maksimovic et al., 2009), validation of the two-dimensional models is hampered by a lack of calibration data (Leandro et al., 2009). Where hydrodynamic sewer models require data on in-sewer water levels and discharges, dual drainage models additionally need calibration data from overland flooding events. Given the infrequent occurrence of such events and practical difficulties to set up monitoring of overland flow characteristics, such data are difficult to obtain. No examples of calibrated dual drainage models have been found in the literature. Due to large data requirements and computational efforts and the lack of calibration data, it will take time before dual drainage models obtain sufficient reliability of application in become common practice.

Urban flood damage modelling

Flood damage can be assessed based on relationships between flooding characteristics and expected damage. This step in flood risk analysis is indicated by either of the terms damage assessment or vulnerability analysis. Flood damage modelling has been frequently applied in fluvial flood risk analyses (e.g. Dutta et al., 2003; Thieken et al., 2005 and 2008, Meyer and Messner, 2005). Most damage assessments focus on direct flood damages that occur within the flooded areas. Indirect damage outside the flooded area is often estimated as a fixed percentage of direct damage (Penning-Rowsell et al., 2005). One feature most flood damage models have in common is that the direct monetary flood damage is a function of the type of building and inundation depth (Jonkman et al., 2003; Wind et al., 1999). Such depth-damage functions are seen as the essential building blocks upon which flood damage analyses are based, and they are internationally accepted as the standard approach to assessing urban flood damage (Smith 1994). Thieken et al. (2005) showed that other flood characteristics, like flow velocity and flood water contamination, are other important factors to explain flood damage. Potential damage to buildings is usually estimated based on building values (e.g. Gersonius et al., 2008), replacement values of buildings, e.g. derived from economic statistics, or more detailed assessments of repair and replacement costs (Meyer and Messner, 2005). Merz and Thieken (2005, 2009- in press) and Apel et al. (2004, 2006, 2008 and 2009) conducted uncertainty analyses for flood risk quantification associated with urban flooding. These studies refer to fluvial flooding in hilly terrain, return periods of over 100 years and flood depths of several meters; they investigate both theoretical scenarios of flooding and data from a large flood event in Cologne in 2002. Their results show, among others, that uncertainty in depth-damage functions dominates overall uncertainty for flood damages with a return period below 10 years. In flood scenario assessments, the type of modelled flood event influences which sources of uncertainty dominate. They emphasise that a prerequisite for all applications of flood risk modelling is an accurate calibration of the model system, which includes hydrodynamic and damage modelling.

Flooding in lowland areas

The majority of studies in the field of flood risk analysis refer to severe flooding such as fluvial flooding and pluvial flash floods, with flood depths of several meters. This thesis focuses on pluvial flooding in lowland areas. In lowland areas and flat terrains, pluvial floods rarely attain large flood depths; flood waters spread over large areas, mostly resulting in flood depths of the order of tens of centimetres. The associated flood damage is relatively small, as is illustrated by the following two examples. A survey among households after the 2002 fluvial floods in Germany showed that 1273 households specified monetary damage to their residential building contents and 1079 specified building damage; associated mean damages amounted to €16,335 and €42,093 per property, respectively (Thieken et al., 2005). In September and October 1998, exceptionally heavy rainfall occurred in the northern part of the Netherlands: more than 75 mm in 24 hours. The average return period of this rainfall event was about 125 years (Jak and Kok, 2000). This event was classified as a national disaster and fell under the Dutch Compensation Act and damage-experts investigated all damage claims. According to their assessment, 1050 households suffered flood damage; the average damage per residential building amounted to €2000 (1999 value) and 80% of the damages were below €2200. The damage in rural areas was much higher: total damage to agricultural companies was estimated at €330M; 85% of the total flood damage. This example illustrates that even for a rare rainfall event, urban pluvial flood damage in lowlands remains small compared to fluvial flooding. As a result of smaller damages per event, higher flood event frequencies are generally accepted in lowland areas. In this thesis an attempt is made to asses how the cumulative damage of flood events over the lifetime of urban drainage systems compares between lowland areas with high flooding frequencies and areas with lower flooding frequencies. A particular difficulty in assessing flood risk in lowland areas is that intangible damage such as traffic delay and inconvenience for pedestrians constitutes an important part of total flood damage. These kinds of damage cannot easily be expressed in monetary values which makes it difficult to assess total cumulative damage.

1.3 Flood event data

In this study data from two case studies in lowland areas were used; the cities of Haarlem and Breda. Both represent medium-size cities of 147,000 and 170,000 inhabitants. One city is located in the western part of the Netherlands, in a transition area between sand dunes and clay polders. The other is located in the south of the Netherlands, on a transition between sandy soils and clay polders. Ground levels vary mostly between 0m and 10m above Mean Sea Level, with maximum ground level variations up to 20 meters. Both cities are primarily served by gravity systems that are connected to a treatment plant by a pumping station at the downstream end of the system. Figure 1.1 gives an overview of construction periods of the urban drainage systems in both cities.

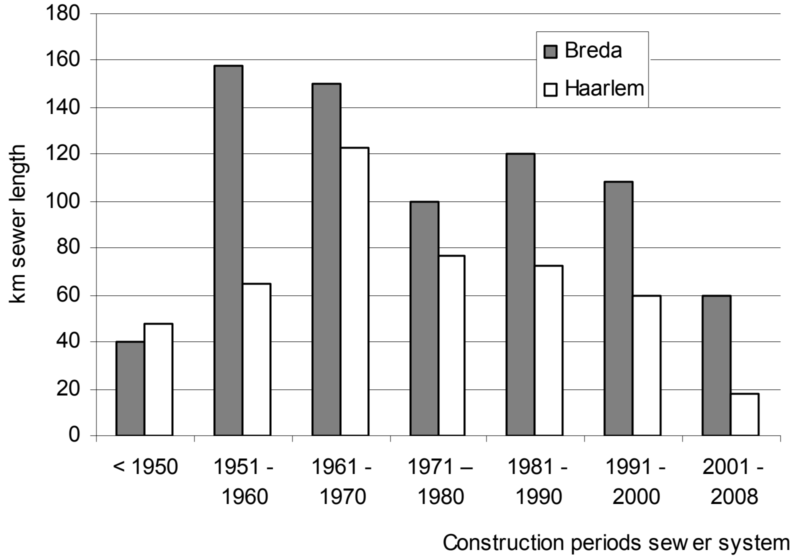

Figure 1.1 Constructed sewer lengths per 10-year-period for the urban drainage systems of Breda and Haarlem.

Figure 1.2 shows the location of the two case studies in the Netherlands; table 1.1 presents a summary of urban drainage system characteristics for the two cases.

Table 1.1 Characteristics of the urban drainage systems of Haarlem and Breda.

Urban drainage system characteristics	Unit	Haarlem	Breda
Number of inhabitants	-	147,000	170,000
Ground level variation	m	20	15
Storage in combined system below lowest overflow weir	m^3	72,000	100,000
Total length of gravity sewers	km	463	736
Total residential area	km^2	32	70
Total impervious area	km^2	12	18

The primary data used in this thesis 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 and 5 years for Breda. Most calls refer to problems of flooding, ranging from local flooding on a road or parking lot to flooding of entire streets and flooding inside residential and commercial buildings. Since call texts describing citizens' observations provide information on time, location and characteristics of flooding, they constitute a detailed series of flood event data. The advantage of these data is that registration took place during or shortly after flood events which limits distortion of the data by after-event actions and experiences. Since in lowland areas flood frequencies are relatively high, time-series of historical flood event data of 5 to 10 years are sufficient to obtain useful analysis results. In addition, daily local rainfall measurements are available for both cases, which were used to cross-check flood event data and rainfall characteristics. Call data and rainfall data were used in various approaches of quantitative risk analysis.

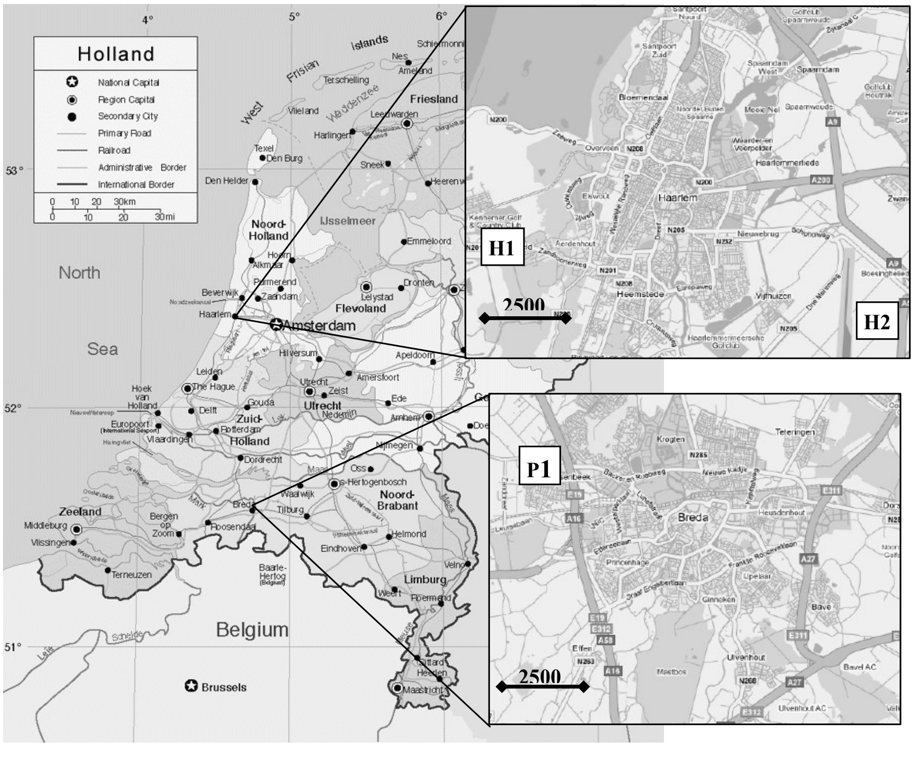

Figure 1.2 Map of the Netherlands, Haarlem and Breda; locations of rain gauges in Haarlem, H1 (Leiduin) and H2 (Schiphol) and in Breda, P1 (Prinsenbeek). Source: Google maps, 2009

1.4 Thesis overview

This introduction chapter describes the context of urban flood management and current research in the field of urban flooding, urban flood risk and flood damage modelling. It identifies a number of shortcomings in existing approaches and addresses some specifics of urban flooding in lowland areas. Based on these observations, the main objective addressed in this study is formulated in the form a central research problem and four research questions that guided the research.

Chapter 2 presents a fault tree analysis for urban water infrastructure flooding. It identifies possible mechanisms in urban water infrastructure that can lead to flooding and their relative contributions to flood probability. While the focus in urban flooding analysis is generally on fluvial flooding and flash floods caused by heavy rain, this chapter compares the contribution of heavy rainfall to that of other failure mechanisms for urban flooding.

In chapter 3 data from municipal call centres are explored to find out whether they can be used to quantify urban flood risks associated with various possible failure mechanisms. A data-driven approach based on historical data-series of flooding events is used to quantify various types of consequences of urban flooding. The results are presented in the form of risk curves that show the probabilities of exceedance of a range of flooding consequences.

The primary function of urban drainage systems is to protect public health by preventing contact with pathogens in wastewater. Chapter 4 investigates the potential health risk to citizens of urban flood waters resulting from combined sewer flooding, based on a screening-level microbial risk assessment.

Chapter 5 presents an attempt to translate tangible and intangible flooding consequences into two types of common metrics in order to directly compare their distribution to total flood risk. It compares the results for the two different metrics and shows how the choice of metrics influences risk analysis outcomes, hence the decisions based on these. The cumulative contribution to flood risk of small flood events is compared to the contribution of rare, severe events to address the question of whether severe events should get priority in flood risk management over series of small events, or not.

Chapter 6 shows how flood risk analysis results can be used to evaluate the efficiency of operational strategies and to identify efficient ways for improvement. Three causes of flooding and associated flood management strategies are compared and opportunities to enhance current strategies to further reduce flood risk are highlighted.

Chapter 7 discusses the contribution of this research to current understanding of urban flooding and urban flood management. Recommendations for further studies are given as well in this chapter

Figure 1.3 shows how chapters interrelate.

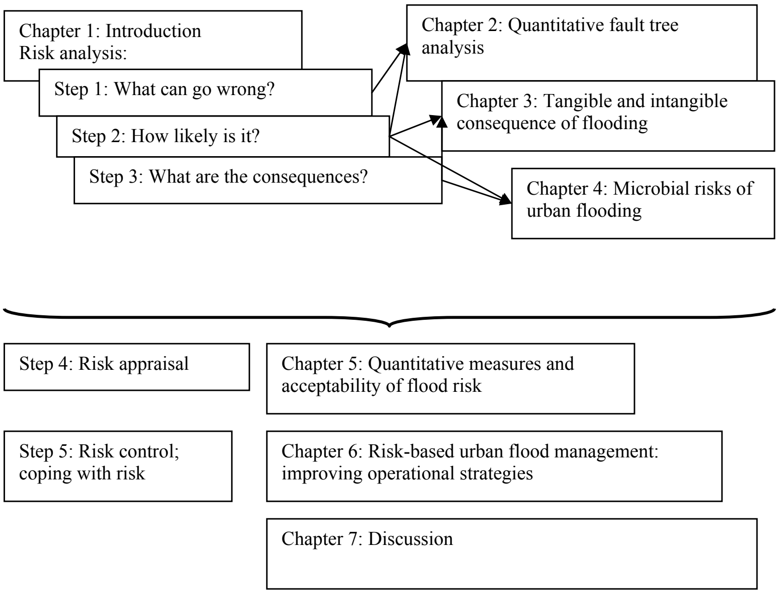

Figure 1.3 Relations between chapters in this thesis.

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Chapter 2

Quantitative fault tree analysis for urban flooding

This chapter is based on an article that was published in Structure and Infrastructure Engineering.
Veldhuis, J.A.E. ten, Clemens, F.H.L.R. and Gelder, P.H.A.J.M. van (2009). Quantitative fault tree analysis for urban water infrastructure flooding. Structure and Infrastructure Engineering, 99999:1, DOI: 10.1080/15732470902985876.

Context

The most common way to apply urban flood risk analysis is to determine expected flood depths and flood extensions by means of some form of hydrodynamic model calculations in order to assess the number and type of properties at risk of flooding. This information is used to assess expected damage and to decide whether flood reduction is required. This approach has been developed for river and coastal flooding to quantify flood risk associated with high water levels that leads to failure of dikes, river levees and other flood protection structures. In the past decades a similar approach is applied to urban pluvial flood risk analysis. The underlying assumption is that heavy rainfall followed by overloading of urban drainage systems is the main cause of urban pluvial flooding. Consequently it assumed that modelling the effects of system overloading by heavy rainfall and quantifying associated flood risk, fully captures urban pluvial flooding problems. Still, overloading by heavy rainfall is only one of the possible failure mechanisms of urban drainage systems. This chapter identifies other possible failure mechanisms of urban drainage systems in a fault tree analysis and quantifies their contributions to overall flood probability.

Abstract

Flooding in urban areas can be caused by heavy rainfall, improper planning or component failures. Few studies have addressed quantitative contributions of different causes to urban flood probability. In this chapter, probabilistic fault tree analysis is applied to assess the probability of urban flooding as a result of a range of causes. Causes are ranked according to their relative contributions. To quantify the occurrence of flood incidents for individual causes, data from municipal call centres were used, complemented with rainfall data and hydrodynamic model simulations. Results showed that component failures and human errors contribute more to flood probability than sewer overloading by heavy rainfall. This applies not only to flooding in public areas but also to flooding in buildings. Fault tree analysis has proved useful in identifying relative contributions of failure mechanisms and providing quantitative data for risk management.

Keywords: fault tree; flooding; risk; urban drainage

2.1. Introduction

Over the last few decades the interest in urban flood risk has been growing steadily, as the frequency of flooding and the damage caused by urban flood events have increased (Ashley et al., 2005). They state that accelerated urbanisation has given rise to increased building in unsuitable areas and expansion of impervious areas, both adding to the inflow into existing urban drainage systems and thus to the probability of flooding. In addition, climate change predictions increase concern over urban flood risk (Semadeni-Davies et al., 2008). In the UK, the problem of urban flood risk has been addressed in many studies. A baseline estimate of the current urban pluvial flood risk in England and Wales concluded that the expected annual damage to residential and commercial properties in urban areas amounts to £ 270 million (Ashley, 2006). Some 5000-7000 properties are flooded annually in England and Wales by sewage (Ashley et al., 2005). No quantitative estimation studies of urban flood risk in the Netherlands were found, not in general nor for specific cases.

Principal causes of flooding addressed in urban flood studies are heavy storm events that lead to overloading of rivers and urban water infrastructures. In addition, urban water systems are susceptible to component failures and human errors. Analysis of call centre data from two municipalities of 10,000 to 170,000 inhabitants in the Netherlands has shown that hundreds of small flood events occur each year in relation to these causes. Material damage to private properties, local disturbance of urban traffic and nuisance for cyclists and pedestrians are common consequences.

Quantification of flood risk requires data on flood incidents related to the complete spectrum of potential causes. Additionally a methodology is needed to quantify flood probabilities and consequences. A number of methods have been developed in high-risk industries, such as the nuclear, aeronautic and chemical industries, to quantify risk, including risk analysis methods and probabilistic fault tree analysis (Kaplan and Garrick, 1981; Haimes, 1998; Vesely et al., 1981 and 2002). Risk-based decision making in water resources matured as a professional niche in the US in the 1980's (Haimes, 1998). These methods have been successfully applied in river flooding (Vrijling, 2001), but application to urban drainage systems remains rare. In the UK, urban flood risk assessment and management have received much attention recently and the approach has been applied to several cases in the UK (FRMC, 2007). Probabilistic techniques have had applications in urban drainage in research projects in Denmark (Harremoes and Carstensen, 1994) and Belgium (Thorndahl and Willems, 2008), amongst others.

Quantitative fault tree analysis is an example of a risk analysis technique that effectively detects potential failure mechanisms and quantifies probabilities of failure of complex systems based on failure data. A fault tree is a deductive model that links a systems failure via reverse paths to all subsystems, components, human errors etc. that can contribute to failure. It is very useful to detect potential causes of flood events including both hydraulic overloading and component failures. It quantifies both overall flood probability and the relative contributions of individual causes of flooding based on their probabilities of occurrence. The Fault Tree Handbook NUREG-0492 issued by the US Nuclear Regulatory Commission in 1981 has been a leading technical information source for fault tree analysis in the USA (Vesely et al.). In 2002 NASA issued a handbook for aerospace applications that contains additional information on recent techniques (Vesely et al., 2002). Both handbooks also provide a short overview of other approaches to the logical modelling of system failure, e.g. failure mode and effect analysis and fault hazard analysis. Ang and Tang provide a short introduction for applications in the field of structural engineering (Ang and Tang, 1984).

In this chapter quantitative fault tree analysis is applied to urban flooding, defined in this context as the occurrence of pools in an urban area. Quantitative fault tree analysis is applied to the cases of two cities in the Netherlands, Haarlem and Breda. These cities have urban drainage systems with a total length of 460

and 1000 km that mainly consist of gravity sewers. Data from municipal call centres, rain gauges and hydrodynamic model calculations are used to quantify the probabilities of various causes of urban flooding.
Uncertainties in urban flood risk quantification are high due to a lack of incident data registration for small incidents, that often pass unnoticed, and low probabilities of large incidents so that long periods of data collection are required to obtain sufficient data for risk quantification. Also attention tends to focus on flood damage relief more than on data registration.

2.2. Urban flood incident data

To quantify probabilities for fault tree events, data on flood incidences must be collected. Potential sources of flood incident data are monitoring networks, call centres, hydrodynamic models, fire brigade records and the media.

Monitoring networks in urban drainage systems can provide flood incident information, if they have sufficient spatial density to detect all flood events throughout urban areas. In practice, monitoring locations are limited to pumping stations, overflow weirs and some additional points e.g. at special constructions. This density is largely insufficient to register in detail all flood incidents in an urban area.

Municipal call centres register call information on flood incidents. Incidents that are sufficiently annoying to prompt citizens to make a call are recorded in the call register. The network of callers is potentially very dense since every citizen can be assumed to have access to a telephone. Still, calls do not give complete coverage of flood incidents, because there is no guarantee that a call is made for every event. It is on the other hand one of the best sources to provide indication of events unacceptable to citizens.

Call data consist of a unique call number, date of the call, street name to indicate the problem location and a telegram style text that describes what the caller has said. In most cases a second text is added that describes the results of on-site checking and actions undertaken to solve the problem. Call databases usually contain categories that calls are assigned to and give an indication of the reason a call was made. To be able to use call information for flood risk analysis these categories are not specific enough and calls must be screened and classified manually.

Data on flood events can also be derived indirectly from simulations of urban drainage system behaviour under various rainfall conditions. One-dimensional sewer models simulate flow through piped systems and can provide estimates of flooding as a result of system overloading during heavy rainfall. Also pipe blockages can be simulated, but flood estimates remain theoretical unless real-life data on occurrence of blockages are available to be used as input. The description of inflow processes in these models is not sufficiently accurate to provide estimates of flood incidents due to gully pot blockages, manifold blockages and surface obstacles.

Overland flow models are developed and coupled with sewer models to support quantification of expected consequences of flooding as a result of sewer overload (e.g. Djordjevic et al., 2005).

Although hydrodynamic models can provide insight into expected flow paths and flood frequencies, their use for probabilistic analysis is not straightforward. Probabilistic analysis can be applied to rainfall data to compose design storms with expected probabilities of occurrence that are fed into hydrodynamic models. Expected rainfall probabilities must in some way be translated into flood probabilities, which can be done for simple systems with linear hydraulic behaviour, but becomes highly complicated for large, complex systems. Alternatively probabilistic analysis can be applied to hydrodynamic model results for long rainfall series of 10 or 25 years or more. This demands long calculation times and a large amount of data storage and extensive data analysis. Additionally hydrodynamic models are subject to uncertainties and tend to focus on hydraulic capacities of systems as designed or 'as built', having difficulty with deviations caused by component failures. Some examples are available where the vulnerability of model outcomes to component failures and data uncertainties is assessed (Clemens, 2001) that show the complex manipulations needed to obtain intended calculation results.

Other sources of flood incident information that have been investigated are newspaper articles and on-line pages and fire brigade action records. The Dutch Central Bureau of Statistics compiles yearly data on fire brigade actions related to flooding. These data show that fire brigades in the Netherlands assisted in between 2671 and 5540 cases of flooding yearly between 1994 and 2005. 80% of these cases concern flooding in buildings and 20% other than buildings. Fire brigade records contain no information on the nature and cause of flooding. Flooding in buildings for instance can be related to street flooding or to burst drinking water mains inside buildings, high groundwater tables or malfunctioning of rain pipes or in-house sewers. This lack of detail makes this source of information unsuitable for fault tree analysis. News paper articles often describe flood situations in detail, but newspaper reporting is selective: calamitous events and events that in other ways disturb life in local communities are likely to reach the newspapers, less striking events are not. Therefore this information source has been discarded.

In this study, model simulations have been used to validate data from municipal call centres by comparison of locations with frequent calls on flooding with flood locations in simulation results for heavy rainfall conditions. In addition rainfall data and calls have been compared directly for some logical checks: do calls on flooding coincide with rain events and if not, is there a good explanation? Do heavy rain events generate more calls than light events? Do calls that indicate sewer overloading coincide with heavy rainfall events?

2.3. Quantitative fault tree model for urban flooding

Definition of failure mechanisms

To explore what incidents can give rise to urban flooding a source-pathway-receptor representation has been used to analyse urban water infrastructure systems. Figure 2.1 shows a block diagram that represents the components of such systems and their interconnections. Possible sources of water occurring on urban surfaces are rainfall, river water that has flown over river banks, drinking water e.g. from a burst pipe, groundwater that rises above ground level and discharges e.g. from construction sites where groundwater abstraction takes place. Under normal conditions, water on urban surfaces evaporates or infiltrates or flows over the surface to an infiltration or storage facility or a sewer system. Sewer systems transport water towards a treatment facility or a pumping station. In case the hydraulic capacity of a pumping station or treatment facility is insufficient to cope with the flow, water passes over a sewer overflow to surface water. Surface water and groundwater are final receptors in this system.

Flooding can occur when flow pathways are interrupted as a result of failing system components. In branched systems interruption of a flow route leads to flooding immediately or as soon as the storage capacity upstream of a failed component is filled. In looped networks alternative flow routes are available when one flow route gets blocked, which makes these networks less vulnerability to component failures. Here the hierarchy of system elements is important: failure of components in a main transport route is likely to cause failure while failure in secondary routes can be compensated by alternative routes. Pathway interruption also occurs due to errors during the design and construction phase, e.g. when components are omitted, like gully pots that are not connected to a sewer system.

Another mechanism that leads to urban flooding is system overload: when water inflow exceeds the storage and transport capacity of one or more system elements. Normally urban drainage systems are designed to cope with weather conditions up to a certain limit and overloads occur several times during a system's lifetime.

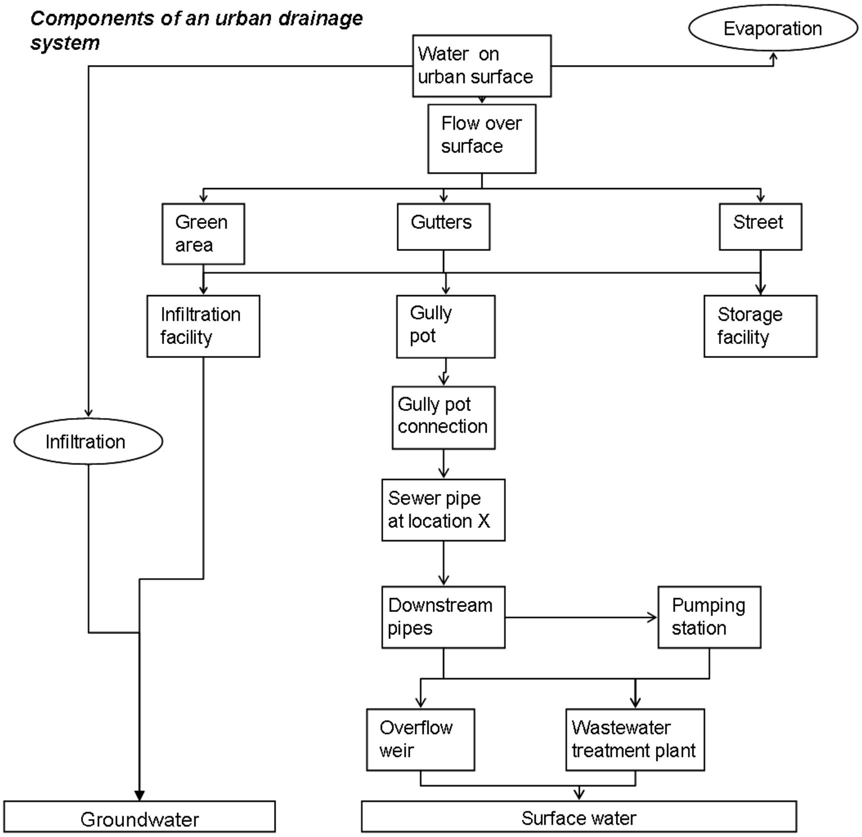

Figure 2.1. Block diagram for an urban drainage system. The diagram shows the system components that, by their failure, can lead to the occurrence of water on urban areas.

Construction of fault tree model

The objective of fault tree analysis is to identify all possible failure mechanisms that can lead to urban flooding in a systematic way. There are four basic elements in the development of a fault tree: top event, basic events, AND gates and OR gates (figure 2.2). The top event of a fault tree is the failure that is subject of analysis, urban flooding in this case. Urban flooding is defined here as the occurrence of a pool of water on the surface somewhere in an urban area lasting long enough to be detected and cause disturbance. This includes the appearance of water on the surface as a result of rainfall that is not properly drained and of water that flows out of the drainage system onto the surface due to a particular component failure. These failure mechanisms are analysed in detail whereas the occurrence of pools on the urban surface due to failure of other urban water systems: drinking water, groundwater or surface water, are included in the fault tree, but not analysed in detail here. Basic events form the most detailed level of a fault tree and stand for failures or conditions that can be combined by AND or OR gates to create higher level states. The choice of the basic level of a fault tree depends on the level of detail that is required for a specific analysis. The AND gate links underlying events that must occur simultaneously for the output condition to exist, while the OR gate generates the output condition for any one of the underlying events.

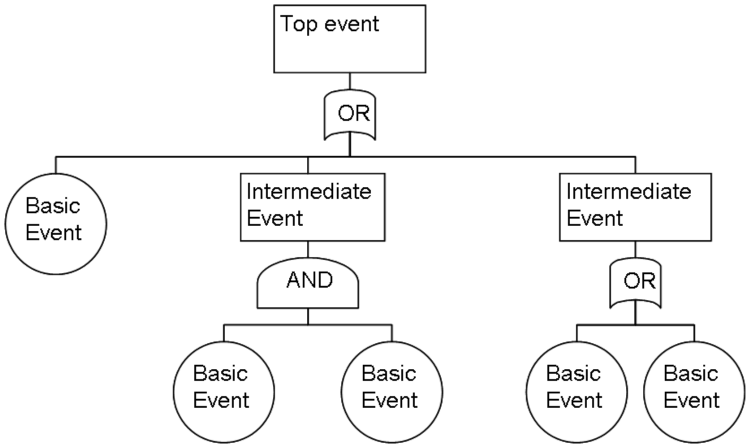

Figure 2.2 Elements of a fault tree model

In a systematic analysis seven failure mechanisms have been found that can give rise to urban flooding, three of which are related to urban drainage systems:

1) Inflow route interruption: rainwater that falls on an urban surface cannot flow away to a drainage facility and as a result forms pools on the surface;
2) Depression filling: Rainwater that has fallen at an upstream location flows over the surface to a downstream location where it cannot enter a drainage facility but remains on the surface;
3) Sewer flooding: Water from the sewer system flows onto the surface due to local system overload or downstream component failure;
4) Drinking water leakage: Drinking water flows onto the surface as a result of a pipe burst or a leaking hydrant;
5) Groundwater flooding: groundwater table rises above ground level;
6) Surface water flooding: Surface water levels rise above bank levels or overflow weir levels and surface water flows onto the surface directly or via an urban drainage system;
7) External water discharge: An amount of water is discharged onto the surface, e.g. extracted groundwater from a construction site or water from a swimming pool that is replenished.

Figure 2.3 shows a fault tree for urban flooding for these 7 mechanisms. The intermediate events form a first level in the tree; they in their turn result from other events. Four events are included as undeveloped events since they will not be analysed in detail. An “OR-gate” connects the top event to this first level of events because occurrence of each individual event results in flooding.

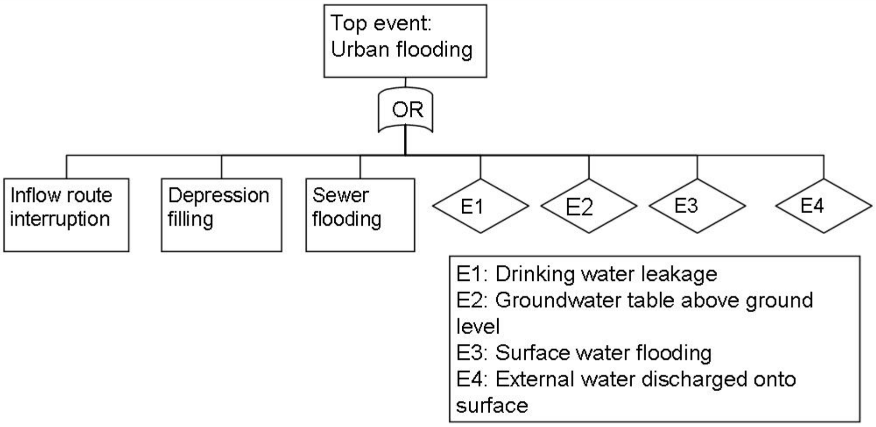

Figure 2.3 Example of a fault tree model for urban flooding, first level. Three events are to be developed deeper, to the level of basic events; four events remain undeveloped. The 'OR' gate indicates that each individual intermediate event can lead to the top event.

Inflow route interruption includes blockage of gutters, gully pots, gully pot manifolds and high road verges that prevent water flow from a road surface to adjacent green areas. Also absence of gutters, gully pots or manifolds is included here. The second mechanism, depression filling is particularly important in steep catchments where water rapidly runs down a slope and fills up depressions at the bottom if no drainage facilities are available. When facilities are available, flow pathways and potential failures become identical to the inflow route interruption mechanism. Depression filling is different in this respect that water that ends up in a depression comes largely from other, upstream areas. The sewer flooding mechanism occurs when water reaches a sewer system, but cannot enter because the system is full, or, in hydraulic terms, the hydraulic gradient in the system is at or above ground level. This can be due to system overload or to partial or complete blockage of components. Sewer flooding also includes the mechanism where water has already entered a sewer system and flows onto the surface due to rise of the pressure level above ground level. A detailed fault tree for these failure mechanisms has been developed and is available upon request.

Quantitative fault tree analysis

Quantitative analysis of a fault tree provides the probabilities of occurrence of basic events and of the top event. It also gives quantitative rankings of contributions of basic events to the top event. A failure probability model must be chosen that suits the type of failure processes in the fault tree. In this analysis the occurrence of events is assumed to be a Poisson process, which implies that the probability that an event will occur in any specified short time period is approximately proportional to the length of the time period. The occurrences of events in disjoint time periods are statistically independent. Under these conditions, the number of occurrences x in some fixed period of time is a Poisson distributed variable:

$$p_X(x) = \frac{(\lambda t)^x e^{-\lambda t}}{x!} \qquad (2.1)$$

Where: $p_X(x)$: probability of x occurrences in a period of time t
λ : average rate of occurrence of events per time unit

The rate of occurrence λ is derived from failure data over a certain period of time. In a homogeneous Poisson process, the event occurrence rate λ is constant. In a nonhomogenous Poisson process, λ is modelled as a function of time; this model is useful to analyse trends, e.g. due to ageing processes. In this fault tree analysis a constant failure rate has been assumed.

Since failure occurs due to the occurrence of 1 or more events, the probability of failure can be calculated from:

(2.2)

Where: $P(X \geq 1)$: probability of one or more events
$p_X(0)$: probability of no events

The time period t can be chosen at will; the longer t, the higher the probability of occurrence. The time scale is preferably chosen so as to fit the frequency of events. In the case of urban flooding flood events typically occur up to several times per month and the duration of events is in the order of several days. A time period of 1 week fits the event occurrence frequency and has been chosen for the fault tree analysis of urban flooding.

This quantitative fault tree model is based on fixed probabilities of occurrence of the basic events. The model can be developed further into a stochastic fault tree model such as Reliability Block Diagrams or Dynamic fault trees in which functional dependencies and fault-ordering is included. These extensions can be subject for future study. The focus of this studyxx is primarily towards fault tree modelling.

Independent events

Probabilistic fault tree analysis is more straightforward if successive events are independent because probability distributions like the Poisson distributions are only applicable on this condition. Successive flood events are independent if the total urban drainage system has returned to its initial conditions between two events. This includes all system components: pipes, basins, surfaces surface infiltration capacity etc.

In practice usually insufficient data are available to check whether initial conditions have been restored. A safe and practical assumption has been made to separate independent events for this fault tree analysis. The main source of urban flood water being rainfall, first a criterion has been defined for independence of rain events. It is based on the length of the intermediate dry period which must be sufficiently long to allow the drainage system to come back to initial conditions. This period is typically in the order of 10 to 15 hours. The intermediate period must not be longer than 24 hours because extremely long events, in the order of several weeks, would result. This exceeds the minimum return period of flood events and thus distorts probabilistic analysis. Even though initial soil conditions may not have been entirely restored after 24 hours, the relative influence on system storage capacity is expected to be minor. In addition it is assumed that blockages that give rise to flood incidents are removed before the start of a new event, to assure independence of successive blockage events. Given that call data are used as data source for blockage incidents, it is likely that problems are solved within a short time after calls are made, since this is the main purpose of municipal call centres.

The identification of a criterion for the spatial independence of events is less straightforward. Since hydraulic relationships control the flow patterns throughout sewer systems, flood events at separate locations are likely to be dependent. For this reason it is more convenient to evaluate the fault tree model for an urban drainage system as a whole. In that case the fault tree model provides probabilities of flood incidents on system level.

The number of flooded locations per event is used to quantify the consequences of individual flood events and this information is combined with probabilities to quantify flood risk. Flood risk, as defined in the European Flood Risk Directive means the combination of the probability of a flood event and the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event (EU, 2007). Other information on the extent of the flooding, if available, can be added to quantify the consequences. There is no longer a need to define a criterion to separate events at different locations, because consequences can be calculated on a gradual scale.

2.4. Results of quantitative fault tree analysis for two case studies

Case studies characteristics and available data

The quantitative fault tree model has been applied to two case studies, Prinsenbeek, a district in the city of Breda, and Haarlem. A municipal call register, local rainfall measurements and a hydrodynamic sewer model are available for both cases. Table 2.1 presents a summary of urban drainage system characteristics for the two cases. Both are gravity systems that are connected to a treatment plan by a pumping station at the downstream end of the system.

Table 2.1 Characteristics of the urban drainage systems of Prinsenbeek and Haarlem

Urban drainage system characteristics	Unit	Prinsenbeek	Haarlem
Number of inhabitants	-	11,000	147,000
Ground level variation	m	1	20
Storage in combined system below lowest overflow weir	m^3	4700	72000
Maximum time needed to empty a full system storage after rainfall: system storage/minimum capacity available to pump rainwater	hour	7.5	24
Total length of gravity sewer pipes (% combined)	km	53.3	460
	%	95	98
Total residential area	km^2	1.75	32
Total impervious area (estimation in year)	km^2	1.01	12.25
- impervious area connected to combined system	km^2	0.86	8.88
- impervious area connected to separate system (% area	km^2	0.15	2.22
where 1st flush pumped to combined system)	%	60	-

Call data are the most important data source to provide estimates of flood incidents as a result of basic fault tree events. Call data are registered in both cases by call centres that are part of the municipality. Call centre numbers are made known to citizens through information brochures and occasional public information campaigns. Calls are recorded in telegram style upon receipt; a text reporting findings of on-site checking of the call is added within a few days, up to a maximum of two weeks after the call. Call texts are analysed manually and every call is assigned to a one of a list of classes that correspond with basic fault tree events. A small number of call texts, about 1%, refer to more than 1 type of basic event; these calls are assigned to the various corresponding classes. To check the reliability of call data, heavy rainfall incident frequencies derived from call centre data are compared with those resulting from model simulations. Also, frequent flood locations are compared. Every heavy rainfall incident that results in flooding according to model simulations is reported by at least 1 call, in the call register. Most locations that suffer frequent flooding in model simulations are reported in the call register as well. Only a number of locations in Haarlem that in model simulations experience a high frequency of flooding do not occur in the call register: these locations are situated in an industrial area and are either not reported or the large impervious areas on private industrial grounds are not well represented in the model so that in reality flood incidents have a far lower frequency. Table 2.2 provides a summary of available call data and rainfall data for the two cases studies.

Two different analyses have been conducted for the two case studies: for Prinsenbeek, the sewer flooding failure mechanism has been analysed (figure 2.3, 2nd failure mechanism from left in fault tree) and for Haarlem the entire fault tree has been analysed, except for depression filling because no data on this mechanism are found in the call register.

Table 2.2 Data sources and characteristics case studies Prinsenbeek and Haarlem

Municipal call registers	**Prinsenbeek**	**Haarlem**
Period of call data	31-07-2003 to 17-10- 2007	12-06-1997 to 02-11-2007
Total nr. of calls[1] in urban-water call category	996	6361
Length of data series	1720 days	3795 days
Rain gauges		
Location of rain gauges (see also: figures 2.4 and 2.5)	1 rain gauge in Prinsenbeek	H1, H2, H3 in Haarlem H4: Leiduin - 3 km SW of Haarlem H5: Schiphol - 10 km SE of Haarlem
Period of rainfall data	01-01-2002 to 31-10-2007	H1, H2, H3: 17-06-2004 to 24-07-2005 H4: 01-01-1997 to 02-10-2007 H5: 01-01-1997 to 31-12-2007
Time interval	5 minutes	H1, H2, H3: 2 minutes H4, H5: day
Hydrodynamic sewer model		
Simulated events:	Rainfall series from local weather station: 01/01/2002-31/10/2007	Stationary rain: 40, 60, 70, 80, 90 l/s/ha Design storms: T=1 year, T=2 years (RIONED, 2004) 3 storms from data series gauge H1
Correlation rain gauges Haarlem		
Correlation between H4 and H5 (2003-2007)		0.635
Correlation betw. H1, H4 (18/11/04-23/07/05)		0.81 (daily rainfall from 8 to 8h for H1)
Correlation betw. H1, H5 (18/11/04-23/07/05)		0.59 (daily rainfall from 8 to 8h for H1)

Calls generated in weekend days are likely to be entered next working day: e.g. in 2004-2005 83 out of 104 Mondays hold complaints (80%), while 303 out of 521 working days hold complaints (58%)

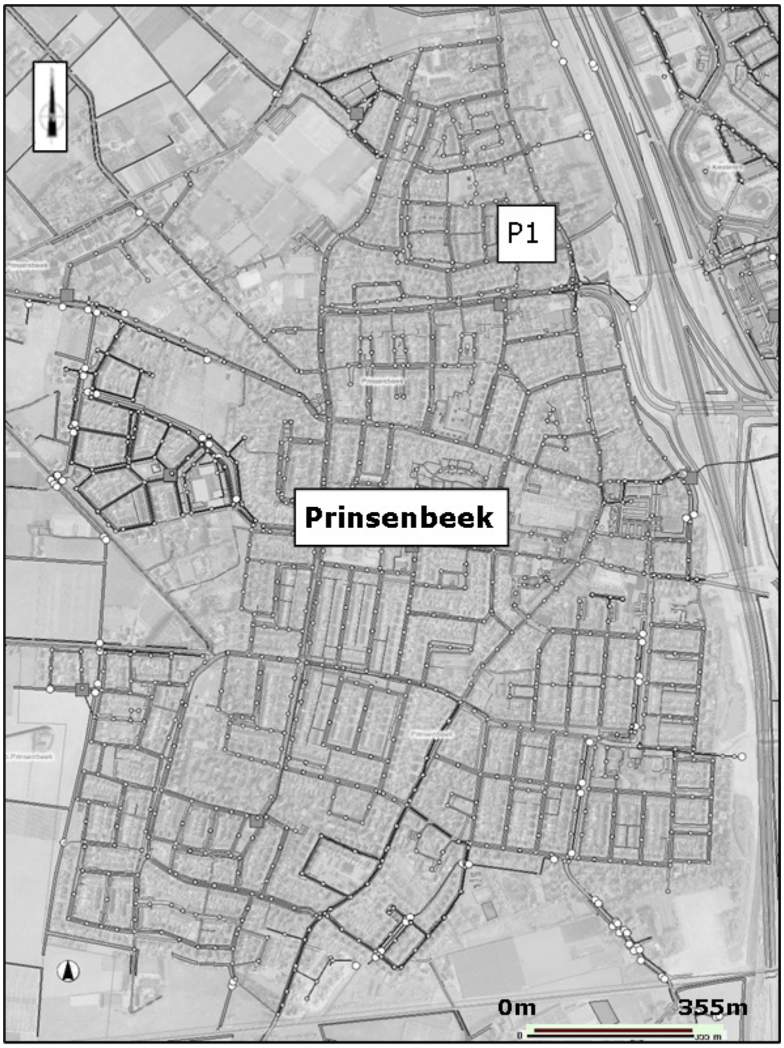

Figure 2.4 Map of Prinsenbeek indicating the layout of the sewer system and the location of the rain gauge P1.

Sewer flooding failure mechanism analysis for Prinsenbeek

The basic events for sewer flooding are sewer overloading by heavy rainfall, pipe blockage and partial blockage or sedimentation of pipes and overflows coinciding with rainfall. To analyse the contribution of these events, incidents from call data are compared to flood incidents from a hydrodynamic model simulation (Infoworks, Wallingford, version 8.5). The rainfall series that is used as input for model simulation entirely overlaps the period of call data. Incidents are counted for independent events; to this end the total rainfall period is separated into independent rain events with dry periods of at least 10 hours in between. This results in 801 independent rain events. For each event, the occurrence of flooding according to call data and to model simulation results is compared and, if so, the number and locations of flood incidents. Figure 2.4 shows the lay-out of the case study area Prinsenbeek and the location of yhe rain gauge.

In the call register 15 incidents of sewer flooding are found; model simulations result in 4 flood incidents. These 4 incidents reflect cases of sewer overloading during heavy rainfall and these are confirmed in textual information of calls related to these incidents, e.g.: "Streets covered with water, water flowing into our house". The other 11 incidents in the call register are related to pipe blockages, a wrong connection and a pump failure in a road tunnel. Call information is not sufficiently detailed to discriminate between total or partial pipe, valve or weir blockages. The frequency of sewer flooding is 0.07 per week or 3.5 per year. The probability of this failure mechanism is 0.07/week or 0.9/year. The relative contribution of blockage events to the sewer flooding failure mechanism is 11 out of 15 (73%). The contribution of sewer overloading is 4 out of 15 (27%). The contribution of blockages is a conservatively biased estimate, since not all potential blockages are reported in a call.

Figure 2.5 Map of Haarlem that shows the location of rain gauges H1, H2 and H3 within the city area and the location of rain gauges H4 in Leiduin and H5 at Schiphol.

Quantitative fault tree analysis for Haarlem

To find incident frequencies of all basic and undeveloped events in the fault tree, every call in the Haarlem call register is screened and classified manually for both causes and consequences of flooding. Cause classes correspond to basic events and undeveloped events. Two “cause unknown” and “no problem detected” classes are added for calls where call texts mention no clear cause or indicate that no problem was found on-site. Consequence classes refer to locations where flooding occurs, indicative of potential severity: flooding in buildings, in basements, on public areas or in gardens and pastures. Figure 2.5 shows the lay-out of the case study area Haarlem and the location of the rain gauges.

Daily rainfall data are available for the whole call data period and a period of 1 dry day is used in this case to separate independent rain events. Calls are assigned to independent rain events based on the date the call was made. Incident frequencies are calculated for each basic event in the fault tree. The fault tree model is used to calculate the top event probability for 4 scenarios of flood consequences: flooding of streets, buildings, basements and gardens, flooding in buildings only, flooding in basements only and flooding of streets only. For each scenario individual contributions of basic events are quantified.

Table 2.3 gives 6 examples of basic events and their probabilities of occurrence. In this case the inter-arrival time $\theta \neq 1/\lambda$, because the duration of events is not negligible. Confidence intervals are calculated for incident frequencies and probabilities based on uncertainties in the call data: 56% of call texts do not explicitly mention occurrence of flooding. Inclusion of these calls in frequency calculations gives a maximum estimate, whereas exclusion provides a minimum estimate of flood incidents. Uncertainty also relates to calls that have been made during dry periods. They represent 23% of the total number of calls. 48% of the “dry event calls” can be explained because they report flood incidents for other causes than rainfall, e.g. drinking water pipe bursts or a high groundwater table. Detailed analysis shows that of the other 52%, some refer to a previous rain event whereas others seem to indicate that at the specific location rainfall did occur. This is explained by spatial rainfall variation that the available data from only two rain gauges for most of the analysed period cannot sufficiently account for. The range between flood incident frequencies including and excluding all dry-period-calls gives another bandwidth of uncertainty in flood incident calculations.

Table 2.3 Six examples of basic events in the fault tree. The second column gives the results for the event occurrence rate, the number of incidents associated with a basic event divided by the number of weeks in the period of analysis (1997-2007). The third column gives the probability of occurrence of basic events. 95% confidence intervals are based on outcomes from different assumptions for incident analysis: in- or excluding calls with no explicit consequence mentioned and in- or excluding calls during dry periods.

Basic events in fault tree for urban flooding Period 1997-2007	**Nr of incidents for basic event [/10 years]**		**Basic event occurrence rate λ [week^{-1}]**		**Probability P of at least one occurrence per week [week^{-1}]**	
Blocked or full gully pot	393	± 209	0.72	± 0.38	0.49	± 0.17
Gully pot manifold blocked or broken	113	± 66	0.21	± 0.12	0.18	± 0.09
No outflow available from a pool to a rainwater facility	60	± 10	0.11	± 0.02	0.10	± 0.02
Sewer overloading	13	± 1	0.02	± 0.002	0.02	± 0.002
Sewer pipe blocked	8	± 4	0.01	± 0.01	0.01	± 0.01
Drinking water pipe burst	29	± 11	0.05	± 0.03	0.05	± 0.03

Gully pot blockages and gully pot manifolds cause the highest numbers of flood incidents (table 2.3) and are subject to larger uncertainty than other basic events. Sewer overloading incidents are reported with high certainty: in most cases consequences are explicitly mentioned and few are reported during dry periods.

The probability of flood incidents in buildings and basements is lower than that of flooding in public areas (table 2.4). This is to be expected since in many cases flood water flows over public areas before it runs into buildings. Flooding of basements is mainly a result of high groundwater tables, for the case of Haarlem. Blocked gully pots and gully pot manifolds, both component failures, cause more flood incidents than sewer overloading by heavy rainfall, not only for flooding in public areas, but also for flooding in buildings.

Table 2.4 Basic event incident numbers and probabilities in urban flooding fault tree for 4 scenarios of flood consequences: (1)sum of all flood consequences, (2)flooding in buildings only, (3)flooding in basements only, (4)flooding of public areas only. Incident numbers of scenario 1 can be lower than sum of incidents of scenarios 2, 3 and 4 because several types of consequences often occur simultaneously during a rain event.

Basic events in fault tree for urban flooding, 4 flood consequence scenarios Period 1997-2007	Nr of basic event incidents [/10years]	Prob. of at least 1 occ. per week [week^{-1}]	Nr of basic event incidents [/10years]	Prob. of at least 1 occ. per week [week^{-1}]
	Scenario	1	Scenario	2
Blocked or full gully pot	314	0.440	45	0.080
Gully pot manifold blocked or broken	70	0.120	6	0.011
No outflow from a pool to a rainwater facility	66	0.110	12	0.022
Sewer overloading	14	0.025	1	0.002
Sewer pipe blocked	8	0.015	0	0.000
Groundwater table above ground level	46	0.066	1	0.002
Drinking water pipe burst	37	0.066	1	0.002
	Scenario	3	Scenario	4
Blocked or full gully pot	17	0.031	304	0.430
Gully pot manifold blocked or broken	2	0.004	68	0.120
No outflow from a pool to a rainwater facility	2	0.004	54	0.095
Sewer overloading	5	0.009	7	0.013
Sewer pipe blocked	0	0	6	0.011
Drinking water pipe burst	3	0.006	21	0.038
Groundwater table above ground level	46	0.081	2	0.004

Quantitative analysis: Monte Carlo simulation of fault tree

Mean basic event probabilities are used to calculate the top event probability and rank the contributions of basic events. The quantitative analysis is based on Monte Carlo simulation: the occurrences of basic events are simulated by use of a random number generator. Each simulation that results in failure is stored, with the combination of basic events that caused the failure. A Monte Carlo simulation for the case of Haarlem results in 7000 failures out of 10.000 simulations. The probability of the top event is 0.7 per week. Table 2.5 shows the contribution of 5 basic events to the overall probability of failure.

Table 2.5 Results of 10.000 Monte Carlo simulations with the fault tree model for Haarlem

Basic events	**Contribution to total number of 7000 flood incidents**	**Contribution to overall probability of failure [%]**
Blocked or full gully pot	5000	71
Gully pot manifold blocked or broken	1770	25
Not outflow available	1020	15
Sewer overloading	210	3
Sewer pipe blocked	95	1
Drinking water pipe burst	510	7

Sensitivity analysis for fault tree calculation

The sensitivity of the fault tree analysis to the probabilities of the basic events is tested by changing the probabilities of the basic events between a lower and an upper limit. Probability estimates based on call data are considered as a minimum probability estimate since the likelihood of a false positive in the register after cross-checking with rainfall data is small. Maximum estimates are based on the number of basic events that could occur under unfavourable conditions, with a minimum if maintenance and a maximum of human errors. Estimates are made by expert judgment. For instance, the maximum expected probability for gully pot blockage has been set equal to the probability of occurrence of a rain event. The maximum estimate for no outflow has been set equal to the average number of road reconstruction projects, assuming that all of these result in some error that creates a no-outflow situation. The mistake is assumed to be repaired after the first rain event.

Table 2.6 Results of the fault tree sensitivity analysis with minimum and maximum probability estimates, for 10.000 Monte Carlo simulations

Basic events	**Minimum estimate**	**Maximum estimate**
Total probability of failure	0.7	0.97
Contribution to overall probability of failure, minimum estimate [%]		
Blocked or full gully pot	71	75
Gully pot manifold blocked or broken	25	44
Not outflow available	15	43
Sewer overloading	3	15
Sewer pipe blocked	1	22
Drinking water pipe burst	7	50

The probability of the top event rises to 0.97 when maximum estimated occurrence probabilities are entered for all basic events (table 2.6). The contribution of most individual basic events to the failure probability increases; nevertheless gully pot blockages still contribute 75% to the top event probability. The contribution of heavy rainfall events to the top event has increased from 5 to 15 %. The percentage contributions of the basic events do not add up to 100%, because basic events can contribute to the top event through various combinations of basic events. The percentage indicates the ratio of the failures in which the basic event is involved to the total number of failures. The pessimistic maximum probability estimates result in many concurrences of basic events.

2.5. Discussion

In this chapter a methodology is provided to conduct quantitative fault tree analysis for urban water infrastructure systems and present results of applications to two cases. To the authors' knowledge, this is the first application of probabilistic fault tree analysis to urban water infrastructure flooding. The results show that component failures contribute significantly to urban flood probability: gully pot blockage contributes 71%, gully pot manifold blockage 25% and pipe blockage 1% in a complete fault tree analysis for the case of Haarlem. An analysis of only the mechanism of sewer flooding for the case of

Prinsenbeek results in a frequency of 0.07 per week, where sewer blockage contributes 73%. Nevertheless this type of failure mechanism receives only minor attention in most flood risk studies that tend to focus on sewer overloading by heavy rainfall which contributes only 3% to urban flood probability and 27% to sewer flooding in the presented cases. The results seem to justify further extension of research and monitoring in this field.

The results presented are mainly based on call centre data and have a conservative bias: only part of potential incidents is reported in calls. It is expected that sewer overload incidents are largely covered, because their call reports are confirmed in sewer model simulation results. The bias in incident estimates for component failure and human errors is difficult to assess. A test should be conducted in practice where urban areas are intensively monitored during a number of rain events to capture all flood incidents and these should be compared to the number of incidents that is reported to the call centre.

Fault tree analysis for urban flooding has been shown to provide useful data for risk analysis and management: it reveals potential failure mechanisms and quantifies failure probabilities and relative rankings of failure mechanism contributions. These can be used to find and improve weaknesses in urban water systems. A complete risk assessment requires two parameters: incident probability and the severity associated with an incident (Haimes, 1998). This chapter does not deal explicitly with incident severity, but some first insights are given by comparing different flood consequence classes. We have shown that the probability of flooding in buildings is lower than that of flooding in public areas as may be expected since water often flows from public areas into buildings. Flooding of basements is in the case Haarlem almost exclusively a result of high groundwater tables and incidents are independent of rain events. To appropriately quantify risk and justify risk reduction investments a good severity metric must be available. Urban flood incidents involve intangible consequences such as traffic delay and social distress and inconvenience. Much information on this subject has been collected in research studies in the UK

(Penning-Rowsell et al., 2005) The next step in this study will be to evaluate possibilities for a severity metric for urban flood consequences based on call data and available references.

Risk management has traditionally been reactive where flood incidents caused by blockages and human errors are concerned. Pipe blockages can be detected by sewer pipe inspections, but inspection frequencies are generally too low, in the order of once in 10 years, to undertake adequate preventive actions. Other components, like gully pots and pumps, tend to have a fixed maintenance frequency and failures are handled after they occur. The question whether a proactive structured approach like fault tree analysis can actually reduce incident frequencies compared to traditional approaches is yet unanswered. Fault tree analysis provides insight into relative contributions of failure mechanisms and can by that draw attention to failure mechanisms that were previously overlooked or underestimated. If preventive maintenance to prevent blockage or at least to prevent flooding caused by blockage can be effective is a difficult question to answer, because the formation of blockages by sediments, tree roots, objects dumped into sewers etc. is highly unpredictable.

Fault tree analysis is a methodology that can easily incorporate different kinds of flood incident causes in the quantification of flood probability. Also detection of weak points and unforeseen failure mechanisms is a strong feature of this methodology. In this sense it complements information provided by hydrodynamic model simulations of flooding: hydrodynamic models are well capable of modelling expected flood frequencies as a result of heavy rainfall, based on rainfall series. They can also, in combination with overland flow models, simulate expected flow paths, if sufficient geographical information is available. But modelling of flood causes related to blockages and errors and quantification of associated flood probabilities requires complex manipulations and can be done in more straightforward way in a fault tree.

This research has revealed opportunities for potential improvement in call data registration to make data more suitable for risk analysis. Categories that are currently used in call data registers primarily serve the purpose of efficient redirection of calls for handling by the relevant departments. If an additional well-defined classification is created based on potential flood causes, and causes of other incident types if desired, incidents reported in these classes could be directly used as input for fault tree analysis. A consequence classification could also be added to be able to derive probabilities of incidents of different severity. Proper use of these classifications requires training of involved personnel at the call centre or call handling departments. Alternatively, automatic classification of calls based on call texts can be considered. First attempts have been to do this for the case of Haarlem. Automatic classification is based on recurrent words or word combinations in call texts and its potential accuracy depends on correct and consistent use of words the texts. In both cases the benefit of improvements relies on awareness of system users of the importance of accurate classification and reporting.

To gain more insight in explanatory factors of flood incidents and their causes, fault tree analysis can be applied to more cases to compare results for different systems. Examples of potential explanatory factors for occurrence of pipe, gully pot, gully pot manifold and pump blockages are system age, system component types or materials, maintenance regime and population composition.

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Chapter 3

Urban flood risk curves

This chapter is based on an article that was accepted for publication in Water Science and Technology.
Veldhuis, J.A.E. ten, Clemens, F.H.L.R. (in press). Flood risk modelling based on tangible and intangible urban flood damage quantification. Water Science and Technology.

Context

In the previous chapter it was shown that overloading of urban drainage systems by heavy rainfall is only one of the possible failure mechanisms that can cause urban flooding. The contribution of this failure mechanism to overall flood probability is small compared to other failure mechanisms. This means that hydrodynamic modelling of sewer overloading by heavy rainfall can provide only a partial picture of flood risk. The question remains what the contribution of sewer overloading is to total flood risk, probabilities and consequences, compared to other failure mechanisms. To answer this question, a method must be found that incorporates all failure mechanisms to fully assess flood risk. Failure mechanisms like blockage of gully pots and sewer pipes are not well enough understood to predict their probabilities of occurrence and associated flood consequences in a deterministic way. This means that data-driven modelling is the only way to quantify total urban flood risk. Such data-driven approach requires historical data-series of flooding events, including information on their causes and consequences. This chapter explores data from municipal call centres to find out whether the information they provide can be used to quantify urban flood risks associated with all possible failure mechanisms.

Abstract

The usual way to quantify flood damage is by application stage-damage functions. Urban flood incidents in flat areas mostly result in intangible damages like traffic disturbance and inconvenience for pedestrians caused by pools at building entrances, on sidewalks and parking spaces. Stage-damage functions are not well suited to quantify damage for these floods. This thesis presents an alternative method to quantify flood damage that uses data from a municipal call centre. The data cover a period of 10 years and contain detailed information on consequences of urban flood incidents. Call data are linked to individual flood incidents and then assigned to specific damage classes. The results are used to draw risk curves for a range of flood incidents of increasing damage severity. Risk curves for aggregated groups of damage classes show that total flood risk related to traffic disturbance is larger than risk of damage to private properties which in turn is larger than flood risk related to human health. Risk curves for detailed damage classes show how distinctions can be made between flood risks related to many types of occupational use in urban areas. This information can be used to support prioritisation of actions for flood risk reduction. Since call data directly convey how citizens are affected by urban flood incidents, they provide valuable information that complements flood risk analysis based on hydraulic models.

Keywords: flood risk; intangible damage; risk curve; urban drainage

3.1. Introduction

Quantitative flood risk assessment consists of two steps: probability estimation and flood damage quantification. Methods to quantify flood damage for severe floods are usually based on stage-damage functions that quantify damage based on inundation depth, flood duration and occupational land use (Thieken et al., 2005). Such functions focus on damage to buildings and building contents, which constitute the main part of total flood damage for severe floods (DEFRA, 2004). Such floods typically have a low probability of occurrence and affect large areas at once.

Urban drainage systems in lowland areas are typically designed to cope with rainfall events with return periods of two to five years (e.g. RIONED, 2004). As a result, urban flood incidents occur at a regular basis. Many of these incidents are characterised by small flood depths and small geographical extension. Stage-damage functions are not applicable to quantify damage for such small flood depths (Merz et al., 2005; Apel et al., 2004; Dutta et al., 2003), because they are generally developed for flood depths between 0 and 5 meters (e.g. Apel, in press, Chang 2008 and Dutta, 2003) and uncertainty increases for applications to smaller flood depths. Additionally, for many urban flood incidents, direct damage forms a small if not negligible portion of flood consequences, where intangible damage in the form of disruption of road traffic and inconvenience for pedestrians caused by pools in front of shops, on parking lots and sidewalks is more important. Indirect and intangible damages are more difficult to quantify than direct damage. For convenience, indirect damage is sometimes quantified as a fixed percentage of direct damage (FHRC, 2003), if indirect damage is expected to be small compared to total damage. 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 (Tapsell et al., 2003). Few references are available on quantitative measures for these indirect and intangible damages, compared to material damage and loss of life. A method to translate intangible consequences into monetary values is by assessing people's willingness to pay (WTP) to prevent flood consequences. This method was applied in the UK, where WTP to prevent health effects of flooding was investigated in a series of questionnaires (DEFRA, 2004) which resulted in an average sum per household. Fewtrell and Kay (2008) attempted to quantify physical and mental health effects in terms of disability adjusted life years (DALYs) based on interview results for people affected by floods. This approach was also adopted by Lulani et al. (2008), who based their study on a list of theoretical assumptions. Most methods that were proposed to quantify intangible damage (e.g. Green et al., 1998 and Lekuthai et al., 2001, DEFRA, 2004) are based on indirect data, if any and include assumptions that are difficult to verify.

In this chapter, municipal call data are used, that provide detailed information on flood problems as encountered by citizens. The advantage of call data as opposed to interviews and questionnaires is that the lag time between incident occurrences and reporting of the consequences is very short. The purpose of this study was to translate call information into quantitative values that can be used for risk assessment. Risk is expressed in the form of a set of risk curves that visualise risks expressed as exceedance probabilities for a range of consequence severities.

3.2. Classification of flooding consequences

Flood incident data

Call data consist of a unique call number, date of the call, street name to indicate the problem location and a telegram style text that describes what the caller has said. In most cases a second text is added that describes the results of on-site checking and actions undertaken to solve the problem. Ten years of call data on flood incidents in Haarlem and 5 years of call data for Breda were analysed to quantify flood risk. Calls on urban drainage incidents were selected from the database which resulted in dataset of 6361 and 7049 calls. Calls were assigned to independent rain events which were defined by a separation of 24 or more hours of dry weather.

Classification results are sensitive to class definition: the more narrowly a class is defined, the lower the number of calls assigned to that class. Class boundaries must be set in such a way that class sizes are more or less equal or, if class sizes are different, these differences must be taken into account when results are interpreted and compared between classes. This is more straightforward for numerical values like ages in a population or flood damage figures than for nominal values like call texts. For example, a class defined as “flooding at bus stop” is by nature likely to receive fewer calls than “flooding on residential road”, for two reasons: the total area of residential roads far exceeds that of bus stops in any urban area and calls with short, undetailed call texts automatically fall into classes of a more general definition, i.e. a class like “residential road” is likely to get assigned many calls.

A consequence classification for urban flood-related calls has been developed for this study, based on the primary functions of urban drainage systems (Davies and Butler, 2004). This results in classes that can directly support evaluation of urban drainage functioning and associated policy guidelines. Table 3.1 shows primary functions and consequence classes that have been used for call consequences classification. For illustration, the numbers of calls in each class for the case of Haarlem are added: the high number of calls in class “flooding on residential/main street” compared to other classes shows how specificity of class definition influences call numbers.

Calls are assigned to damage classes based on observations described in the call texts: for instance, calls texts mentioning observations of toilet paper or excreta are assigned to wastewater flooding; call texts indicating flooding of a shop or a bus stop are assigned to the corresponding class. Classification results consist of a matrix with individual flood incidents I_1 to I_n in rows and damage classes in columns. Table 3.2 shows a schematised example of the matrix.

Table 3.1 Primary functions of urban drainage systems and consequence classification

Primary functions	Consequence classes	Nr. of calls in class (city of Haarlem)
Protection of human health: physical harm or infection	Flooding with wastewater (toilet paper/bad smell/ excreta)	20
	Manhole lid removed	4
Protection of buildings and infrastructure against flooding: damage to public and private properties	Flooding in residential building (house/flat/garage/shed)	78
	Flooding in commercial building (shop/restaurant/storage hall)	26
Prevention of road flooding: traffic disruption	Flooding in tunnel(road/cycleway)	13
	Flooding at bus stop/bus station/taxi stand	18
	Flooding in shopping street/market place/commercial centre	115
	Flooding in front of entrance to shop/bar/restaurant/ library/hospital	55
	Flooding on residential/main street	596
	Flooding of sidewalk/cycle path	344

Table 3.2 Example of damage classes and call classification results

	Damage classes				
Flooding incident nr.	Flooding in commercial building	Flooding in residential building	Flooding of residential road	Flooding in road tunnel	Flooding of wastewater
I_i	0	1	20	0	0
I_j	0	0	5	0	1
I_k	1	0	12	0	0

3.3. Risk curves

Risk assessment studies often present the expected value of risk as a summary value for a range of probabilities and consequences or they give a risk value for a given scenario, e.g. a certain return period. Risk curves go one level deeper and present risks for a range of probabilities and consequences (Kaplan and Garrick, 1981). Risk curves for urban flooding depict flood damages on the horizontal axis and their associated exceedance probabilities on the vertical axis. Figure 3.1 gives an example of a risk curve, for a flood damage x_i varying from 0 to 100 on the horizontal axis and associated exceedance probabilities on the vertical axis. The intersection of the curve with the vertical axis gives the probability of any damage at all; the intersection with the horizontal axis gives the maximum possible damage, with zero probability of exceedance. Values in between are interpreted as probabilities of at least damage x_i; this probability increases or remains constant for decreasing damages. The staircase function is the plotted result of a series of points representing damage for scenario i and for each scenario. The staircase function can be regarded as a discrete approximation of a continuous reality, represented by the smooth curve.

The area below the risk curve is a measure of total risk; the further risk curves shift to the top-right-hand corner of the graph, the higher their associated total risk. The advantage of risk curves compared to one value for expected risk is that risk curves give insight into the contributions of small and large damages to flood risk. If flood risk is mainly associated with small damage incidents, the curve decreases steeply for small damages and more gently for high damages, as is the case of the example in figure 3.1. If large damages mainly compose risk, the curve is more or less flat for small damages and steeply decreases at large damage values.

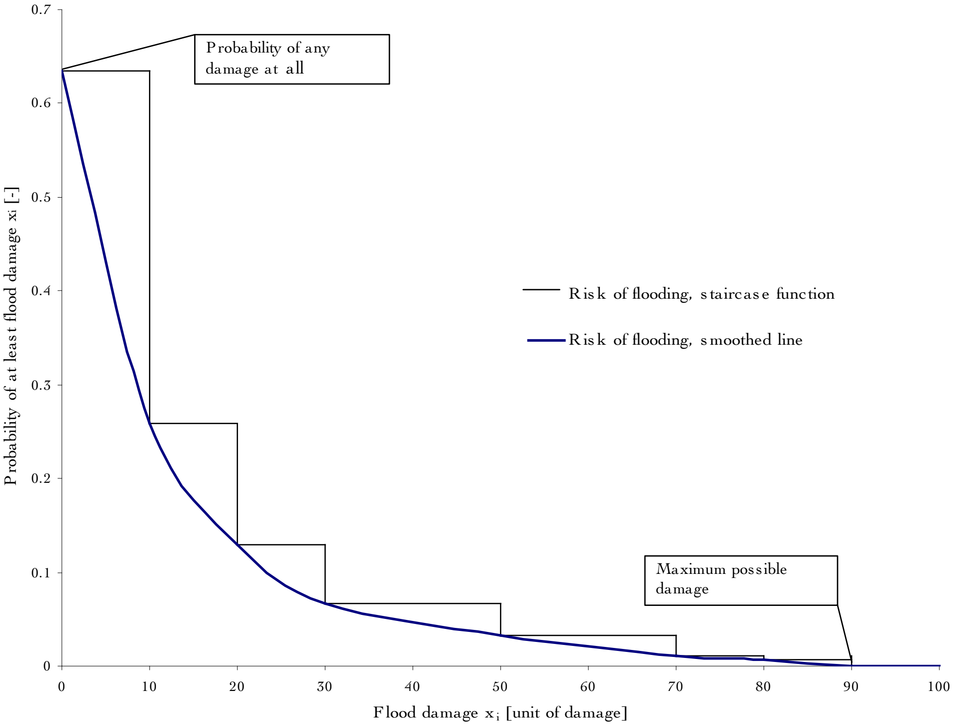

Figure 3.1. Example of a risk curve (based on: Kaplan and Garrick, 1981): a complementary cumulative distribution function (CCDF), i.e. the probability of exceeding a given damage

Representation of risk in the form of risk curves requires availability of flood incident data for a range of small to large flood damages. In this chapter call classification results are used as a quantitative measure for intangible flood damage, based on the assumption that the amount of calls per incident is indicative of the number of affected citizens. This is confirmed by the correlation between rainfall volume and numbers of flood-related calls per rainfall event: a correlation coefficient of 0.76. This indicates that call numbers increase with increasing rainfall volumes which are likely to induce more flooding (figure 3.2). The resulting curves for the number of calls per flood incident are similar to FN-curves that show the probability of exceedance (F) as a function of the number of fatalities (N) and are often used to quantify societal risk (e.g. Bedford and Cooke, 2001).

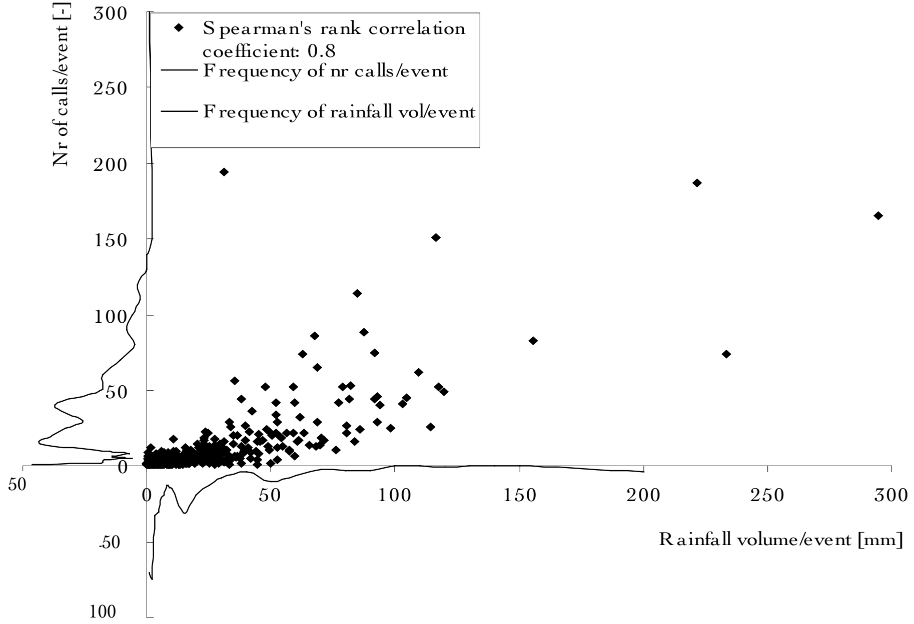

Figure 3.2 Correlation between the number of calls per event and rainfall volume per event. Frequencies of the number of data for call number per event and rainfall volumes are displayed as well.

The probability of a certain damage, or amount of calls per incident, is derived from the occurrence frequency of the damage. The occurrence of a given damage is assumed to be a Poisson process. This implies that the probability that a given damage will occur in any specified short time period is approximately proportional to the length of the time period, that occurrences of evens in disjoint time periods are statistically independent and that events do not occur exactly simultaneously. Under these conditions, the number of occurrences x in some fixed period of time is a Poisson distributed random variable:

$$p_X(x) = \frac{(\lambda t)^x e^{-\lambda t}}{x!} \tag{3.1}$$

Where: $p_X(x)$: probability of x occurrences of a given damage in a period of time t

λ : average rate of occurrence of a given damage per time unit

The rate of occurrence λ is derived from call data over a certain period of time and is assumed to be constant. The probability of any occurrence of a given damage can then be calculated from:

$$P(X \geq 1) = 1 - p_X(0) = 1 - e^{-\lambda t} \tag{3.2}$$

Where: $P(X \geq 1)$: probability of at least one occurrence

$p_X(0)$: probability of no occurrences

The time period t can be chosen at will; the longer t, the higher the probability of occurrence. The time scale is preferably chosen so as to fit the frequency of events. In our dataset flood incidents occur up to several times per month and the duration of events is in the order of several days. A time period of 1 week fits the incident occurrence frequency and has been chosen for this analysis.

The results are used to plot risk curves for individual damage classes separately and for aggregated groups of damage, where calls over several classes are added up. Risk curves are plotted in the form of smooth lines.

3.4. Results and discussion

The municipal call classification results are given in table 3.3. Out of all classified calls, 28% of the calls for Haarlem and 16% for Breda mention consequences related to flooding. Flooding on streets is reported most often as a consequence. This can be explained by the more general definition of this class as opposed to e.g. flooding in front of entrance to building Therefore this class contains both calls of real street-flooding and calls that due to a lack of detail in the call text could not be assigned to more specific classes. This is a drawback of different levels of detail in class definition that can only be avoided by generalising classes which in its turn leads to a loss of information from detailed call texts.

Table 3.3 shows that detailed classification results in a number of sparse consequence classes. In second instance, classes are lumped to a higher aggregation level in order to obtain a more balanced classification dataset. The classification results at the higher aggregation level are shown in table 3.3, as totals in bold numbers.

Table 3.3 Call classification results for aggregated and for detailed flood consequence classes, for the cases of Breda and Haarlem, for periods of 10 years and 5 years

Primary functions	Consequence classes	Nr. of calls/ class:Haarlem		Nr. of calls / class:Breda	
		(nr)	(%)	(nr)	(%)
Human health: physical harm or infection	Flooding with wastewater	61	3.4	28	1.5
	Manhole lid removed	7	0.4	9	0.5
Total		**68**		**37**	
Protection of buildings and infrastructure: damage to public and private properties	Flooding in residential building (house/ garage/shed)	116	6.5	141	7.6
	Flooding in commercial building (shop/ storage hall)	34	1.9	16	0.9
	Flooding in basement	173	9.7	63	3.4
	Water splashes onto building	26	1.5	26	1.4
	Flooding of gardens/park	74	4.1	63	3.4
Total		**423**		**309**	
Prevention of road flooding: traffic disruption	Flooding in tunnel	13	0.7	22	1.2
	Flooding at bus stop/taxi stand	18	1.0	17	0.9
	Flooding in shopping street/place/ commercial centre	117	6.5	4	0.2
	Flooding in front of entrance to shop/bar/ library/hospital	55	3.1	43	2.3
	Flooding in front of entrance to residential building	65	3.6	66	3.6
	Flooding on residential/main street	655	36.5	1229	66.6
	Flooding on cycle path	133	7.4	23	1.3
	Flooding on sidewalk/footpath	73	4.1	25	1.4
	Flooding on parking space	173	9.7	70	3.8
Total		**1302**		**1499**	
Total number of calls relevant for flooding		1793	100%	1845	100%
No consequence mentioned		3563		3035	
Consequence other than flooding		1005		2169	
Total number of calls		6361		7049	

Figure 3.3 shows the classification results for the flood-related consequence classes in percentages of the total number of flood-related calls. Flooding in residential streets occurs most frequently in Haarlem and more dominantly so in Breda. The 3 classes that relate to flooding in buildings represent 19% and 13% of the flood-related calls.

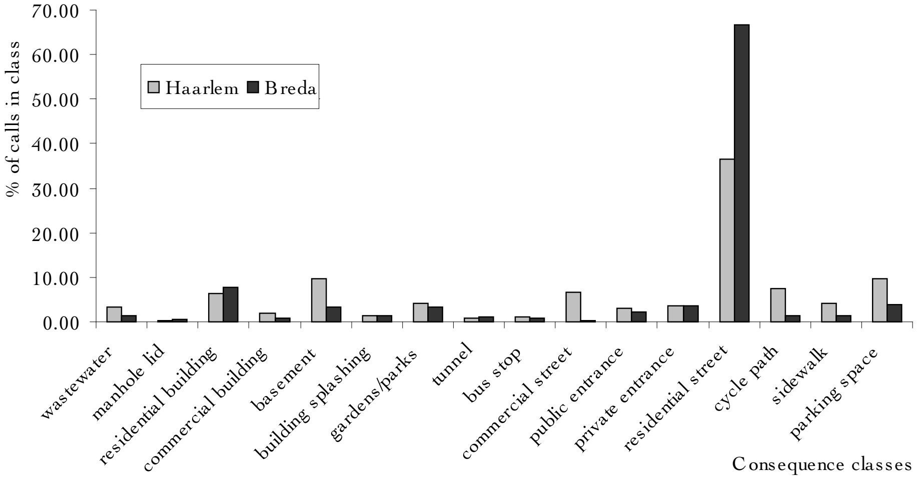

Figure 3.3 Call classification results for flood-related consequence classes, for the cities of Haarlem and Breda

Classification results at both aggregation levels are used to plot risk curves. Figures 3.4 and 3.5 give 2 examples of risk curves for individual damage classes. Flood consequence severity on the horizontal axis is expressed as amount of calls per incident. The risk curves show that the maximum amount of calls for flooding on streets is more than twice as high as for flooding in residential buildings. The probability of at least 1 call is more than 3 times higher for flooding on streets than flooding in residential buildings.

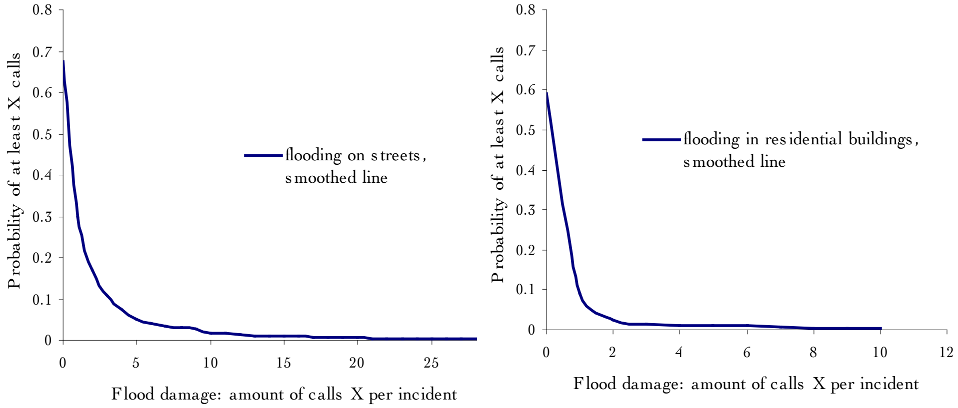

Figure 3.4. Risk curves (smoothed lines) and staircase functions for consequence class 'flooding on streets', based on call amounts per incident as a measure for consequence severity

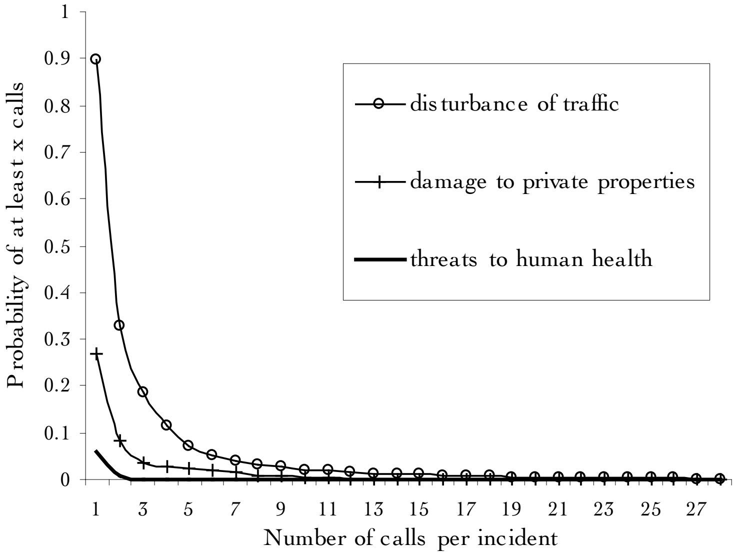

Figure 3.5. Risk curves (smoothed lines) and staircase functions for consequence class 'flooding in residential buildings', based on call amounts per incident as a measure for consequence severity.

Risk curves for other consequence classes (see appendix 3) indicate that for most consequence classes, maximum amount of calls per incident is below 5. Maximum probabilities of at least 1 call per event vary from 0.009 per week for lifted manholes to 0.13 per week for flooding on parking spaces. Risk curves provide this information in a more accessible way than lists of numerical data. The results indicate that most call texts are not detailed enough to be assigned to detailed consequence classes and end up in a general class, here "flooding on streets". Still, detailed classification results help to identify which consequences are mentioned more often than others. For instance flooding in residential buildings is a detailed class that is mentioned up to 10 times per flood incident, whereas flooding of tunnels is never mentioned more than once per incident in our dataset.

Figure 3.6 shows 3 risk curves based on aggregated flood consequence classes. The curves show that consequences for traffic are far more likely to be mentioned by callers than damage to private properties and human health consequences. The probability of at least 1 call on traffic consequences is almost 0.9 per week and the maximum amount of calls per incident is 28. Human health consequences are mentioned in maximum 3 calls per incident; the probability of at least 1 call per incident is 0.06 per week. Damage to private properties generates a maximum of 12 calls per incident; the probability of at least 1 call is almost 0.3 per week. Risk curves for aggregated consequences are useful to quickly distinguish between higher and lower risks.

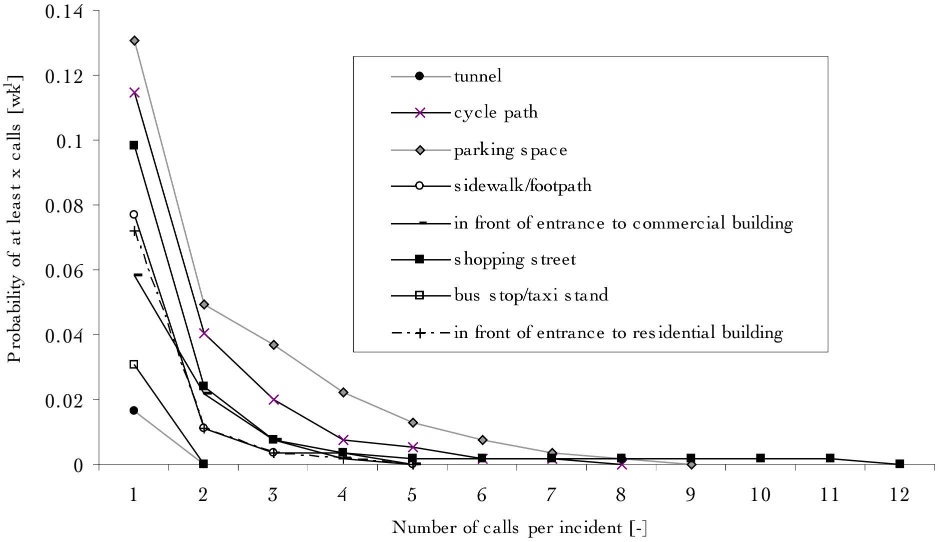

Figure 3.6 Risk curves for aggregated urban flood consequence classes

In figure 3.6, the risk curve for 'disturbance of traffic' lies furthest towards the upper right corner of the graph, so the total associated risk is highest for this curve. Total risk for damage to private properties is lower than for disturbance of traffic and higher the risk of threats to human health. All risks are mainly related to low-severity incidents in the sense that for most incidents only few people report consequences.

This information is a useful input to check system performance for compliance with policy guidelines. For instance if health protection is a priority, the lower health risk compared to other risks as illustrated in figure 3.6 is in accordance with policy guidelines. If prevention of traffic disturbance has a high priority, the aggregated risk curve in figure 3.6 is a reason to consider the need for improvements. Aggregated consequences give information about risks at the level of primary functions of urban drainage systems. More detailed information is required to decide whether the underlying types of consequences indeed justify investments for improvement and if so, which actions are most effective.

For instance, figure 3.7 shows risk curves for detailed consequence classes within the aggregated class 'traffic disturbance'. Main contributions to the risk of traffic disturbance are flooding of cycle paths and parking spaces, whereas flooding of tunnels and bus stops contribute only little to traffic disturbance risk. The more detailed the level of risk curves, the better investment needs can be identified and motivated.

Uncertainty aspects

Flood risk estimations are subject to large uncertainties, whether based on historical data, theoretical modelling or a combination of both (see e.g. Apel et al., 2004 and Merz et al., 2004). Call data are a valuable source of historical data on flood incidents that has been little researched so far. A source of uncertainty particular for flood risk estimations based on these data is that call data report only a portion of the actual flood incidents. It is unknown whether reported incidents are representative nor what proportion they form of the total amount of incidents. Also, call information can be subjective and comes from non-experts whose information can be incorrect. This source of uncertainty is greatly reduced when calls are checked on-site by technical experts or when calls are handled by trained people using good protocols. On the other hand, call data directly convey citizens' experiences regarding adverse effects of wastewater and flooding, which urban drainage systems are designed to protect citizens from. Therefore call data are a useful source of information to prioritise actions for flood risk reduction.

Risk curves can be made for data sources of historical flood incidents other than call data as well. When data from various sources are available these can be used to draw separate curves and compare these. Alternatively, historical flood incident data can be combined by design a classification that fits the data and can be used to draw risk curves. Combination of data sources does require a careful assignment of data to individual incidents and consequence classes so as to avoid double counting of consequences.

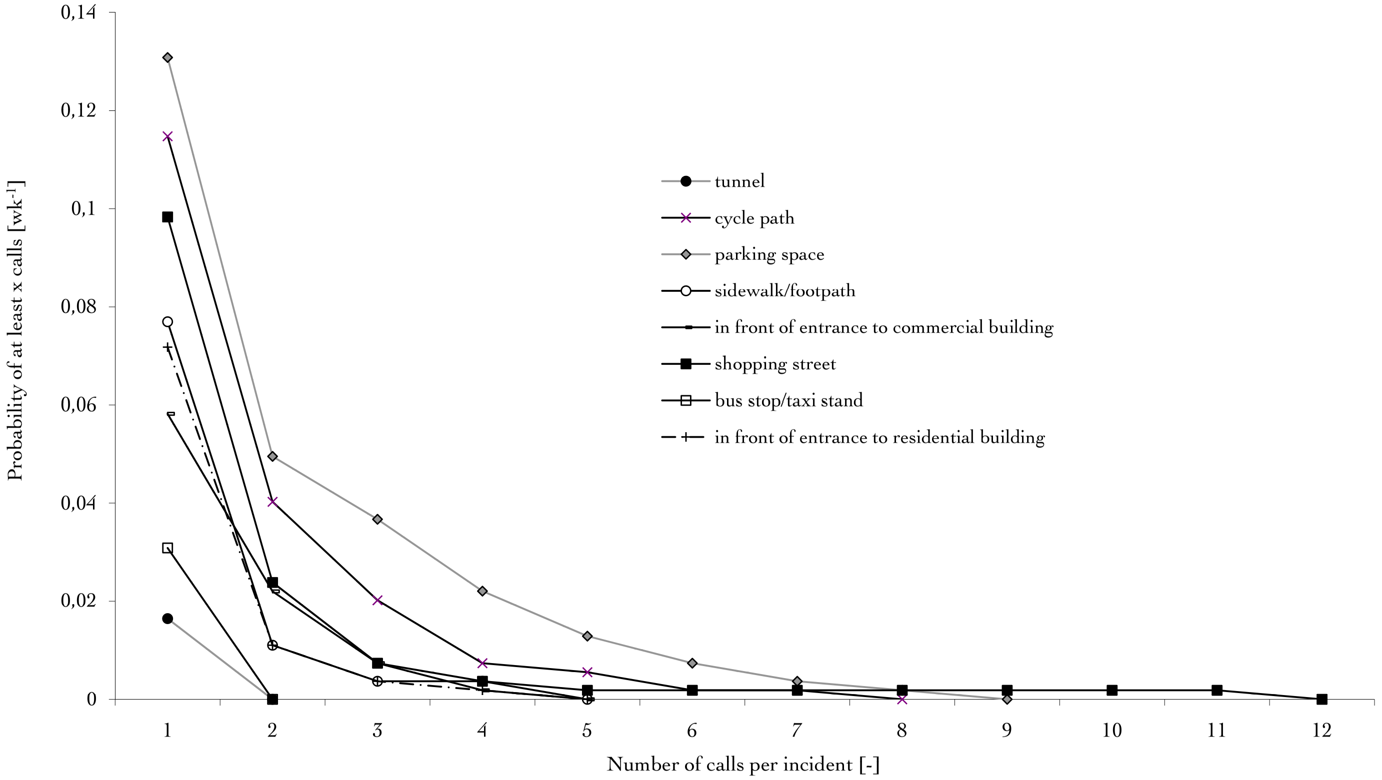

Figure 3.7 Risk curves for detailed classes related to traffic disturbance

3.5. Conclusions

A strong correlation was found between the amount of call data per incident and rainfall volumes per incident. Based on this result, call data per incident were used as a measure for incident severity. Risk curves were drawn that depict flood risk for a range of flood incidents, from high-probability low-consequence incidents to low-probability high consequence ones. Risk curves were plotted for individual consequence classes and for aggregated consequence classes. The risk curve for aggregated consequence classes showed that urban flood risk related to traffic disturbance is high compared to damage to private properties. Total flood risk related to human health is small. Examples of risk curves for detailed consequence classes showed how distinctions can be made between flood risks related to many types of occupational use in urban areas. This information is useful to prioritise actions for flood risk reduction.

Since call data directly convey citizens' experiences in urban flood incidents, they give valuable information about the degree of protection that urban drainage systems provide against adverse affects of wastewater and flooding. Flood risk analysis based on hydraulic modelling and stage-damage functions do not provide this type of information and mostly focus on severe, low probability flood incidents. Call data complement these analyses in a valuable way.

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Chapter 4

Microbial risks of exposure to contaminated urban flood water

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Context

The primary function of urban drainage systems is to protect public health by preventing contact with pathogens in wastewater. Urban flood risk analyses tend to focus on damage to flooded properties. If urban pluvial flooding involves combined sewer systems, flood waters can be contaminated and pose health risks to citizens. In this chapter it is investigated whether urban flood waters can pose a health risk to citizens based on a screening-level microbial risk assessment.

Abstract

Urban flood incidents induced by heavy rainfall in many cases entail flooding of combined sewer systems. These flood waters are likely to be contaminated and may pose potential health risks to citizens exposed to pathogens in these waters. The purpose of this study was to evaluate the microbial risk associated with sewer flooding incidents. Concentrations of *Escherichia coli*, intestinal enterococci and *Campylobacter* were measured in samples from 3 sewer flooding incidents. The results indicate faecal contamination: faecal indicator organism concentrations were similar to those found in crude sewage under high flow conditions and *Campylobacter* was detected in all samples. Due to infrequent occurrence of such incidents only a small number of samples could be collected; additional data were collected from controlled flooding experiments and analyses of samples from combined sewers. The results were used for a screening-level quantitative microbial risk assessment (QMRA). Calculated annual risks values vary from 5×10^{-6} for *Cryptosporidium* assuming a low exposure scenario to 0.03 for *Giardia* assuming a high exposure scenario. The results of this screening-level risk assessment justify further research and data collection to allow more reliable quantitative assessment of health risks related to contaminated urban flood waters.

Keywords: combined sewer, health risk assessment, urban flooding, wastewater

4.1. Introduction

The frequency of flooding and the damage caused by urban flood events have increased over the past decades, mainly due to accelerated urbanisation (Ashley et al. 2005). When urban flooding occurs in areas with combined sewer systems, flood water is likely to be faecally contaminated and may pose health risks to citizens exposed to pathogens in these waters. Faecal contamination of urban flood waters was investigated after severe flooding in New Orleans following Hurricanes Katrina and Rita (Sinigalliano et al., 2007) and after the Elbe floods in Germany in 2002 (Abraham and Wenderoth, 2005). Elevated levels of faecal indicator bacteria and microbial pathogens were found in floodwaters and in sediments left in the urban environment after the flood. Faecal contamination of floodwaters and subsequent contamination of drinking water sources have been found for severe flood events in Bangladesh and Indonesia (Sirajul Islam et al., 2007; Phanuwan et al., 2006). Physical and mental health effects associated with severe floods have been studied by several authors (Fewtrell and Kay, 2008; Ohl and Tapsell, 2000; Tapsell and Tunstall, 2003 and Tunstall et al., 2006) based on interviews with people affected by floods. Lulani et al. (2008) quantified combined health effects of flooding in terms of disability-adjusted life years based on a list of assumptions.

Microbial health risks associated with faecally contaminated flood waters are not only induced by severe, extensive flood events. Especially in lowland areas flooding of combined sewers occurs almost yearly. For instance in the Netherlands, a commonly applied design criterion for combined sewer systems is a maximum flood frequency of once per year or per two years (RIONED, 2004). The reason why higher flood frequencies are accepted in lowland areas is that expected damage of sewer flooding in flat areas is less than in sloping areas: flood waters spread over larger areas, resulting in smaller flood depths compared to sloping areas where flood waters concentrate in local depressions. This implies that exposure of citizens to faecally contaminated flood waters may occur on a regular basis. The spatial extent of these flood incidents is usually small, flood waters covering a part of a street up to several streets (ten Veldhuis and Clemens, 2009).

Occurrence of urban flood incidents is expected to increase in the future, as climate change will induce more intense rainfall (e.g. Lenderink and van Meijgaard, 2008) and ongoing urbanisation continues to increase inflow to urban drainage systems. In addition, flooding caused by infrastructure failures like pipe blockages is expected to occur more frequently in the future as systems are ageing (ten Veldhuis et al., 2009). Increased flood frequencies and growing population densities will increase health risks associated with exposure to contaminated urban flood waters. Health risks associated with combined sewer overflows (CSOs), which occur at a higher frequency than flood incidents, have been investigated by Donovan et al. (2008) who find a probability of contracting gastrointestinal illness from incidental ingestion of water near CSOs ranging from 0.14 to nearly 0.70 over the course of a year for visitors and recreators (e.g. swimmers), respectively, associated with the presence of faecal pathogens indicated by the presence of faecal *Streptococcus* and *Enterococcus*. Schets et al. (2008) investigated microbial quality of surface water in canals and recreational lakes in Amsterdam that receive polluted water from CSOs, raw sewage from houseboats and dog and bird faeces. The estimated risk of infection with *Cryptosporidium* and *Giardia* per exposure event ranged from 0.00002% to 0.007% and 0.03% to 0.2%, respectively, for occupational divers professionally exposed to canal water. The effect of CSOs on surface water quality has been investigated by Kay et al. (2008). They quantified faecal indicator concentrations and export coefficients for catchments with different land use and under specific climatic regimes. Urban areas are identified as one of the key sources of faecal indicator organisms, with significantly higher values occurring for high flow conditions, during or after rainfall. Curriero et al. (2001) analysed the more general relationship between precipitation and waterborne disease outbreaks for 548 reported outbreaks in the USA from 1948 through 1994. They found a statistically significant association between weather events and disease; overflows from combined sewer systems are mentioned as one of the potential sources of contamination.

The purpose of this study was to conduct a screening-level quantitative microbial risk assessment (QMRA) to evaluate the risk associated with exposure of citizens to pathogens in flood waters resulting from combined sewer flooding. Samples were collected and analysed for 3 sewer flooding incidents and controlled flooding experiments were conducted to test survival of pathogens in flood water. The results were used to conduct a screening-level quantitative microbial risk assessment.

4.2. Materials and methods

Experiments

Flooding incidents occur infrequently and often unpredictably in terms of time and location; this makes sampling from flooding incidents a difficult task. During a measurement campaign in the summer of 2007, several heavy rainfall events occurred; one of those caused flooding at locations that were known to flood regularly. During and shortly after a heavy rainfall event on 16 July 2007 water and sediments were sampled from 3 flooding incidents in the Hague, the Netherlands. Rainfall lasted for more than 7 hours; the total rainfall volume amounted to 25 mm. All 3 locations were served by combined sewers; streets were partially flooded over a length of several hundred meters (figure 4.1). Water samples were taken in duplicate during the flooding incidents; duplicate sediment samples were taken at one location after flood waters had withdrawn. The samples were cooled and analysed within 18 hours after sampling.

Figure 4.1 Flooding on 16 July 2007 at sampling site Scheveningen Boulevard II, the Hague.

In addition, controlled urban flooding experiments were conducted to test survival of microbial organisms in flood water. A metal ring (Ø 0.5 m) was cemented to the street surface on a parking lot and the ring was filled with wastewater from a nearby combined sewer. The wastewater was diluted with non-chlorinated tap water to simulate dilution of wastewater with rainwater during sewer flooding incidents. The dilution factor was chosen based on values of *E.coli* and intestinal enterococci found in samples from the flood incidents and values found in wastewater samples from the combined sewer system. The controlled flooding experiments were carried out twice per day and on two separate days, on 10 and 17 October 2007. A dilution factor of 1:20 was chosen for the first experiment, under dry weather conditions; a factor 1:10 was chosen for the second, when moderate rainfall had preceded the day of the experiment. Samples were taken from the water in the ring every 10 minutes for a total duration of 60 minutes, a typical timescale for urban pluvial flood events in lowland areas. Samples of the undiluted wastewater were taken at t = 0 and 60 minutes.

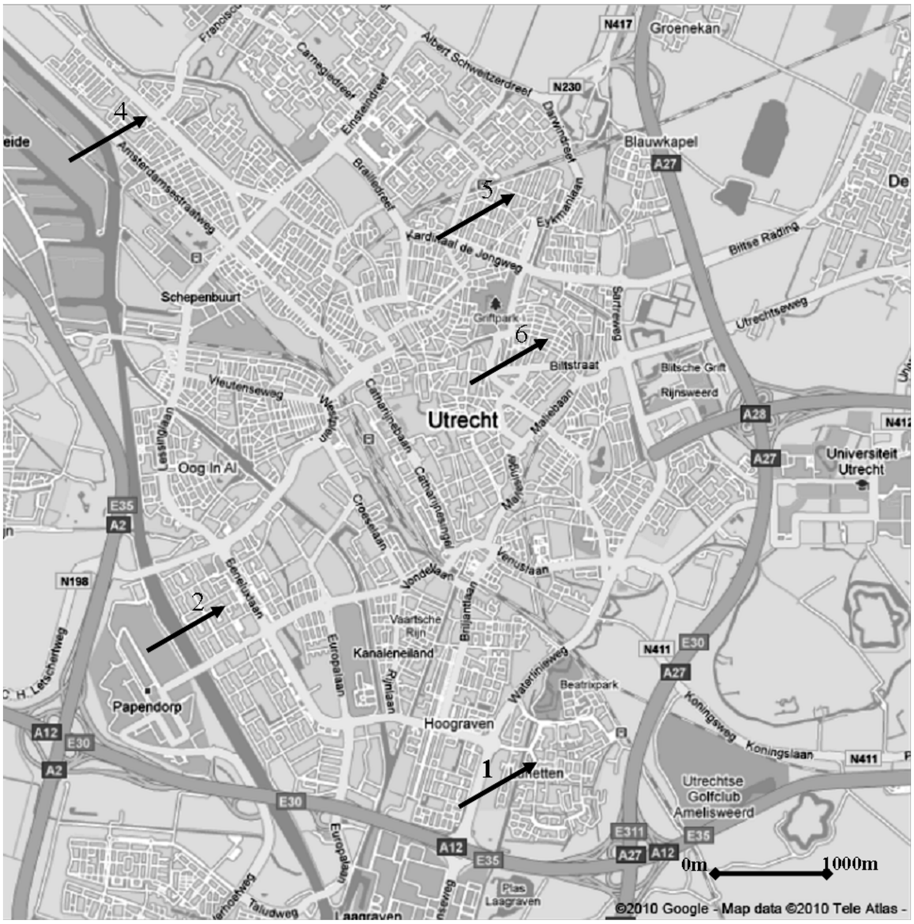

Figure 4.2 Map of Utrecht city centre; numbered arrows indicate 6 locations where samples were taken from the combined sewer system. The controlled flooding experiment was conducted on a parking lot near location 3.

A series of samples was taken from combined sewers during dry weather flow, to collect data on concentrations of *E.coli*, intestinal enterococci, *Cryptosporidium*, *Giardia* and *Campylobacter* in combined sewer water. *E.coli* and enterococci concentrations were used to compare values in crude sewage to those in sewer flood water to obtain a rough estimate of the dilution of sewage during flooding incidents. Samples were taken from combined sewers in the city of Utrecht, the

Netherlands, where the controlled flooding experiments were also conducted, at 6 locations (figure 4.2) and on two subsequent days. In addition, 23 samples were taken from a combined sewer at 1 location throughout a day, between 7AM and 6PM, at time intervals of 30 minutes. This experiment was conducted twice, on separate days. All samples were taken in duplicate; dilution series on count plates were made in duplicate or triplicate. Table 4.1 gives an overview of the experiments and analyses.

Table 4.1 Overview of experiments

Experiment	Purpose of experiments	Sample analyses
Sampling from urban flooding incident, The Hague, 16 July 2007, 3 locations	Study concentrations in water and sediment samples from an urban flooding situation	4 water samples, 1 sediment sample: *E.coli*, intestinal enterococci, *Campylobacter*
Controlled flooding experiments. Days: 10 and 17 October 2007	Study survival of micro-organisms in urban flood water; duration: 60 minutes	4 samples: *E.coli*, intestinal enterococci
Spatially distributed sampling from combined sewers: 6 locations Days: 8 and 15 October 2007.	Study concentrations of microorganisms and 3 types of pathogens in combined sewer water under dry-flow conditions	42 samples: *E.coli*, intestinal enterococci, *Cryptosporidium*, *Giardia*, *Campylobacter*
Temporally distributed sampling from a combined sewer: 1 location, 7 AM to 6 PM, time step 30 minutes. Days: 3 and 22 October 2007	Study concentration range of microorganisms over a weekday	82 samples: *E.coli*, intestinal enterococci

Analytical procedures

Samples from the flooding incidents, controlled flooding experiments and from the combined sewers were analysed for *E.coli* and intestinal enterococci. *E.coli* and intestinal enterococci were enumerated according to international standards EN ISO 9308-3 (ISO, 1998a) and EN ISO 7899-1 (ISO, 1998b)). *Cryptosporidium*, *Giardia* and *Campylobacter* were analysed in samples from 6 locations in the combined sewer system; analyses for *Cryptosporidium* and *Giardia* were conducted according to EN ISO 15553 (ISO, 2006); *Campylobacter* was determined as a most probable number according to EN ISO 17995 (ISO, 2005).

Risk assessment

A screening-level quantitative microbial risk assessment was conducted according to the approach described in WHO (2003) for recreational waters, as the first step to identify where further data collection and quantitative assessment may be most useful. The risk of infection with *Cryptosporidium*, *Giardia* and *Campylobacter* was calculated for urban flood water, based on concentration values found in combined sewer water, multiplied by a dilution index and dose-response relations available in the literature (Haas et al., 1999, Teunis et al., 1996, Schets et al., 2008).

Pathogen concentrations

Estimates of concentration values for *Cryptosporidium*, *Giardia* and *Campylobacter* in flood water were based on arithmetic mean concentrations in samples from the combined sewer system, since *Cryptosporidium*, *Giardia* and *Campylobacter* were not analysed for the flooding incidents. The concentrations for the combined systems were multiplied by a dilution factor that was chosen based on values of *E.coli* and intestinal enterococci found in samples from the flooding incidents and values found in samples from the combined sewer system. The origin of dilution water during the flooding incidents was rainwater run-off that flowed into the combined sewer system, mixed with sewage water, then flowed onto the surface as the sewer became overloaded. Additionally, rainwater that directly fell on the flooded location further diluted the flood water. The resulting concentration values were used to determine the ingested pathogen dose, which equals the pathogen concentration in flood water multiplied by the individual ingested volume per exposure scenario.

Exposure scenarios

Two exposure scenarios were used to estimate infection risks for *Cryptosporidium*, *Giardia* and *Campylobacter*: accidental ingestion of contaminated flood water by a pedestrian splashed by passing traffic and accidental ingestion by a child playing in the water. Ingestion volume for pedestrians was based on values used for recreators, e.g. fishermen who have accidental contact with water:

10 ml per incident (Donovan et al., 2008). For children playing in the water, the ingestion volume was based on that for swimmers (Schets et al., 2008), assuming that children splash each other and crawl through the water: 30 ml per incident. For each exposure scenario, infection risk was calculated for a single exposure event.

Annual risk was then determined based on the assumption that a pedestrian or a child experiences exposure events with an estimated exposure frequency, according to:

$$P_{Inf,annual} = 1 - (1 - P_{Inf,single})^{EF} \qquad (4.1)$$

Where:

$P_{Inf,Annual}$: annual infection risk
$P_{Inf,Single}$: single exposure infection risk
EF : exposure frequency (exposures/year)

The exposure frequency depends on flood frequency and the presence of a person at a flooded location. Both vary widely from one system to another and between locations within a system. A range of exposure frequencies was used to get an indication of annual risk, from 1 exposure in 10 years (exposure frequency 0.1/year) to 1 exposure per year.

Dose response relationships

The risk of infection was estimated by using the exponential dose-response model for *Cryptosporidium* and *Giardia* (Teunis et al., 1996, Teunis et al., 1997 and Ottoson et al., 2003):

$$P_{Inf,Single} = 1 - e^{-r\mu} \qquad (4.2)$$

Where:

$P_{Inf,Single}$: single exposure risk of infection by a certain pathogen
r : organism-specific constant: $r_{Cryptosporidium}$ =0.0040 and $r_{Giardia}$ =0.0199
μ : pathogen dose (ml)

The Beta Poisson dose-response model was used for *Campylobacter* (Medema et al., 1996):

$$P_{Inf,Single} \approx 1-\left(1+\frac{\mu}{\beta}\right)^{-\alpha} \qquad \text{Provided } \beta >> \alpha \qquad (4.3)$$

Where:

P^{*}_{inf} : single exposure risk of infection by a certain pathogen
μ : pathogen dose (ml)
α, β : organism-specific constants; α=0.145, β=7.589.

Comparison with water quality standards

To get a further indication of the potential risk associated with urban flood waters, concentrations of *E.coli* and intestinal enterococci in samples from flood incidents were compared to water quality standards for bathing water as defined by EU Bathing Water Directive 2006/7/EC (EU, 2006), outlined in table 4.2. The guideline values refer to levels of risk based on exposure conditions in large epidemiological studies. From Wiedenmann et al. (2006) it can be inferred that the guideline value for excellent water quality of 200 intestinal enterococci/100ml corresponds with an attributable risk of 1 to 3%. Although ingestion volumes for flood water are smaller and exposure times are shorter than for recreational use of water, the EU Bathing Water Directive is used to evaluate *E.coli* and intestinal enterococci values found in samples from urban flood waters since no health-related standards for flood water exist.

Table 4.2 Bathing water classification values for inland waters, according to EU Directive 2006/7/EC (EU, 2006).

Parameter	Excellent quality** (cfu* 100 ml^{-1}*)	Good quality** (cfu 100 ml^{-1})	Sufficient quality*** (cfu 100 ml^{-1})
E.coli	500	1000	900
Intestinal enterococci	200	400	330

* cfu: colony forming units

** based upon a 95th-percentile evaluation

*** based upon a 90th-percentile evaluation

4.3. Results and discussion

Flooding incidents

High numbers of *E.coli* and intestinal enterococci were found in samples of the flood waters (table 4.3); values found in the sediment were 100 times higher than in flood water. *Campylobacter* was detected in all samples. Enterococci counts in water samples ranged from $5.0x10^4$ to $3.7x10^5$ cfu 100 ml^{-1}, which is slightly lower than concentration ranges found by Kay et al. (2008) in storm sewage overflows during high-flow conditions in 12 study areas in the UK: $3.2x10^5$ to $4.5x10^5$ cfu 100 ml^{-1}. The values could not be compared to values from other flooding incidents, since in the references found samples were taken weeks after the floods, from remnant flood waters in cellars or surface waters affected by the floods (Abraham and Wenderoth, 2005; Phanuwan et al., 2006; Sinigalliano et al., 2007). Analysis methods and parameters analysed in those studies were also different.

Table 4.3 *E.coli* and intestinal enterococci counts and presence/absence test results for *Campylobacter* in samples from 3 urban flooding situations in The Hague on 16 July 2007.

Location	Sample type	*E.coli* cfu 100 ml^{-1}	Intestinal enterococci cfu 100 ml^{-1}	*Campylobacter*
Boulevard, I	Flood water	$8.7x10^3$	$5.0x10^4$	Positive
Boulevard, II	Flood water	$7.0x10^4$	$3.7x10^5$	Positive
Johan de Wittlaan	Flood water	$5.0x10^4$	$2.4x10^5$	Positive
Valkenbosplein	Flood water	$1.0\ x10^5$	$2.1x10^5$	Positive
Valkenbosplein	Sediment	$1.08\ x10^7$	$1.3x10^7$	Positive

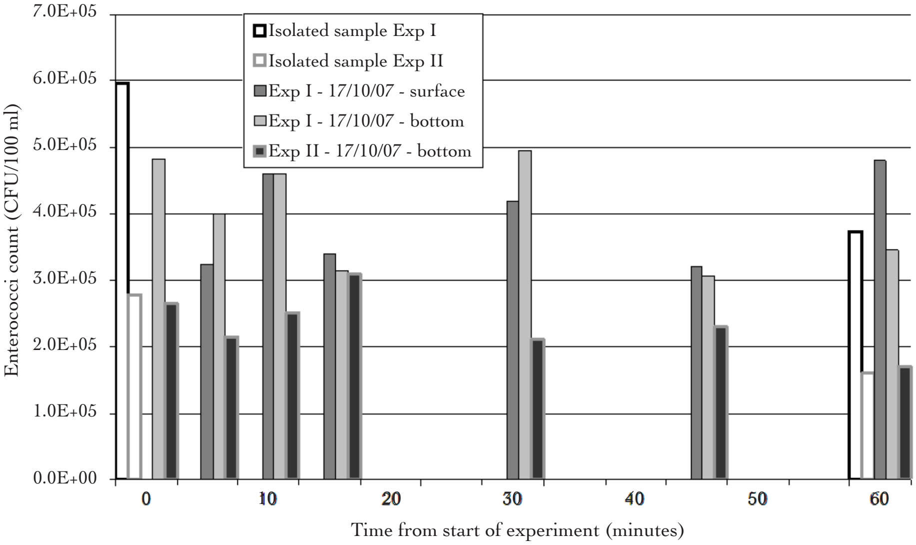

Figure 4.3 Enterococci counts in samples from two controlled flooding experiments on 17 October 2007; a volume of wastewater that was used in the experiment was kept separate and tested at the beginning and at the end of the experiment (isolated samples)

Controlled flooding experiments

Figure 4.3 shows intestinal enterococci values of two controlled flooding experiments on 17 October 2007. During the first experiment, samples were taken near the bottom of the flooded ring and near the water surface. Enterococci values for these samples showed no difference between bottom and surface sample values. Enterococci values found in the second experiment were lower than in the first for no clear reason; the difference appeared to be due to accidental variations in the sewer system where the samples were taken from. Enterococci values did not show a downward trend with time over the period of the experiment; the values varied only slightly and did not differ from values in the volume of water that was kept in a closed, separate container. The same was observed in the first experiment for enterococci values and in the first and second experiments for *E.coli* values. This indicates that concentrations of microorganisms in flood water did not change over the duration of the flood incident, for incident durations up to 60 minutes. Abraham and Wenderoth (2005) found high concentrations of pathogenic bacteria in flooded buildings and on playgrounds days after the river Elbe floods in 2002 (Abraham and Wenderoth, 2005). These results indicate that sewer flooding leads to the presence of pathogens in the urban environment over prolonged periods of time.

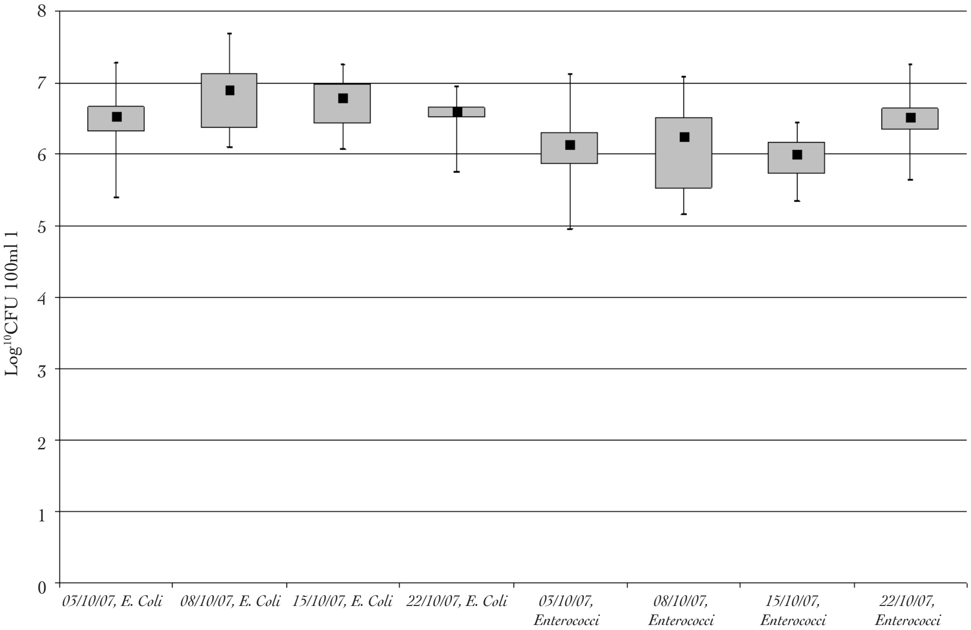

Figure 4.4 Mean, 95% confidence intervals and range of log10 E.coli and enterococci concentrations in samples from combined sewer systems on 4 sampling days.

Sampling from combined sewer system

The variability in *E.coli* and intestinal enterococci values found (figure 4.4) was low compared to values found by Kay et al. (2008) in samples of untreated sewage in the UK, where values of faecal coliforms and enterococci vary by up to a factor of 6. Mean values of enterococci were in the same order of magnitude as those found by Kay et al. (2008) in crude sewage under base-flow conditions: around 10^6 cfu 100 ml^{-1}.

Intestinal enterococci values in combined sewer water were one order of magnitude higher than values found in flood water (table 4.3), which corresponds to a dilution factor of about 10 for flood water. For *E.coli*, values in combined sewer water and in flood water varied almost 2 orders of magnitude. Kay et al. (2008) found enterococci concentrations in untreated wastewater and crude sewage 2 to 4 times higher under base-flow conditions compared to high-flow conditions. A dilution factor of 10 was chosen in this study to obtain an estimate for pathogen concentrations in flood water.

The results of pathogen analyses for 12 samples from combined sewers are summarised in table 4.4. *Cryptosporidium* was found in 17% of the samples, *Giardia* in 75% and *Campylobacter* in 25% of the samples. *E.coli* and intestinal enterococci were present in 100% of these samples.

These values were of the same order of magnitude as those found by Schijven et al. (1996) who analysed pathogen concentrations in crude wastewater at 5 locations in the Netherlands. They reported average *Cryptosporidium* concentrations of 17 oocysts/l and maximum concentration of 5.4×10^3 oocysts/l. They found average *Giardia* concentrations of 200 cysts/l, with seasonal variations from about 10 to 500 cysts/l and a maximum of 1.5×10^3 cysts/l. Few studies report on *Campylobacter* in wastewater; the presence of *Campylobacter* in Dutch surface waters influenced by sewage was confirmed by Schets et al. (2008).

Table 4.4 *Cryptosporidium*, *Giardia* and *Campylobacter* in samples from combined sewers in the city of Utrecht

	Cryptosporidium (oocysts/l)	*Giardia* (cysts/l)	*Campylobacter* (cfu l^{-1})
Mean (of positives)	12	5.8 x10^{2}	1.66x10^{4}
Range (min – max of positives)	10-15	20 -1.7 x10^{3}	2.3x10^{3}-2.4 x10^{4}
No. of positive samples/ total samples	2/12	9/12	3/12

Comparison with European bathing water quality guidelines

Values of intestinal enterococci and *E.coli* found in samples from urban flooding situations are 1 to 3 orders of magnitude higher than values for good bathing water quality according to the EU Directive 2006/7/EC. While ingestion volumes and exposure frequencies for flood waters are lower, compared to bathing water, pathogen concentrations are much higher. This means that health risks of exposure to flood waters might rise above acceptable risk levels that this directive is based on.

Risk assessment

A screening-level risk assessment was conducted based on values of *Cryptosporidium, Giardia* and *Campylobacter* found in samples from combined sewers and a dilution factor 10 for flood water. Table 4.5 summarises the values used in the risk assessment calculations for each of the three pathogens. Table 4.6 shows single exposure and annual infection risks for 2 exposure scenarios. These values give an indication of potential infection risks for urban flood water. It is important to note that the development of a disease after infection depends on a variety of factors specific to an individual's immunity. Calculated annual infection risks vary from to 5x10^{-6} to 0.3; the minimum value is for *Cryptosporidium* based on 12 oocysts/l diluted by a factor 10, 10 ml ingestion volume, exposure frequency once per 10 year and the maximum value for *Campylobactor* based on 1.66x10^{4} cfu l^{-1}, diluted by a factor 10, 30 ml ingestion volume and exposure frequency once per year.

Infection risk values were available in the literature for exposure to pathogens in surface waters affected by sewage discharges. Schets et al. (2008) found infection risks per exposure event ranging from 6x10^{-7} for mean *Cryptosporidium* concentrations in Amsterdam canal waters to 1.2 x10^{-2} for maximum *Giardia* concentrations. Donovan et al. (2008) found annual risks of contracting gastro-intestinal illness of 0.14 to nearly 0.70 for visitor and recreator scenarios respectively, based on faecal *Streptococcus* and *Enterococcus* concentrations in surface waters in the Lower Passaic River in New York. The results of the screening-level risk assessment for urban flood waters showed that infection risk values for urban flood water were in the same range as those found for surface waters that receive sewage discharges.

Table 4.5 Summary of values used in risk assessment calculations for *Cryptosporidium*, *Giardia* and *Campylobacter*, for 2 exposure scenarios. Annual risks correspond to exposure frequencies of 0.1 (min) and 1 (max) per year

Microorganism	Mean concentration	Dilu-tion factor	Ingestion volume adult-child	Exposure frequency for annual risk	Dose-response relationship
Cryptosporidium	12	10	10-30	0.1-1	Exponential
Giardia	5.8 x10^{2}	10	10-30	0.1-1	Exponential
Campylobacter	1.66x10^{4}	10	10-30	0.1-1	Beta-Poisson

Table 4.6 Single exposure and annual infection risks for urban flooding situations, for *Cryptosporidium*, *Giardia* and *Campylobacter*, for 2 exposure scenarios. Annual risks correspond to exposure frequencies of 0.1 (min) and 1 (max) per year

Microorganism	Pedestrian	Playing child[a]
Single exposure infection risk		
Cryptosporidium	5 x 10^{-5}	1 x 10^{-4}
Giardia	1 x 10^{-2}	3 x 10^{-2}
Campylobacter	2 x 10^{-1}	3 x 10^{-1}
Annual infection risk (min-max)		
Cryptosporidium	5 x 10^{-6} - 5 x 10^{-5}	1 x 10^{-5}-1 x 10^{-4}
Giardia	1 x 10^{-3}-1 x 10^{-2}	3 x 10^{-3}-3 x 10^{-2}
Campylobacter	2 x 10^{-2}-2 x 10^{-1}	3 x 10^{-2}-3 x 10^{-1}

[a] In reality infection probabilities for a playing child are higher than the values calculated here, due to the fact that the dose-response relations used are based on healthy adults

In lowland areas like the Netherlands, incidents of sewer flooding occur on a regular, i.e. almost yearly, basis. Repeatedly, citizens are exposed to these flood waters, as they walk or cycle through them. Abraham and Wenderoth (2005) have drawn attention to health risks associated with faecally contaminated flood waters during flood recovery and cleaning activities. In lowland areas, where sewer flooding is a frequent phenomenon, exposure of people to contaminated flood waters during daily life activities is at least as serious a reason for concern. Given the regular occurrence of sewer flooding in lowland areas, it is especially important that more data on pathogen concentrations in flood waters be collected to make a more reliable health risk assessment. The need for more and reliable data becomes more urgent as health risks associated with urban flood incidents are expected to increase in the future, due to more intense rainfall induced by climate change, ongoing urbanisation and increasing probability of component failures in ageing systems (Ashley et al., 2005).

Health risks associated with combined sewer overflows to surface waters receive much more attention than those related to urban flooding: the EU Directive 2006/7/EC, EU Water Framework Directive and United States Clean Water Act place requirements on regulators to manage sources of microbial pollution for surface waters. The main reason is that recreational use of contaminated surface waters is associated with higher ingestion volumes thus a higher likelihood of exposure to pathogens compared to flood waters. On the other hand, concentrations of pathogens in surface waters are lower (e.g. Schets et al., 2008; Donovan et al., 2008) than those found in flood water from overloaded combined sewers. Our study shows that the resulting health risk could be of the same order of magnitude for both situations. Further studies are needed to confirm this result; if they do, recommendations or guidelines to limit exposure of citizens to flood waters in urban environments seem appropriate.

4.4. Conclusions and recommendations

Flood waters resulting from combined sewer flooding incidents are likely to be contaminated and may pose potential health risks to citizens exposed to pathogens in these waters. The aim of this study was to evaluate the microbial risk associated with sewer flooding incidents. Concentrations of *Escherichia coli*, intestinal enterococci and *Campylobacter* were measured in samples from 3 sewer flooding incidents. The results indicate faecal contamination: faecal indicator organism concentrations were similar to those found in crude sewage under high flow conditions and *Campylobacter* was detected in all samples. Due to infrequent occurrence of such incidents only a small number of samples could be collected; additional data were collected from controlled flooding experiments and analyses of samples from combined sewers. The results were used for a screening-level quantitative microbial risk assessment (QMRA). Calculated annual risks values vary from $5x10^{-6}$ for *Cryptosporidium* assuming a low exposure scenario to 0.03 for *Giardia* assuming a high exposure scenario. The results of this screening-level risk assessment justify further research and data collection to allow more reliable quantitative assessment of health risks related to contaminated urban flood waters.

Collecting samples from flooding incidents is complicated by their unpredictability. Registration of flood incidents by responsible organisations will help to point out suitable locations for sampling. Many water authorities have a call centre that receives calls from citizens who observe problems; this information can be used to select locations that are repeatedly flooded. Traditional monitoring by local sensors is not well fitted to collect information on flooding incidents because spatial resolution is usually too low. Given a flooding frequency of about once per year per city, instalment of permanent sampling stations is not an option. A more efficient strategy could be to have sampling teams stand-by when weather forecast predicts heavy storms and have local representatives call out when flooding actually occurs. Samples must be collected from a large geographical area or sample collection must be extended over long periods of time to collect a sufficient amount of samples to be able to draw reliable conclusions.

Exposure of citizens to waterborne pathogens is generally controlled by limiting access to sites where pathogens are present, e.g. at wastewater treatment plants and combined sewer overflows, or by reducing sources of pathogens to control pathogen concentrations as is the case of surface waters for recreational use. Pathogen concentrations in flood waters cannot be controlled by treatment and exposure to flooded sites can hardly be avoided for flooding that occurs in urban environments, on streets and pathways. The best way to control exposure to pathogens in flood water is probably by raising awareness. If citizens are aware of potential contamination of flood waters, they are more likely to avoid ingestion of water and will keep their children away from flood pools.

4.5. References

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Chapter 5

Quantification and acceptability of urban flood risk

This chapter is based on an article that was presented at the “Road Map Towards a Flood Resilient Urban Environment” conference in November 2009 and was submitted for a special issue of the Journal of Flood Risk Management.
J.A.E. ten Veldhuis, F.H.L.R. Clemens (2010). How the choice of flood damage metrics influences urban flood risk assessment.

Context

Previous chapters have shown that various causes contribute to urban flood risk and that flood risks in lowland areas are characterised by frequent flooding of roads and occasional flooding of buildings. The question is to what extent flood risks are acceptable and how flood risks and investments to prevent or reduce flood risk can be balanced to constitute a proper urban flood management strategy. This chapter uses the results of flood risk quantification in earlier chapters and translates there values into measures that can be used to set priorities and to justify investments for flood risk reduction.

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. 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 compared to 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.

These quantitative risk outcomes provide a more comprehensive basis to decide whether the current flood risk is acceptable compared to frequency analyses based on design storms: 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.

Keywords

Flood risk, flood damage assessment, urban flooding

5.1. 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 (Tapsell and Tunstall, 2003). 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. This is understandable from a decision-making point of view, since monetary values are most easily compared to 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 ƒ5000/household (1998 value, van der Bolt and Kok, 2000; net present value 2009 €3500, for an interest rate of 4% and translated into euros). 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 increases. The situation of river floods and flash floods is entirely different. Here, 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 to the costs of traffic delay or inconvenience. The nature of intangible damage is different as well: severe floods may cause 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 becomes important.

Current standards for urban pluvial flooding are usually based on flooding frequencies and do not take flood damage into account explicitly. European standards recommend a flooding frequency depending on occupation land use: 1 in 10, 20, 30 or 50 years for rural, residential, commercial and city areas and underground railway and underpasses. Usually these flooding standards are interpreted as maximum road flooding frequencies: hydrodynamic models are used to check compliance with the standards and these calculate manhole flooding. Implicit in this 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 2D overland flow modelling should enable flooding calculations at building level in the future.

Climate change predictions have triggered a debate urban 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. 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 chapter is to compare two types of metrics for urban pluvial flood damage estimation incorporating tangible and intangible damage to buildings, roads and other public spaces: monetary values based on stage-damage functions and the number of people affected by flooding based on municipal call centre statistics. 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, decisions to prioritise urban flood risk alleviation.

5.2. Quantification method of flood consequences

Data from call centres were classified according to damage classes. Table 5.1 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 that were used in this study are added.

Table 5.1 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 (calls totalled for rain events and dry events).

Primary functions		Damage classes	# 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

The assignment of classified calls to independent 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 and total damage estimates per damage class. Translations are based on a number of assumptions with respect to the amount of damage and number of affected people per call for different damage classes. Uncertainty is introduced through the assumptions made for translation due to a lack of data. This uncertainty is incorporated 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:

$$f(x)=\begin{cases}\dfrac{1}{\beta-\alpha} \text{ for } \alpha \le x \le \beta \\ 0 \text{ for } x<\alpha \text{ or } x>\beta\end{cases} \tag{5.1}$$

Where: *x* : uniformly distributed variable

f (x) : probability density function of *x*

α, β : minimum and maximum boundaries of *x*

The expected value and the variance of a uniform distribution are calculated as follows:

$$E(X)=\frac{\alpha+\beta}{2} \tag{5.2}$$

$$VAR(X)=\frac{(b-a)^2}{12};STD(X)=\sqrt{VAR(X)} \qquad 5.3$$

Where: *E(X)* : expected value of *X*

VAR(X) : variance of *X*

STD(X) : standarddeviation of *X*

Assumptions for urban flood risk assessment metrics: stage damage curves
Stage-damage curves that are usually used in flood damage assessment are 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 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. Since 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., 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. Since 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 higher cleaning costs.

Assumptions for urban flood risk assessment metrics: costs of traffic delay and annoyance

No references of stage-damage curves for traffic losses due to 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-Ubillo (2008) quantified congestion costs in urban areas at €12.50 per hour of delay. Based on traffic counts for main roads in Haarlem (Haarlem, 2008) a minimum and a maximum amount of vehicles were estimated for residential roads. A traffic delay of 5 minutes 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 annoyance to 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 more serious flooding situations, 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 5.2, for all classes.

Table 5.2 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	30000	Min: cleaning costs only; max: flood depth 10 cm, medium building value
C4	Flooding in commercial building	2000	30000	Idem C3; min cleaning costs for larger building surface
C5	Flooding on residential/main road	10	700	10-700 vehicles; 5min 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

Assumptions for urban flood risk assessment metrics: affected people

Table 5.3 summarises assumptions used in this study for the numbers of affected people per call in every damage class. Assumptions for car and cycle traffic were based on figures from the yearly statistics report for the city of Haarlem, year 2007 (Haarlem, 2008). Other assumptions are based on oral communications.

Table 5.3 Assumptions for number of affected people per call in damage class

Damage classes		# affected people		Remarks
		Min	Max	
C1	Flooding with wastewater	10	100	10-100 pedestrians or cyclists 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 minutes*
C7	Flooding at bus stop/taxi/train station	10	20	10-20 travellers waiting at bus stop/station

*Source: Haarlem, 2008. Yearly statistics 2007

Acceptability of flood risk

Based on the quantified risk outcomes, the acceptability of flood risk was assessed. The acceptability of flooding and the need for investments to reduce flood risk can be based on societal consideration or it can be viewed as an economic decision problem or a combination of these. Economic cost-benefit analyses offer the advantage of a direct comparison between costs and benefits in monetary terms; the disadvantage of translating all parameters into monetary values is the amount of uncertainty that is introduced through assumptions that have to be made for translation. Additionally, the damage schematization made by this translation does not necessarily reflect public perception of the potential loss.

Societal risk is usually expressed in the form of an FN-curve that displays the probability of exceedance of the number (N) of deaths or casualties. A limit line can be drawn in a graph depicting an FN-curve to define maximum acceptable risk. Such limit lines can be described by the following formula (e.g. Jonkman et al., 2003):

$$1 - F_N(x) < \frac{C}{x^n} \tag{5.1}$$

Where n is the steepness of the limit line and C the constant that determines the position of the limit line. A limit line with a steepness of n = 1 is called risk neutral; a line with steepness n = 2 is called risk averse (Vrijling and van Gelder, 1997). Similarly, an FD-curve displays the probability of exceedance as a function of the economic damage, D (Jonkman et al., 2003).

The type of flood events investigated in this thesis cause some tangible and a lot of intangible damage. The results can be depicted as an exceedance curve of the number of calls (C) per event, an FC-curve. The expected value of flood risk equals the area under the FN-curve (Vrijling and van Gelder, 1997). Similarly, the expected value of flood risk in terms of the number of calls per event equals the area under the FC-curve.

5.3. Results and discussion

The results of flood damage quantification for the case of Haarlem are summarised in table 5.4. The results show that total flood damage over the period 1997 to 2007 amounts to between 153 kEUR and 1688 kEUR and that 18,000 to 296,000 people are affected by flooding. Table 5.5. shows expected values and variances of damage in each consequence class, calculated according to formulas 5.2 and 5.3.

Table 5.4 Total urban flood damage for damage classes C1 to C7 for the city of Haarlem, period 1997-2007; based on assumptions for damage quantification according to monetary values and numbers of affected people.

	Damage classes	**monetary damage** *1000 EUR		**monetary damage** *1000 EUR		**affected people** *1000		**affected people** *1000	
		min	%	max	%	min	%	max	%
C1	Flooding with wastewater	0	**0**	2	**0**	0	**0**	1	**0**
C2	Manhole lid removed	0	**0**	1	**0**	0	**0**	2	**1**
C3	Flooding in residential building	98	**64**	980	**58**	0	**0**	1	**0**
C4	Flooding in commercial building	50	**33**	250	**15**	0	**0**	0	**0**
C5	Flooding on residential/main road	5	**3**	349	**21**	15	**83**	250	**85**
C6	Flooding of sidewalk/foot/cycle path	0	**0**	87	**5**	2	**11**	41	**14**
C7	Flooding at bus stop/taxi/train station	0	**0**	19	**1**	1	**6**	2	**1**
	Total	153	**100**	1688	**100**	18	**100**	296	**100**

Table 5.5 Total urban flood damage for damage classes C1 to C7 for the city of Haarlem, period 1997-2007; expected values and variance

	Damage classes	**monetary damage** *1000 EUR E(X)	**monetary damage** *1000 EUR STD(X) %	**affected people** *1000 E(X)	**affected people** *1000 STD(X)
C1	Flooding with wastewater	1	0.5	0	0.2
C2	Manhole lid removed	0	0.2	1	0.4
C3	Flooding in residential building	539	255	0	0.08
C4	Flooding in commercial building	150	58	0	0.06
C5	Flooding on residential/main road	177	99	132	68
C6	Flooding of sidewalk/foot/cycle path	44	25	22	11
C7	Flooding at bus stop/taxi/train station	10	5.5	1	0.3
	Total	921		156	

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. In other words: flooding incidents that affect many people do not cause large monetary damage. This outcome was obtained for one of the two case studies, the city of Haarlem. The results presented in chapter 4 show that ratios between consequences classes related to building flooding and those related to street flooding are similar for the 2 case studies, Haarlem and Breda. Therefore, the results shown in table 5.4 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 chapter 7.

Figure 5.1 gives a graphical presentation of the data in table 5.5. It shows that monetary damage to residential building (class C3) is significantly larger than monetary damage to commercial buildings (C4) and monetary damage due to 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 due to flooding of roads. This is a result of a low incidence of flooding of commercial buildings associated with large damage per incident and of a high incidence of road flooding with 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 C7 are less than 1% of the expected value of the number of people affected for class 5. Figure 5.1 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.

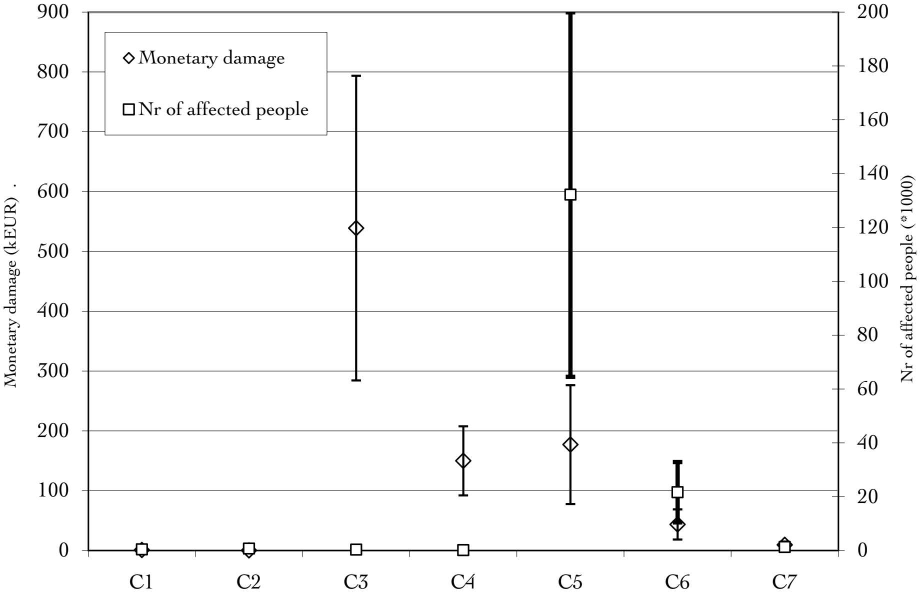

Figure 5.1 Total urban flood damage for damage classes C1 to C7 for the city of Haarlem, period 1997-2007. Data points show mean values of monetary damage and number of affected people per class, error bars show standard deviations from the mean.

Figure 5.2 is based on the same results as table 5.4; instead of total values at city level, the minimum and maximum values in figure 5.2 are expressed in terms of damage per km sewer length per year. 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.

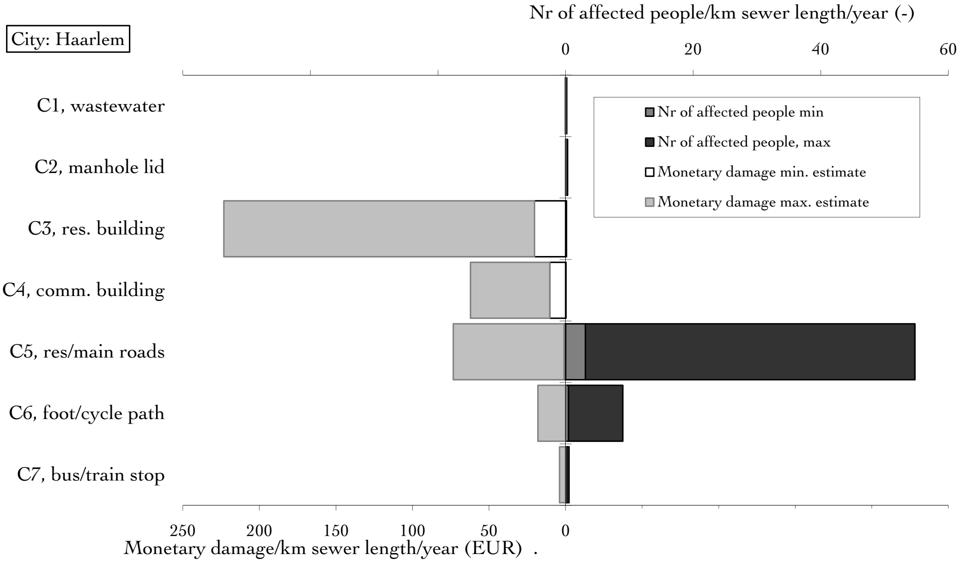

Figure 5.2 Monetary flood damage in EUR per km sewer length per year and number of people affected by flooding per km sewer length per year for damage classes C1 to C7, case of Haarlem

Acceptability of flood risk

Based on the quantified risk outcomes presented in table 5.4 and figure 5.2 FC-curves were drawn for urban flood risk expressed in terms of numbers of calls. The resulting FC-curve is shown in figure 5.3. The expected value of flood risk equals the area under the FN-curve (Vrijling and van Gelder, 1997). Similarly, the expected value of flood risk in terms of the number of calls per event equals the area under the FC-curve in figure 5.3 An example of a limit line for damage to properties is drawn in figure 5.3, for n=1 and $C=10^{-2}$, according to formula 5.1. This example shows that for the chosen risk neutral limit line, the risk of damage to properties is acceptable for events with more than 7 calls, that are below the limt line and is unacceptable for small events, with 1 to 7 calls above the limit line. The result signifies that the risk level resulting from current flood protection strategy is risk-averse, protection from larger events is higher than required according to a risk neutral approach whereas protection from small events is low compared to a risk neutral approach.

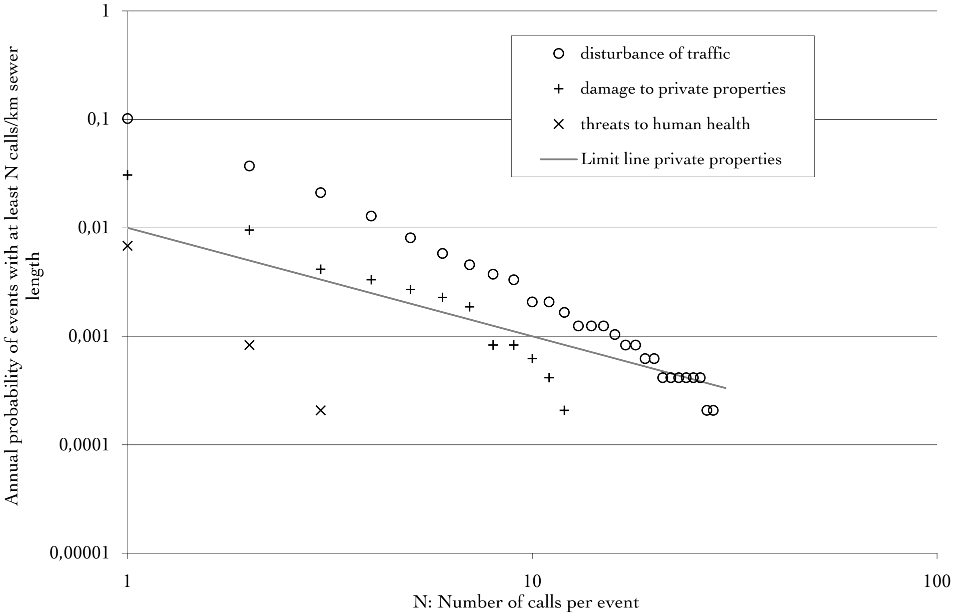

Figure 5.3 Exceedance curves of the number of calls per event, for 3 types of flood damage, for the case of Haarlem. A limit line for damage to properties, for n=1, is drawn as an example.

Economic evaluation of risk acceptability is usually based on monetarised values of flood risk. The acceptable economic risk can be defined as a fixed maximum expected flood damage or can be the outcome of an economic optimisation of flood damage versus investment costs for flood protection.

For comparison, the cumulative costs of building flooding as a result of small flood events, as calculated in this study, is compared to the costs of building flooding as a result of a singular rare event. The cumulative costs for small events are derived from table 5.4; 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 Compensation Act. Table 5.6 presents a summary of the cumulative costs of successive events over a 10 year period versus the costs of the T=125 years event.

This table shows 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. Damage per affected person is based on the expected value of damage estimates and estimates of the number of affected people.

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

Table 5.6 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	134
Costs per household of T=125 years event	3.1[1]	2400[2]	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[3]	147,000	450	45

[1] 2009 value, based on1999 value €2000 and interest rate 4%

[2] 1050 houses, average household size 2.3 (CBS)

[3] Average sewer tax 1997-2007: €90/year; 76,000 households

This outcome confirms a risk-averse attitude: small accidents are more easily accepted than one single rare accident with large consequences, even though the expected damage is similar in both cases (Vrijling, 2001). 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.

In an economic evaluation, the question is whether more efficient flood protection could be achieved by investments to reduce flood risk 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. Appendix 1 illustrates the effect of call data uncertainty on potential decisions for flood risk reduction. 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. that can be obtained from experiments, preferably on real-world scale.

5.4. 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 to larger events. The results also show that the number of people affected by tangible damage is small compared to 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. The final 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. This is in essence a political question, because costs and benefits of flood protection contain 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. Recent development of two-dimensional overland flow models can help to make a distinction between flooding consequences related to roads and buildings. Data on asset failures are essential to quantify their contribution to flood risk. Call data, complemented with other flood incident observations can help to provide data on asset failures and can be used for flood model calibration and verification.

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Chapter 6

Risk-based urban flood management: improving operational strategies

This chapter is based on an article that was presented at the LESAM conference in Miami, November 2009.
J.A.E. ten Veldhuis, J. Dirksen and F.H.L.R. Clemens, Evaluation of operational strategies to control sewer flooding based on failure data. In: Proceedings of the 3rd International Leading Edge Conference on Strategic Asset Management (LESAM), AWWA, Miami, 2009.

Context

As previous chapters have shown, various causes contribute to urban flood risk, thus various kinds of actions can be undertaken to reduce flood risk. In this chapter three causes of flooding are compared, evaluates associated flood management strategies and specifies efficient ways to enhance current strategies to further reduce flood risk.

Abstract

Data from call centres at two municipalities were analysed in order to quantify flooding frequencies and associated flood risks for three main failure mechanisms causing urban flooding. The aim was to find out whether current operational strategies are efficient for flood prevention and if directions for improvement could be found. The results show that quantified flood risk for the two cases is well above the standard which is defined in sewer management plans. The analysis pointed out that gully pot blockages are the main cause of flooding. Reactive handling of calls, as is currently applied, is inefficient if all calls are reacted upon since a small portion of all calls report serious consequences like flooding in buildings or wastewater flooding. Preventive cleaning of sewer pipes proves to be an efficient strategy to reduce flooding due to sewer blockages as flood risk associated with sewer blockages is lower in case of higher cleaning sewer frequencies. Sewer blockages often have serious consequences, thus preventive handling is to be preferred to reactive cleaning. According to the results of this analysis, reduction of flooding sewer overloading is not of primary concern, because serious consequences for this failure mechanism are rare compared to other failure mechanisms.

Three flood reduction strategies are compared with respect to their efficiency in flood risk management in a fictitious decision making example. The results show that increasing gully pot blockages frequency is a more efficient strategy to reduce flood risk than increasing sewer cleaning frequency or increasing sewer pipe capacity. **Keywords:** asset management, flooding, urban drainage

6.1. Introduction

In recent years, increased media attention for urban flood incidents and uncertainties in climate change predictions, have inspired discussions among urban drainage managers about the need for investments in sewer systems to improve urban flood prevention. Research in the area of civil structures like dams, dikes and water supply systems (Tuhovčák, 2007) has shown how risk analysis can support design and operational decisions, in particular those that involve uncertainties. These may include uncertainties about future developments like climate change as well as uncertainties about the functioning and condition of drainage systems. In chapter 2, quantitative fault tree analysis was applied to urban flooding in order to detect and quantify causes of urban flooding. It was shown that the contribution of component failures to flood incident frequency was larger than that of sewer overloading by heavy rainfall. Typically, component failures in urban drainage systems are hard to detect and inspection techniques are costly, since most of the system is underground. As a result, inspection frequencies are usually low and urban drainage operators often resort to reactive maintenance to solve failures. The objective of this chapter is to evaluate operational strategies for prevention of sewer flooding based on a risk assessment, in order to find out whether currently applied strategies are efficient and how they can be improved. Current strategies largely build upon many years of practical experience supported by few quantitative data. This study uses failure data related to sewer flooding incidents to quantify flood risks.

Operational strategies fall into two main categories (Bedford and Cooke, 2001): corrective and preventive strategies. Corrective strategies aim to repair a defect, fault or failure after it has occurred; preventive strategies form part of regular servicing. Table 6.1 summarises types of strategies and scheduling of operational activities.

Table 6.1 Strategies and scheduling of operational activities (from: Bedford and Cooke, 2001)

Scheduling of activities	Corrective	Preventive
Calendar-based	-	Fixed cycles of operational activities
Condition-based	Upon observation of degradation; functionality still in place	-
Opportunity-based	If suitable opportunity presents itself and degradation has been observed	If suitable opportunity presents itself, while no degradation has been observed
Emergency	When component is in a state that disables the system; usually immediately after failure	-

Corrective strategies are applicable when failures can be detected rapidly and do not have immediate disastrous consequences. They consist of repair actions in response to detected failures. Corrective strategies require condition monitoring and inspection to identify the point at which repair is needed. Preventive strategies consist of maintenance activities based on a fixed schedule or following opportunities. Operators decide upon what strategy to prefer based on efficiency in terms of time, energy and costs. In urban drainage practice such decisions are usually made implicitly, without explicit quantification of time, energy or costs of strategy implementation versus prevented consequences.

This chapter focuses on three sewer failure mechanisms that are main contributors to sewer flood risk: sewer overloading, sewer pipe blockage and gully pot blockage. Common strategies to avoid failure according to these mechanisms are briefly summarised for the situation in the Netherlands.

Sewer overloading is dealt with by defining a design standard for flooding frequency, usually once per year or per 2 years (RIONED, 2004). Compliance with this standard is checked by mostly unvalidated model calculations conducted in the design stage. Calculations are repeated approximately every 10 years. If according to these calculations sewer flooding frequency exceeds the design standard, an improvement measure is designed and implemented following a preventive approach. If model results are not trusted or if insufficient budget is available, improvements are postponed or cancelled. Besides the preventive approach, complaints from citizens about flooding may form a reason to react and implement structural improvements.

Sewer blockage is tackled in two ways: following inspection and upon citizens' complaints. Sewer inspection is complicated and expensive compared to other infrastructure, because it must be done with special equipment that can enter the sewers, typically a camera mounted on a robot vehicle, which in addition requires previous sewer cleaning. As a result, sewer inspection frequencies are usually low, of the order of once every 10 years. When blockages occur in the period between inspections and lead to flooding, these are resolved only if citizens complain about the flooding. Since most sewer systems in the Netherlands are looped networks, pipe blockage normally leads to flooding in main transport routes and where local transport capacity is critical. Gully pots are usually cleaned once a year; vulnerable locations like market places and shopping streets are often cleaned 2 or 4 times yearly. In addition, gully pots are cleaned upon complaints, usually within a maximum period of 1 or 2 weeks after the complaint was made. These strategies have developed over many years of practical experience and in the Netherlands there is a common agreement among sewer managers that this is an efficient way to cope with failure mechanisms. This is reflected in corresponding recommendations laid down in the Dutch Sewer Guidelines (RIONED, 2007). The aim of this chapter is to find out whether failure data confirm this common agreement about the efficiency of current strategies and if analysis of failure data can point out directions for improvement.

6.2. Methods

Urban flood incident data

Data on urban flood incidents were obtained from municipal call centres that register information from citizens' calls about observed flood problems and ensuing information from technical staff after on-site investigation. Sewer inspection data were not used, since data sets were small and inspection data have proved to be unreliable (Dirksen et al., 2007). Call data from the cities of Haarlem and Breda were analysed to detect characteristics of failure processes for the three failure mechanisms described in the introduction of this chapter. Table 6.2 summarises characteristics of the sewer systems and maintenance regimes for the two cases.

Table 6.2 Summary of data for the cities of Haarlem and Breda: sewer system characteristics, maintenance regime

Data case study	Haarlem	Breda
Number of inhabitants	147000	170000
Length of sewer system (% combined)	460 km (98%)	740 km (65%)
Total surface connected to sewer system	1110 ha	1800 ha
Total number of gully pots	42500	80000
Maximum ground level variation	20 m	10 m
Maintenance regime		
Gully pot cleaning	1x/year + upon calls	1x/year + upon calls
Sewer cleaning	62km/yr (13% of total sewer length)	65km/yr (6% of total length)

Relative contributions of the failure mechanisms to flooding frequency were quantified as well as their expected consequences. Consequences were quantified in terms of the number of calls per failure mechanism per flooding incident. Most calls refer to only 1 location, so that the number of calls per incident equals the number of reported flooded locations per incident for 95% of all incidents. Call data were verified by checking consistence of call information with respect to rainfall data and hydrodynamic model calculation results (see chapter 2).

Probabilistic risk analysis

Occurrence of flooding was evaluated in terms of flooding frequencies and flood risk related to various consequences: flooding in buildings, wastewater flooding and flooding in general, including the former two and flooding of streets, sidewalks, gardens etc. Flooding frequencies were drawn from incident occurrences over the period of available data. Flood risk was quantified by multiplication of incident occurrence probability by average number of locations per incident. The average number of locations per incident was assumed to be equal to the average number of calls per incident; this generalisation holds for 95% of all incidents.

$$R = P\left(flooding\right) * \overline{C} \qquad (6.1)$$

Where: R : risk of flooding in amount of flood locations in period of time t

$P(flooding) = P\left(X \geq 1\right)$: probability of flooding in period of time t

$\overline{C}$: Average consequence of flooding incidents expressed as the number of locations per incident: total number of calls divided by total number of flooding incidents

Risk-based decision making for flood risk reduction

Risk-based urban flood management uses outcomes of urban flood risk analysis to support decisions for flood reduction. Quantitative risk analysis results for the case of Breda were used to demonstrate how quantitative risk values based on call data analysis can support decisions for urban flood risk reduction. Three possible actions to reduce flood risk were compared: increasing sewer capacity to reduce sewer overloading, increased sewer cleaning frequency to reduce sewer blockage and increasing gully pot cleaning to reduce blockage. To account for the effect that call data represent only a part of the total number of flood incidents true an estimate is made of the percentage of citizens that is expected to make a call to a municipal call centre out of the total number of citizens who observe unsatisfactory urban drainage conditions. Based on Wiechen et al. (2002) and Devereux and Weisbrod (2006) the expected percentage of citizens who make a call was estimated between 2% and 30%.

The effect of uncertainties in call data on flood risk estimates is discussed in detail in a sensitivity analysis in Appendix 1. The effects of flood risk reduction actions were estimated based on expert judgment, since insufficient data were available to quantify the effect of these actions.

6.3. Results

Tables 6.3 and 6.4 give the results of call data analysis for the 3 failure mechanisms ‘gully pot blockage’, ‘sewer pipe blockage’ and ‘sewer overloading’, for the cases of Haarlem and Breda. A distinction is made between the classification results for rain events and dry events and between various groups of consequences.

Comparison between failure mechanisms

Tables 6.3 and 6.4 show that calls which explicitly report flooding-related consequences make up 25% of all calls for Haarlem and 38% for Breda. A small portion of these calls report flooding in buildings or flooding with wastewater. The results for flooding in buildings and flooding with wastewater were analysed separately, because these are severe consequences compared to flooding of streets and parks. Flooding of streets never causes traffic disruption or damage according to the call texts, probably because both case study areas are more or less flat.

For both cases gully pot blockages are reported far more often than the other two failure mechanisms. The amount of calls per incident is also highest for gully pot blockages, indicating that more locations per incident are affected. This applies for all flooding-related calls together as well as for calls on flooding in buildings and calls on wastewater flooding separately. Sewer overloading rarely leads to flooding in buildings or flooding with wastewater. The same applies for sewer blockage in Haarlem; in Breda blocked sewers are a frequent cause of flooding in buildings. In Haarlem blocked sewers are the main cause of wastewater flooding Calls that report wastewater flooding caused by gully pot blockage mostly refer to erroneous connections to gully pot mains which results in wastewater flooding. Some calls were misclassified and refer to blockage of house connections instead of gully pots.

The amount of flood-related calls during dry incidents is lower than during rain incidents, except for flooding with wastewater which occurs more or less as often during dry and rain incidents. Detailed investigation of call texts shows that flood-related calls during dry incidents often refer to rainfall on previous days. Reference to previous days is especially common on Mondays, since call centres are closed during the weekend. Other dry incident calls do not refer to particular incidents; these calls usually report minor flooding.

Table 6.3 Results call data analysis Haarlem, 3 failure mechanisms for sewer flooding. Call data for Haarlem cover a period of 10 years; in this period 566 independent rain incidents occurred and 566 dry incidents following each rain incident.

Haarlem	# of incid	# of calls	# of incid.	# of calls	# of incid	# of calls
Failure mechanisms	flooding-related consequence classes		flooding in buildings		flooding with wastewater	
Rain incidents						
Gully pot blockage	202	897	55	110	2	2
Blocked sewer pipe	6	6	0	0	3	3
Sewer overloading	10	15	5	6	0	0
TOTAL	218	918	60	116	5	5
Dry incidents						
Gully pot blockage	111	178	7	8	3	3
Blocked sewer pipe	5	5	0	0	5	5
Sewer overloading	2	2 *	1	1 *	0	0
TOTAL	118	185	8	9	8	8

**Calls refer to rainfall on previous days; 1 call was misclassified: should have been 'Illegal discharge'*

Table 6.4 Results call data analysis Breda, 3 failure mechanisms for sewer flooding. Call data for Breda cover a period of 5 years; in this period 251 independent rain incidents occurred and 251 dry incidents following each rain incident.

Breda	# of incid.	# of calls	# of incid.	# of calls	# of incid.	# of calls
Failure mechanisms	flooding-related conseq. classes		flooding in buildings		flooding with wastewater	
Rain incidents						
Gully pot blockage	137	978	40	66	5	5
Blocked sewer pipe	28	36	14	14	2	2
Sewer overloading	18	25	4	6	2	2
TOTAL	183	1039	58	86	9	9
Dry incidents						
Gully pot blockage	108	265	22	22	6	7
Blocked sewer pipe	24	28	11	12 *	1	1
Sewer overloading	7	7 **	3	3 **	0	0
TOTAL	139	300	36	37	7	8

**some of the calls were misclassified; they refer to blocked house connections instead of blocked main sewers*

***calls refer to rainfall on previous days or problems that occur during rainfall in general; for 1 call the cause is not entirely clear*

Comparison between cases

To allow for comparison between the two cases, the results in tables 6.3 and 6.4 were divided by the total sewer length and the total length of the measurement period for each case. This results in incident frequencies per 100 km sewer length per year for the 3 failure mechanisms. Figure 6.1 shows incident frequencies for Haarlem and Breda per 100 km of sewer length and per year, for rain incidents. The graph shows that incident frequencies of gully pot blockages are similar for the cases of Haarlem and Breda: 4.2 and 3.9 per 100 km sewer length per year, for all flood-related consequences. Gully pot blockages cause about 1 incident of flooding in buildings per 100km per year for both cases. The frequency of flooding with wastewater is low: below 0.2 per 100km per year for both cases, for each of the flooding mechanisms.

Incident frequency of sewer pipe blockages is approximately 8 times higher for Breda compared to Haarlem, for all flood related consequences. The same applies to dry incidents (results not shown here). A possible explanation is that sewer cleaning frequency in Haarlem is twice as high as in Breda (see table 6.2). In addition, a recent evaluation report of urban drainage management in Breda (Gemeente Breda, 2008) mentions that in 2004 and 2005 many sewers were cleaned that hadn't been cleaned for a long time. This was not reflected in a reduction of the amount of 'sewer blockage' calls for 2006 and 2007, which may indicate remaining backlog in maintenance work. Ages of sewer pipes cannot account for the difference in blockage frequency; the distribution of pipe lengths over pipe ages is similar for both cities.

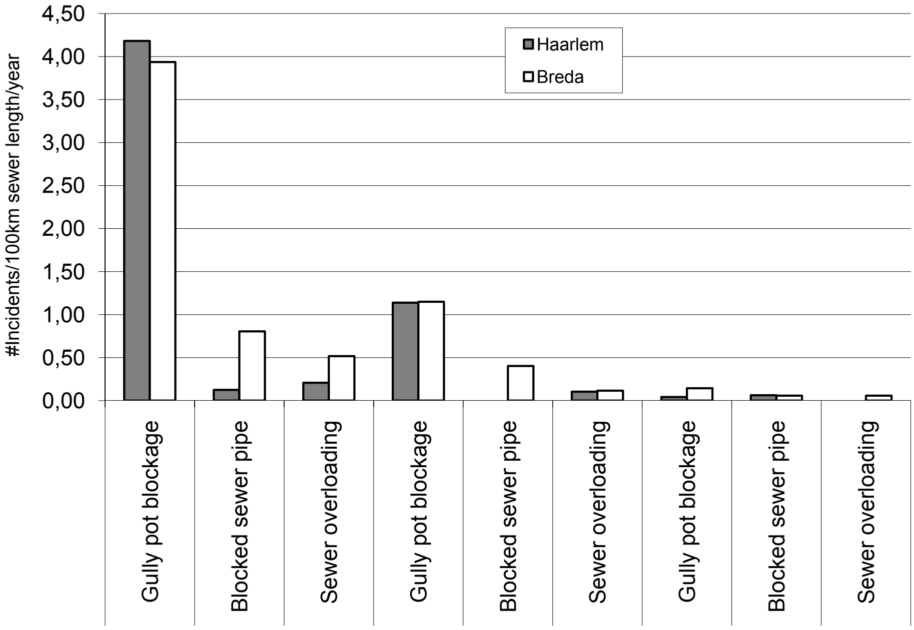

Figure 6.1 Comparison of the number of incidents per kilometre sewer length per year for between Haarlem and Breda for 3 different selections of flood consequence classes, for rain incidents

Incident frequency of sewer overloading is three times higher for Breda compared to Haarlem. A possible explanation is that older parts of the system in Breda were designed according to a lower design standard and that system capacity was not adjusted at a later stage. Recent hydrodynamic calculations for 4 subcatchments in Breda have indeed shown that system capacity in 3 of these areas does not comply with the design standard (Gemeente Breda, 2008). Other areas will be evaluated in the coming years. Also, the frequency of occurrence of rainfall incidents in Breda could have been higher over the study period compared to Haarlem. This could not be confirmed, since only daily rainfall data were available for Haarlem and sewer overloading is mainly influenced by peak intensities over short durations.

As mentioned earlier, detailed investigation of call texts for dry incidents shows that many of these calls in fact refer to previous rain incidents or do not refer to a particular event. This implies that most calls for dry incidents do not report additional incidents, thus that probabilities calculated for rain incidents are representative of total probabilities of flooding, as reported by citizens.

Probabilities of occurrence of incidents in various classes were quantified following equation 3, as well as average consequences per incident in terms of the number of reported locations per incident. These values were used to quantify flood risk, according to equation 1. Table 6.5 gives the results of probabilities and quantified risk for flooding-related consequences. The accumulated risk of flooding incidents for 3 failure mechanisms is 0.19 locations/km sewer length/year for Haarlem and 0.29 locations/km/year for Breda, for rain incidents and for all flood-related consequences. The accumulated risk of flooding in buildings is less than 10% of risk for all flood-related consequences. In both cases, gully pot blockages contribute most to flood risk. These quantified risk values can be used in decision making in order to decide whether flooding risks should be reduced and what failure mechanism should be handled with priority for risk reduction.

Table 6.5 Summary of flooding risks for case studies of Haarlem and Breda, for rain incidents: probabilities of flooding incidents and average risk per failure mechanism per year. All values are calculated per year and per kilometre of sewer length.

	Prob. of incid. (km^{-1}.year^{-1})	Flood risk (locations. km^{-1}. yr^{-1})	Prob. of incid. (km^{-1}.year^{-1})	Flood risk (locations.km^{-1}. yr^{-1})
	flooding-related consequences		Flooding in buildings	
Haarlem				
Gully pot blockage	0.041	0.180	0.010	0.020
Blocked sewer pipe	0.001	0.001	0.000	0.000
Sewer overloading	0.002	0.003	0.001	0.001
Total		**0.19**		**0.024**
Breda				
Gully pot blockage	0.039	0.280	0.010	0.019
Blocked sewer pipe	0.008	0.010	0.004	0.004
Sewer overloading	0.005	0.007	0.001	0.002
Total		**0.29**		**0.025**

Evaluation of operational strategies

- Gully pot cleaning

The results show that handling of gully pot blockages should be a priority in sewer management, since these are the main cause of flooding in general as well as for flooding in buildings. At present, investments in preventive cleaning constitute 15% of the total maintenance budget in both municipalities; 5% of the total budget is spent on reactive handling upon gully pot calls. The results in tables 6.3 and 6.4 show that reactive handling upon calls is not an efficient strategy, because only 3% of all gully-pot-calls report serious consequences, i.e. flooding in buildings or flooding with wastewater. Nevertheless it is current practice in many municipalities to conduct investigation or direct cleaning actions on-site upon every call. Much efficiency can be gained in handling of gully pot blockages by reacting only to those calls that indeed have serious consequences. This selection can be made at the call centre, by obtaining additional information from callers, e.g. based on a number of standard questions.

The blockage process of gully pots largely unknown so that occurrence of blockages remains unpredictable, which complicates preventive handling. Since most municipalities in the Netherlands apply similar regimes of gully pot cleaning, no reference is available to compare the effect of higher or lower preventive gully pot cleaning frequencies. The costs of planned gully pot cleaning are low: about €3 to €6 per gully pot compared to €100 to €200 per reactive action. On the other hand, preventive cleaning involves all gully pots, whereas reactive cleaning according to current strategies applies to less than 1% of all gully pots yearly. Therefore, two options should be investigated for their potential for cost reduction: experimenting with selective handling to reduce reactive cleaning costs and optimizing preventive cleaning frequencies.

- Sewer pipe blockage

The difference in sewer blockage probability and associated risk of flooding between Breda and Haarlem indicates that increasing preventive sewer cleaning frequency can be an efficient strategy to reduce flooding induced by sewer blockage. Preventive handling is a more desirable strategy than reactive handling, since in the case of Breda half of the sewer blockages have serious consequences, i.e. flooded buildings and wastewater flooding.

- Sewer overloading

The cities of Breda and Haarlem established standards for sewer flooding induced by sewer overloading in their strategic plans: a maximum flooding frequency of once per 2 years. In Breda a lower standard of once per year applies to some areas. The standards do not specify to what geographical area they apply: single location, street, sewer catchment of the entire city. The risk of flooding caused by sewer overloading is about 1 location per year for Haarlem and 5 locations per year for Breda. If the standard applies to the city as a whole it is not satisfied; if it applies to a district or subcatchment it is easily satisfied. The risk of flooding by sewer overloading is low compared to other failure mechanisms; probability is low and few calls report serious consequences, i.e. flooding inside buildings or flooding with wastewater. The costs of prevention can be high, if pipe dimensions have to be increased. In those cases, prevention of blockages is a more efficient strategy to reduce flood risk. Prevention of flooding by sewer overloading should only be considered in cases of serious consequences or if prevention can be achieved by low-cost measures like increasing the heights of doorsteps at building entrances.

Risk-based decision making for flood risk reduction

The urban drainage policy plan for the city of Breda states the following maximum acceptable flooding frequencies for roads: once or twice per year for residential areas, once per two years for commercial areas and the city centre (Gemeente Breda, 2008). Flooding of buildings is not explicitly distinguished from flooding of roads; protection levels of buildings therefore depend on the relation of their building level to street level: building levels above street level are likely to experience less flooding, those below street level more frequent flooding than roads. This aspect is not addressed in the urban drainage policy plan.

Table 6.6 summarises the results of call data analysis for the case of Breda, for flooding of roads and of buildings separately. The contribution of the three most important causes of flooding was also quantified. This table shows that flooding frequencies exceed maximum values prescribed in the policy plan and indicate a need for flood reduction.

Table 6.6 Outcome of call data analysis: flood risk in nr of calls/km sewer length/year, city of Breda, period 2003-2007, total sewer system length 740km.

Flooded Locations/km/yr	**Roads**	**Buildings**
Total all causes	**0.3**	**0.03**
Sewer overloading	0.003	0.002
Sewer blockage	0.003	0.004
Gully blockage	0.2	0.02
Total	**0.206**	**0.026**

Under the assumption that calls represent 2% to 30% of all real flood occurrences (Wiechen et al., 2002; Devereux and Weisbrod, 2006), the uncertainty range in real flood risk in terms of the number of calls per km sewer length per year is summarised in table 6.7.

Table 6.7 Uncertainty range of quantified flood risk in nr of calls/km sewer length/year, city of Breda, under the assumption that calls represent 2% to 30% of real flood occurrences.

Flooded Locations/km/yr	Roads			Buildings		
	#calls	Min real occurr	Max real occur	# calls	Min real occurr	Max real occurr
Sewer overloading	0.003	0.01	0.15	0.002	0.007	0.10
Sewer blockage	0.003	0.01	0.15	0.004	0.013	0.20
Gully blockage	0.200	0.67	10.00	0.020	0.067	1.00
Total	0.206	0.69	10.30	0.026	0.087	1.30

If, based on these results it is decided that flood risk should be reduced, various actions can be taken to address these flooding causes. Table 6.8 summarises actions that can be undertaken to reduce flood risk for three individual causes of flooding: sewer overloading, sewer blockage and gully pot blockage. Due to a lack of data on the effect of actions, especially of maintenance related actions, the estimated effect of each action was based on expert judgment.

Table 6.8 Actions to reduce flood risk, for each of the three analysed flooding causes. Costs were estimated based on investment and maintenance costs for 2 case studies; effect was estimated based on expert judgment

Flooding cause	Action to reduce associated flood risk	Estimated cost M€/km/year	Estimated effect: flood risk reduction outcome (locations/km/yr)
Sewer overloading	Enlarge sewer pipe:	0.05*	Reduction by 16.67% of sewer overloading-related events
Sewer blockage	Increase cleaning frequency	0.05	Reduction by 14% of sewer blockage-related events
Gully blockage	Increase cleaning frequency	0.05	Reduction by 10% of gully pot blockage-related events

* based on €1000/m sewer length replacement, 40 years amortization, interest rate 0.04

Sewer overloading is reduced by implementation of a structural measure: enlargement of a sewer pipe. Blockages are handled by increasing maintenance frequencies. Three measures of similar yearly investment cost are used for comparison. The following assumptions were made with respect to the effects of measures in relation to investment costs (table 6.9).

Table 6.9 Assumptions underlying estimates of the costs and effects of measures to reduce flood risk

Flood reduction	Cost assumptions	Effect assumptions
Enlargement of sewer pipe to reduce flooding due to sewer overloading	1 location at a time: 1000 m pipe enlargement by replacement with larger diameter; Investment cost: €1,000,000 or €50,000 per year;	Reduction of 1 flooded location per year (where capacity is enlarged) out of average 6 flooded locations per year: reduction 1/6 or 16.67%.
Increase sewer cleaning frequency	Yearly costs of sewer cleaning are €180,000. Increase cleaning costs with €50,000/yr: cleaning frequency increases by 28%.	Comparison of 2 cases with different cleaning frequencies shows that 2 times higher cleaning frequency corresponds with half the number of calls/year (50% reduction). It is assumed that 28% increase of frequency results in 14% reduction in the number of calls/year
Increase gully pot cleaning frequency	Yearly costs of gully pot cleaning are €150,000. Increase cleaning costs with €50,000/yr: cleaning frequency increases by 33%.	No data are available to estimate the effect of increased gully pot cleaning. The expected bandwidth of reduction induced by 33% frequency increase is 0-33%. It is assumed that 33% increase in cleaning frequency leads to 10% reduction in the number of calls.

Table 6.10 Uncertainty range of quantified flood risk in nr of locations/km sewer length/year, city of Breda, as a result of 3 different flood reduction measures, for road flooding and for building flooding.

Locations/km/yr Road flooding	Enlarge sewer pipe		Increase sewer cleaning frequency		Increase gully pot cleaning frequency	
	Min occur	Max occurr	Min occur	Max occurr	Min occur	Max occurr
Sewer overloading	0.008	0.125	0.010	0.150	0.010	0.150
Sewer blockage	0.010	0.150	0.009	0.129	0.010	0.150
Gully blockage	0.667	10.000	0.667	10.000	0.600	9.000
Total	0.685	10.275	0.685	10.279	0.620	9.300

Locations/km/yr Building flooding	Enlarge sewer pipe		Increase sewer cleaning frequency		Increase gully pot cleaning frequency	
	Min occur	Max occurr	Min occur	Max occurr	Min occur	Max occurr
Sewer overloading	0.006	0.083	0.007	0.100	0.007	0.100
Sewer blockage	0.013	0.200	0.011	0.172	0.013	0.200
Gully blockage	0.067	1.000	0.067	1.000	0.060	0.900
Total	0.086	1.283	0.085	1.272	0.080	1.200

The relation between actions and reduction of call numbers is summarized in table 6.10. Comparison of the results in table 6.10 with those in table 6.7 shows that increasing gully pot cleaning frequency is most effective of the 3 strategies to reduce flood risk. Sewer pipe enlargement and increasing sewer cleaning frequency have only marginal effect on total flood risk. This follows from the small number of calls, thus flooded locations, related to sewer overloading and sewer blockage compared to gully pot blockage.

Table 6.11 summarises investment costs and minimum and maximum flood risk estimates in terms of the number of flooded locations per year for the current situation and after execution of each of the three flood reduction measures. Figure 6.2 gives a graphical representation of the data in table 6.11. It shows that for the same investment level, increasing gully pot maintenance is the most effective measure to reduce flood risk. The effect of increased gully pot cleaning frequency is about 10 times higher than that of enlarging sewer pipe capacity or increasing sewer cleaning frequency. Uncertainty in flood risk results derived from call data does not influence this conclusion. It only influences absolute values of quantitative flood risk outcomes.

Table 6.11 Summary of yearly investment costs and resulting flood risk in terms of the number of flooded locations/km sewer length/year, for 3 flood reduction measures. Uncertainty margins are based on the estimated representation of flood-related calls compared the real number of flooded locations

Effect of investments; nr. of flooded locations/km/yr	**Do nothing**	**Enlarge sewer pipe**	**Increase sewer cleaning frequency**	**Increase gully pot cleaning frequency**
Investment	€0/yr	€50,000/yr	€50,000/yr	€50,000/yr
Road flooding				
Min (calls represent 30% of real occurrences)	0.687	0.685	0.685	0.620
Max (calls represent 2% of real occurrences)	10.300	10.275	10.279	9.300
Building flooding				
Min (calls represent 30% of real occurrences)	0.087	0.086	0.085	0.080
Max (calls represent 2% of real occurrences)	1.300	1.283	1.272	1.200

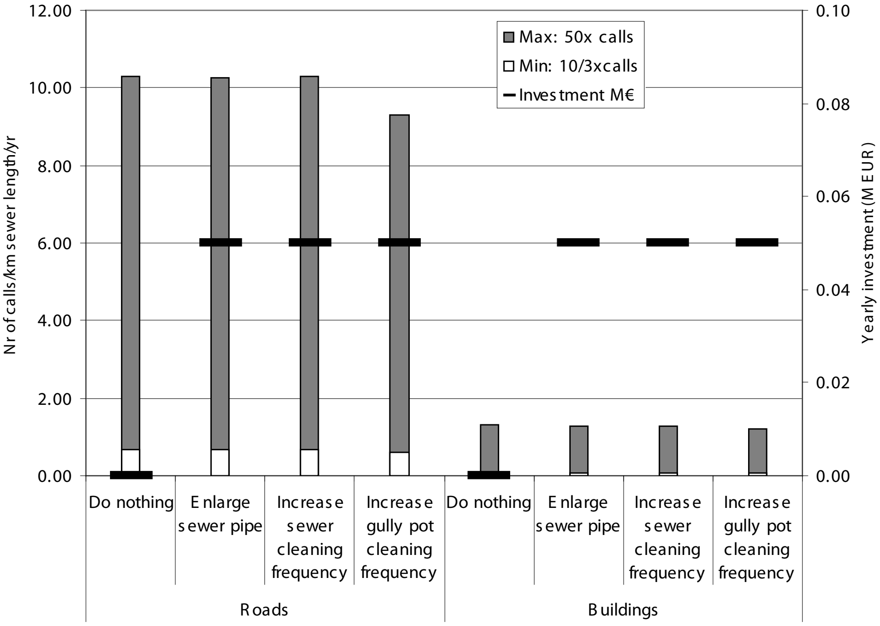

Figure 6.2 Yearly investment costs and resulting flood risk in terms of the number of flooded locations/km sewer length/year, for 3 flood reduction measures.

6.4. Conclusions

Data from call centres at two municipalities reporting problems related to urban drainage were analysed in order to quantify flooding frequencies and associated flood risks for three main failure mechanisms. The results were used to evaluate current operational strategies for prevention of flooding. The aim was to find out whether current operational strategies based on practical experience are efficient and if directions for improvement could be found. Quantified flood risk for the 2 cases is 0.19 flooded locations per km sewer length per year and 0.29 locations per km per year. This is well above the standard defined as a flooding frequency of once per year. The analysis pointed out that gully pot blockages are the main cause of flooding. The efficiency of current gully pot cleaning strategy can be increased by limiting reactive handling to those calls that report serious consequences, which is a small portion of all calls. Also optimisation of preventive cleaning frequencies can reduce costs. Preventive cleaning of sewer pipes proves to be an efficient strategy to reduce flooding due to sewer blockages as flood risk associated with sewer blockages is lower in case of higher cleaning sewer frequencies. Sewer blockages often have serious consequences, thus preventive handling is to be preferred to reactive cleaning. According to the results of this analysis, reduction of flooding sewer overloading is not of primary concern, because serious consequences for this failure mechanism are rare compared to other failure mechanisms.

It was shown that based on call data analysis effective strategies flood risk reduction can be identified. Currently, information about the effect of flood reduction measures is lacking to adequately assess the effect of actions for flood risk reduction. Based on the availability it could be shown that increasing gully pot blockage is the most efficient action to reduce flood risk, given data uncertainty. If differences between cause incidences are large, as in the presented case study, call data are sufficient to decide how flood risk can be most efficiently reduced. If differences are small, call data do not provide sufficient accuracy to distinguish between causes. Additional data must be collected to assess flood risk more accurately and to estimate the effect of flood reduction measures. The effect of structural measures can be estimated based on model simulations if a reliable hydrodynamic model is available. Little information is currently available to estimate the effect of different maintenance frequencies; experiments with varying maintenance frequencies and methods should be conducted to obtain insights into the effect varying maintenance strategies and to support relating decisions in urban flood risk management.

6.5. References

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Chapter *7*

Discussion and recommendations

Historical series of data from municipal call centres show that urban flooding in lowland areas occurs frequently, up to hundreds of times per year (ten Veldhuis et al., 2009). Research in the field of urban flooding tends to concentrate on flooding caused by rare, heavy rainfall events: hydrological studies are dedicated to extreme rainfall characteristics and the effects of climate change (Ntegeka and Willems, 2008) and modelling studies develop routines to simulate system overloading by heavy rainfall and overland flow patterns (Maksimovic et al., 2009; Djorjevic et al., 2005). Since heavy rainfall events typically occur at low frequencies, of the order once per several years, they cannot account for the high frequency of occurrence of urban flooding in lowland areas. The question is what causes these high-frequency events, what consequences they have and what the distribution of causes and consequences is over the series of events? Risk analysis addresses causes and consequences of events and associated probabilities of occurrence. Hence the general problem statement for this thesis: what new insights can risk analysis based on historical series of flood occurrence data provide with respect to characteristics of flood events in lowland areas?

This chapter addresses the contributions of the research reported in this thesis to respond to the four research questions that in the introduction chapter were derived from the general problem statement. In this thesis data from municipal call centres that describe observations by citizens of urban flood events are used. The advantage of this type of data is that it is flexible to accommodate descriptions of many kinds of flooding characteristics; the disadvantage is that the information characteristics change with observation qualities of individual citizens and their readiness and ability to provide details. The uncertainty aspects of the use of call data in flood risk analysis and how data uncertainty influences the validity of results and conclusions drawn is addressed in appendix 1. Recommendations for further study are given at the end of this chapter, as well as directions for practical application of risk analysis in urban flood management.

7.1. Contribution to answer research questions

1. What causes contribute to urban pluvial flood risk and how can these causes be quantified?

Fault tree analysis is applied to identify causes of urban flooding and to quantify the contribution of different causes to overall flood probability. The results of this study show that gully pot blockages are the main cause of flooding. They contribute 71% to the overall probability of flooding in the investigated case study. Other causes are, in decreasing order of contribution magnitude:

- blocked gully pot manifolds;
- areas not connected to urban drainage systems;
- high groundwater tables, drinking water pipe bursts;
- sewer overloading and blocked sewer pipes.

This result shows that asset failures are a more important cause of urban flooding than overloading of urban drainage systems due to heavy rainfall. The same applies to road flooding and flooding of buildings. In a study for the UK, Arthur et al. (2009) obtained a similar result for the city of Edinburgh, showing that more than 75% of sewer-related flood events were due to blockages, while 16% was due to hydraulic overloading. Renard and Volte (2009) conducted a study of flood observation data for Grand-Lyon and found that 43% of flood events was due to blockages of inflow devices like gully pots, 27% was related to problems in sewer pipes and 19% concerned infiltration facilities, for the period 1988-2005. Caradot et al. (submitted) state that, in a study for the city of Mulhouse, 400 to 600 interventions were made yearly since 1993 to solve flooding problems. Of these interventions, 37% of flooding problems was due gully pot blockages, 27% was caused by improper behaviour of building constructors and 27% was due to improper behaviour of citizens. A summary of results from the case studies is given in table 7.1.

Table 7.1 Contributions of failure mechanisms in urban drainage systems to urban flooding. Only percentage values for mechanisms that appear in all studies are shown.

Failure mechanism	**Results case study the Netherlands**	**Results case study UK** (Arthur et al., 2009)	**Results case studies France** (Renard and Volte, 2009; Caradot et al., submitted)	
	Haarlem	**Edinburgh**	**Lyon**	**Mulhouse**
Gully pot blockage	71%		54%, 37%	
Blockages		75%		
Hydraulic overloading	3%	16%		
Problems in sewer pipes	1%		27%	

These results point out the important role of asset failures as a cause of urban flooding. This implies that risk analysis based on hydrodynamic modelling of design storm and rainfall series provides an incomplete picture of urban flood risk, since it only addresses flooding caused by overloading due to heavy rainfall. Presently, many urban flooding studies ignore the effect of asset failures on flooding. If asset failures are not taken into account in flood risk analysis, flood frequencies and flood risk are likely to be underestimated. Additionally, flood risk reduction measures that are chosen and designed based on these results are likely to be ineffective, as a part of flooding problems remains unaddressed. Flood risk analysis should include all potential causes of flooding to obtain flood risk estimates representative of reality and to properly determine what type of flood risk reduction measures are most effective.

2. What consequences of urban pluvial flooding should be taken into account in a risk analysis and how can these be quantified?

Various kinds of urban flooding consequences are compared in this thesis, including material damage and intangible consequences of flooding and potential microbial infection due to exposure of citizens to contaminated flood waters.

In chapter 4 of this thesis, tangible and intangible damages of urban pluvial flooding are investigated for two lowland case studies. Tangible damages include flooding of residential and commercial buildings, intangible damages refer to traffic delay caused by road flooding and inconveniences to road users, especially pedestrians and cyclists. It is shown that lowland areas are frequently affected by flooding and that the frequency of occurrence of intangible damages is higher than that of tangible damage.

A first attempt is made to translate both tangible and intangible damage into common quantitative measures in order to be able to directly compare their contributions to total flood damage. Two types of quantitative measures are compared: monetary values and the number of people affected by flooding. The results show that even though the frequency of occurrence of tangible damage is lower, the monetary damage associated with tangible damage is much higher than that for intangible damage. On the other hand, the number of people affected by tangible damage is far smaller than the number of people affected by intangible damage: over a period of 10 years, intangible damage affects up to hundreds of times as many people as tangible damage.

The cumulative monetary damage to buildings from small flood events over a period of 10 years, is estimated at about 10% of the damage to buildings during the 1998 pluvial flood event in the Netherlands, with an estimated return period of 125 years. This result illustrates that the cumulative damage of small flood events over a period of 125 years is likely to be of the same order or magnitude as the singular-event damage of a 125 year return period. This result shows that, while flood risk analyses tend to focus on severe events and tangible damages (e.g. Jonkman et al., 2003; Dutta et al., 2003; Apel et al., 2006; Thieken et al., 2005), damage of small flood events should be taken into account to obtain a complete and representative flood risk estimate for urban catchments.

The results of this thesis also show that large numbers of people are affected yearly by intangible flood damage. Translation of this damage into costs to citizens and society is not straightforward. In a study by Defra and the Environment Agency in the UK (Defra, 2004) willingness-to-pay (WTP) was used to quantify human-related intangible impacts of flooding. This study involved 1510 face-to-face interviews and focused on willingness to pay to prevent physical and psychological health effects of flooding of private property. Similar studies could be conducted to develop methods for translation of intangible flood damage into values that can be used in decision making and policy related to urban flood risk.

Studies, e.g. in New Orleans, Dhaka and Jakarta (Sinigalliano et al., 2007; Sirajul Islam et al., 2007 and Phanuwan et al.) demonstrated elevated concentrations of microbial contaminants in flood waters and sludge after severe flooding events. In chapter 3 of this thesis, a screening level microbial risk analysis for urban pluvial flooding shows that flooding of combined sewer systems produces health risks of the same order of magnitude as those associated with swimming in recreational waters affected by combined sewer overflows. This result indicates that small urban flooding events, with frequencies of occurrence of up to several times per year, pose non-negligible health risks to citizens, due to their high frequency of occurrence.

3. Can the results of quantitative urban pluvial flood risk analysis based on historical data series from municipal call centres be used to support decisions on how to effectively improve flood protection?

Call data provide details on causes of flooding events, consequences of flooding and locations affected by flooding. 92% to 95% of the calls analysed in this thesis contain information on flooding causes; 32% to 52% of the calls contain details on flooding consequences; all calls include address details. This thesis shows that call data analysis enable identification of flooding causes and quantification of their contributions to flood risk. Call data also enable to distinguish between contributions of flood causes to different types of consequences, such as flooding of buildings, roads and tunnels. Thus, it supports selection of most effective measures to improve flood protection. In chapter 5 it is shown that for the cases analysed in this thesis, flood protection is most effectively improved by prevention of gully pot blockages and sewer pipe blockages. Additionally, it is shown that sewer pipe blockages can effectively be reduced by increasing sewer cleaning frequency based on a comparison between cleaning frequencies and flooding induced by sewer blockage for two cases. Available data do not provide sufficient information to conclude whether increasing the frequency of routine gully pot cleaning is effective to prevent gully pot blockages. Insight obtained from call data analysis does suggest that reactive handling of gully pot blockages can be made more efficient if actions are prioritised according to the severity of observed consequences. The same holds for prioritisation of investments for flood prevention: building flooding and tunnel flooding have more disruptive consequence than flooding of residential streets and these locations should therefore get priority in preventive action.

To summarise, call data analysis is useful to support decisions by setting priorities based on observed consequences and predicting what type of flood prevention strategy is likely to be most effective based on contributions of flooding causes. The reliability of such decisions depends on the reliability of call data. The influence of call data uncertainty on flood risk analysis outcomes and related decisions is discussed in appendix 1.

4. Can risk-based standards for urban pluvial flooding provide a better basis to evaluate urban drainage systems than current frequency-based standards and guidelines?

Most current flooding standards and guidelines (e.g. CEN, 2008; RIONED, 2004) are expressed in terms of flooding frequency with no or limited reference to flooding consequences. In addition, standards often do not make explicit whether they are applicable at city level, or at the level of individual locations or sewer subcatchments. For instance, if a few locations in a city suffer from high flooding frequencies, this means that the system does not comply with flooding standards at city level; yet all other individual locations inside the city experience lower flooding frequencies and individually do comply with standards.

In chapter 6 of this thesis, urban flood risk is quantified in terms of the number of flooded locations per km sewer length per year. The number of flooded locations is specified for various types of consequences: health-related consequences, flooding of buildings and flooding of roads. In table 7.2 the results based on call data analysis for 2 case studies are compared to flooding guidelines as defined in policy plans for each case study. The urban drainage policy plans for Breda and Haarlem (Gemeente Breda, 2008; Gemeente Haarlem, 2008) state that those parts of the system that are covered by hydrodynamic models (circa 25% for Breda and 75% for Haarlem) were evaluated based on design storms with a return period of 2 years (RIONED, 2004; van Mameren and Clemens, 1997; van Luijtelaar and Rebergen, 1997). Remaining areas are to be evaluated in the future. Evaluation took place per subcatchment area, i.e. area connected to a main pumping station; the size of subcatchment varies from about 100 ha to 1000 ha of semi- and impervious connected to urban drainage systems. When model simulations indicated locations prone to flooding, these were studied in further detail and solutions were designed and included in future investment programs. Complaints were looked at to identify additional problem locations; these were likewise studied in further detail.

The comparison shows that the investigated systems are far from complying with flooding guidelines at city level: flooding frequencies vary from 9 to 33 flood events per year. Evaluation of frequency-based standards and guidelines is often based on design storms, which implies that hydraulic overloading is the sole failure mechanism taken into consideration. The results show that for hydraulic overloading only, the investigated systems do not comply with the standards at city level, unless flooding consequences are limited to building flooding. If guidelines are evaluated per kilometer sewer length, guidelines are easily complied with, both for street flooding and flooding of buildings, for all failure mechanisms together.

Table 7.2 Policy guidelines for urban flooding the Netherlands and outcomes of quantitative flood risk analysis based on historical flood incident data.

Policy guideline		**Flooding frequency analysis**			
Return period of design storm that urban drainage system can cope with		Based on historical flood incident data			
Spatial scale undefined		**City level (year^{-1})**		**Per km sewer length (year^{-1})**	
Breda	**Haarlem**	**Breda**	**Haarlem**	**Breda**	**Haarlem**
Residential areas:	All areas:	All flooding consequences			
T=1 year	T=2 years	33	25	0.045	0.055
frequency: 1.0/year	frequency: 0.5/yr	Street flooding			
Commercial areas:		31	22	0.042	0.047
T=2 years		Building flooding			
frequency: 0.5/year		16	9	0.021	0.020
		Flooding due to hydraulic overloading only			
		Breda	**Haarlem**	**Breda**	**Haarlem**
		All flooding consequences			
		3.8	1.0	0.005	0.002
		Street flooding			
		2.5	0.6	0.003	0.001
		Building flooding			
		0.8	0.5	0.001	0.001

These results point out a number of shortcomings of frequency-based standards and evaluation for urban flooding. First, all potential causes of flooding, including hydraulic overloading and asset failures should be taken into account to obtain a realistic flood risk estimate. Second, flooding standards should specify to what spatial scale they apply to ensure proper evaluation. If the applicable spatial scale is not specified, the scale for application can be chosen at will and outcomes of different evaluation can no longer be compared. Third, standards should take flooding consequences into account, because damage to society differs with various types of consequences. For instance, the results in table 7.2 show that street flooding frequencies for roads are about two times higher than flooding frequencies of buildings. This is a direct consequence of the general construction level of buildings, which is about 15 cm above street level in the Netherlands. If maximum flooding frequencies defined in the standards are interpreted as road flooding frequencies, a safety margin for flooding of buildings follows as an automatic result. Standards cannot allow for such ambiguity of interpretation; their conditions of application should be explicitly defined. It must be clear whether standards apply to all areas and occupational functions alike, or whether specific functions need higher protection levels than others to reflect differences in expected flood damage.

Unlike frequency-based standards, risk-based standards incorporate flooding consequences and they take all known failure mechanisms into account instead of focusing on one failure mechanism. This study showed how quantitative flood risk values can be obtained from time-series of flood event data, in the form of a number of flooded locations per year per km sewer length. This result was further specified to flooded buildings per year per km and flooded roads per year per km. The results were also used for quantification in terms of monetary values and the number of people affected by flooding, per year, per km sewer length, based on a number of assumptions with respect to the monetary damage and number of people affected per flooded location.

Risk values, whether expressed in terms of flooded locations, number of people affected or monetary damage per km sewer length per year can be used as a starting point to develop risk-based standards. The setting of standards is in essence a political decision that is informed by knowledge of current flood risk and required investments to obtain flood risk levels in the future. Risk-based standards in terms of monetary risk values have the advantage of providing a direct investment cost versus damage costs comparison. The advantage of number of flooded locations per km per year, specific for buildings, roads, economical and societal functions is that flood risk can be directly derived from flood occurrence data, without the need for translations based on uncertain assumptions, as is the case for translation into monetary values.

Priority setting between different urban functions takes place either way: or by differentiating protection levels between urban functions or by assuming different monetary values associated with flooding of locations occupied by different urban functions. The first makes priority setting an explicit part of the political decision process, the latter makes it part of the risk assessment process.

7.2. Generalisation of results from case studies

This research was based on an analysis of historical flood event data from 2 case studies in the Netherlands. The case studies are representative of conditions in densely populated, lowland areas in developed countries: small ground level gradients, high groundwater tables, high building density, urban drainage mainly provided by combined sewer systems. Studies based on case studies in France and the UK (Caradot et al., submitted; Arthur et al., 2009) found that urban flooding occurs at frequencies of hundreds of times per year in these case studies as well and that flooding is mainly caused by asset failures. Since these case studies are not situated in lowland areas, these conclusions are likely to be true in general, in lowland and in hilly areas.

Another outcome for the Netherlands' case studies was that the cumulative risk of small pluvial flood events over a period 10 years is of the same order of magnitude as the risk associated with a 100-years return period pluvial flood event. Studies that quantify flood risks associated with small, high-frequency events are rare and no references have been found that describe the cumulative effect of these events. Frequencies of flooding are similar for the Dutch case studies and those in France and the UK; the question is whether the amount of damage associated with high-frequency events and with rare events is also of the same order of magnitude. High-frequency events are characterised by small flood depths; damage consists of intangible damage and small tangible damage. The amount of damage mainly depends on population density, the type of urban functions affected and lay-out of streets and buildings. Areas with similar population density and urban lay-out are likely to experience similar high-frequency flood damage. Areas with smaller spatial building density and elevated building constructions are likely to experience less high-frequency damage. Damage associated with rare events depends on urban lay-out and ground level gradients: during these events, urban drainage systems get overloaded and water flows mainly over the surface towards depressions. If gradients are steep, flood depths in depressions rise rapidly and associated damage to urban functions located in these depressions is likely to be high compared to that in lowland areas. In that case, tangible damage for rare events may exceed the cumulative damage due to high-frequency events.

7.3. Recommendations for further research

The method applied in this thesis to quantify urban flood risk based on historical flood event data is only a first step towards a unified approach for quantitative urban flood risk assessment and risk-based evaluation of urban drainage systems. Several knowledge gaps exist that impede a proper quantification of urban pluvial risk and that need further attention.

1. Knowledge of flooding causes:

Flood risk analysis includes an analysis of all potential failure mechanisms leading to urban flooding. In chapter 2 of this thesis it is shown that the contribution of asset failures to flood risk is large compared to the contribution of overloading due to heavy rainfall events. Blockage of inflow devices (especially gully pots) is the most frequent cause of flooding, for flooding of buildings and of roads. The discrepancy between the contribution of this cause of flooding and others is large enough to draw this conclusion given data uncertainty.

Other causes of flooding, like heavy rainfall and pipe blockage, have lower frequencies of occurrence that differ less from one another. More extensive data collection and analysis is required to properly quantify contributions of these causes to urban flood risk and to asses what causes lead to severest damage.

Insufficient data are available presently to assess how contributions of flooding causes depend on system characteristics and maintenance activities. As more data on flooding causes become available for various urban drainage systems, it will be possible to analyse these relationships. Understanding of blockage processes will enable prediction of blockage occurrence. This knowledge supports development of efficient maintenance strategies, preventive handling of assets and improved design of assets to reduce their failures sensitivity. The importance of such knowledge is growing as the failure potential of assets is expected to increase in the future due to ageing of urban drainage systems, especially in western countries.

2. Knowledge of flooding consequences:

In this thesis an attempt is made to quantify consequences of urban flooding and to translate tangible and intangible consequences into two kinds of common measures: monetary values and numbers of affected people. Many assumptions have to be made for such translation, due to a lack of information on relations between various consequences and the chosen common measures. Assumptions relate to the amount of damage to buildings and building contents as a result of uncertain flood characteristics and uncertain property values; to the amount of damage due to traffic delay and to the amount of intangible damage related to inconveniences for road-users as roads and parking lots are flooded.

Uncertainty in direct damage to properties can be reduced by collecting data on costs of flood events, e.g. from insurance reports, in combination with data on flood characteristics. Indirect costs like traffic delay and inconvenience are difficult to translate into monetary terms; such translations inevitably result in uncertain outcomes, because traffic densities and velocities in urban areas are difficult to predict (Liu et al., 2006) and the costs of traffic delay for urban traffic are difficult to estimate (Bilbao-Ubillos, 2008). Information on stress and inconvenience can be obtained via interviews with affected people or through call centres by asking specific questions to callers. Willingness-to-pay is a possible way to obtain monetary assessments of intangible damage due to traffic delay and inconvenience; this method was applied in the UK to assess intangible health effects of flooding (Defra, 2004).

The question is whether translation into common measures, monetary or other, is desirable given the large variety of consequences and the uncertainties involved in translation. Instead of translating consequences into common measures, the numbers of events and affected locations per consequence category can be directly used to quantify flood risk, as shown in this thesis. Alternatively, a common measure can be applied per consequence category, for instance: monetary values for damage to buildings and building contents, time loss for flooding of roads, number of lives threatened for flooding of emergency routes, number of people affected by inconvenience for flooding of sidewalks and parking lots.

Further research is needed to find out whether translation of flood risk into common measures is feasible and if so, what common measure should be chosen and what uncertainty as a result of this translation can be accepted. If uncertainties involved in translation in common measures are unacceptable, common measures per consequence category are an alternative option. This leaves the question of how to integrate or compare risks associated with different consequence categories to decision makers.

3. Knowledge of efficiency of flood risk reduction measures:

Risk-based standards form a basis to assess the performance of urban drainage systems and the need for flood risk reduction. The efficiency of alternative flood reduction measures is to be assessed by comparing the costs of measures with the benefits of reduced flood risk. Cost-benefit analysis is a possible method to do this. Even though it offers the advantage of a direct comparison between costs and benefits in monetary terms, it has several important drawbacks: translation of benefits of flood risk reduction into monetary terms requires many assumptions that are subject to uncertainty and the translation of all costs and benefits as a result of the investment to monetary values for the year the investment is to be made, introduces additional uncertainty. Finally, the damage schematization made by this translation does not necessarily reflect public perception of the potential loss.

Further research is needed to develop a method to quantify the benefits of flood reduction measures that properly incorporates tangible and intangible consequences, that accumulates benefits over the application time of reduction measures and compares accumulated benefits with investment costs.

In addition, there is a lack of knowledge on the effect of flood reduction measures on flood risk, thus a lack of knowledge to assess the benefits of flood reduction investments. The effect of investments to increase system capacity can be assessed using hydrodynamic models to a certain extent. There are some questions to be answered as to how to properly use these models to quantify flood risk:

- What model accuracy is required to be properly assess flood occurrence;
- What combination of underground sewer model and surface flow model can provide sufficient accuracy to assess flood depths and flood extent;
- What accuracy is required to be able to quantify differences between flood reduction measures;
- What rainfall series is to be used to assess future benefits of flood reduction measures?

The effects of changes in maintenance strategies are largely unknown. Since the development of blockages is difficult to predict, field experiments should be conducted to determine the effect of variations in maintenance frequencies and methods on the occurrence of flooding associated with blockage and to assess the effect of combinations of preventive and reactive maintenance strategies on flood risk.

4. Knowledge on acceptability of flood risk

Once methods become available to quantify flood risk, the outcomes can be used to evaluate urban drainage system performance and to decide upon the need for flood risk reduction. Contrary to frequency-based analysis, risk analysis enables to evaluate the acceptability of flooding in view of the consequences (Vrijling, 2001). Such evaluation is based on a comparison to some standard or guideline that represents acceptable flood risk. An important question to be addressed in the definition of risk-based standards is what level of flood risk is acceptable in relation to the level of investment required for flood protection.
There are no absolute answers as to what flooding consequences are acceptable and how much investment can be borne by society to prevent more severe

consequences. Answers to these questions are the outcome of societal preferences, political and management discussions. Societal and economic developments can give rise to changes in the desired protection level; for instance, higher economic values at risk of flooding can lead to higher protection levels, lower willingness to pay for flood protection due to poor economic conditions can lead to lower protection levels.

The results of this study demonstrate that the cumulative direct, monetary damage associated with small, frequent flooding events over the lifetime of the investigated systems (50-100 years) is of the same order of magnitude is that associated with rare, severe events. This implies that for the cases investigated in this study, investments for urban flood protection provide an equal balance between protection from small flooding events and severe events, for direct, tangible damage. This balance is not the deliberate outcome of a chosen flood protection strategy, as flood risk was never quantified at the time the strategy was established. It is worthwhile to investigate whether the present situation is considered acceptable by society: residents, property owners and politicians. The numbers of calls received yearly at municipalities suggests this is not the case.

Possibly, flood protection can be improved by shifting the balance towards one side or another, without changing flood protection investments: for instance by increasing protection from small events while decreasing protection from severe events. This option is relevant in the light of climate change: if climate change will give rise to a higher frequency of occurrence of severe events, flood protection can be kept stable by increasing system capacity to bring back flood risk associated with severe events to present levels or by increasing cleaning frequencies, while maintaining current system capacity.

Shifting the balance means that citizens will be affected by flooding differently: damage associated with small events comes frequently and is borne by individual citizens and partly covered by insurance companies where it concerns damage to building contents. Damage of severe events is rare and is borne by individuals, sometimes covered by insurance and sometimes compensated by regional

or national government. Severe events tend to affect large areas at once and are more likely to cause societal and economic disruption than small events. Shifting the balance towards better protection from small events means people and properties will be affected by flooding less frequently, thus will have to recover from flood damage less frequently. Even if total damage over systems' and people's lifetimes remains unchanged, it may preferably to have to recover rarely from severe damage than frequently from small damage. On the other hand, the possibility of societal or economic disruption due to severe events may be a reason to prefer flood risk reduction associated with these events.
Severe urban flood events are almost invariably caused by heavy rainfall (not including river and sea flooding that are outside the scope of this thesis). Blockages usually have a local effect; they are the main cause of small flood events, yet are unlikely to cause severe flood events. This implies that a reduction of flood risk associated with small events requires investments in intensified cleaning of gullies and gully pots to prevent blockage, whereas risk reduction associated with rare events requires investments to increase transport capacity or to protect properties from flooding.

Further research is needed to find out what aspects of flood risk should be taken into account to assess acceptability of flooding. Once the aspects that influence flooding acceptability are known and can be assessed quantitatively, risk-based standards can be developed. The risk level in the standard represents the acceptability of flooding; the aspects that are to be taken into account to assess acceptability are to be based on knowledge of flood risk characteristics; the choice of the level of acceptable flood risk is the outcome of a political decision process.

5. Knowledge to support risk-based decisions to manage urban flooding

As stated earlier, risk-based evaluation provides a more complete and realistic picture of flooding problems than evaluation based only on frequencies. A risk-based approach offers additional advantages in decision support: If flood risk is too high compared to the standard, flood risk can be reduced in two ways: by reducing flood frequency and by reducing flood consequences. This approach opens up additional options for system improvement: a decision maker can decide to give priority to reduce flood frequencies of all main road tunnels or to reduce flood consequences by increasing protection of flood-prone buildings by raising pavement levels and door-sills. Given that intangible damage affects many people, this can be a reason to prioritise investments to reduce flood risk associated with this type of damage, even if associated monetary damage is small.

If required investments for flood protection exceed the amount of damage that can be prevented, a reactive approach to flood risk can be a viable alternative. Especially if investments prevent flood damage that affects only a few people, as is the case for flooding of buildings due to small flood events, the question is whether investments are justifiable if the costs are to be borne by society as a whole. This broadens the spectrum from flood risk prevention to raising flood resilience, i.e. the ability of a physical and socio-economic system to recover from flooding (de Bruijn, 2004). Possible reactive actions to promote resilience include compensation of flood damage to individuals and offering the possibility of insurance, which shifts the choice of reactive action on flood risk from water authorities to individual owners of flood-prone property.

Risk-based urban flood management comprises finding a balance between protection from frequent and rare flood events, between preventive and reactive actions, between protection of different regions and occupational functions, between tangible and intangible damage. Development of a unified approach for quantitative urban flood risk assessment and risk-based evaluation of urban drainage systems begins with the definition of a common method to assess and evaluate flood risk. The following components of this method particularly need to be clearly defined:

- how to assess flood frequencies and consequences: how to quantify flood frequencies, including definition of individual flood events, what consequence categories to include, how to quantify consequences;

- how to quantify flood risk: as a probability distribution of flood consequences or as the expected value of flood consequences; in terms of damage per km sewer length per year, per consequence category or alternative terms that allow for a comparison between systems of different sizes and characteristics.
- how to evaluate flood risk: to compare expected value or maximum value or 90th or 95th percentile value of flood risk to the risk level defined in the flood risk standard.

The risk level established in flood risk standards or guidelines is a political decision, yet the way it is defined is preferably prescribed at a central, i.e. national or supranational, level to enable comparison between systems in different regions.

7.4 Recommendations for data collection for quantitative urban flood risk analysis

The implementation of methods for quantitative urban flood risk analysis can be started by setting up data collection and storage of urban flood event characteristics. Figure 7.1 schematizes data about urban flooding, data characteristics and relations. In this thesis, call data and rainfall data are used to quantify urban flood risk. Rainfall data are used to define independent rainfall events and to look for relation between rainfall volumes and numbers of calls. Call data are used to identify causes and consequences of flood events and their frequencies of occurrence. In figure 7.1, the option of including additional measurements is indicated; data characteristics are given only for call data and rainfall data.

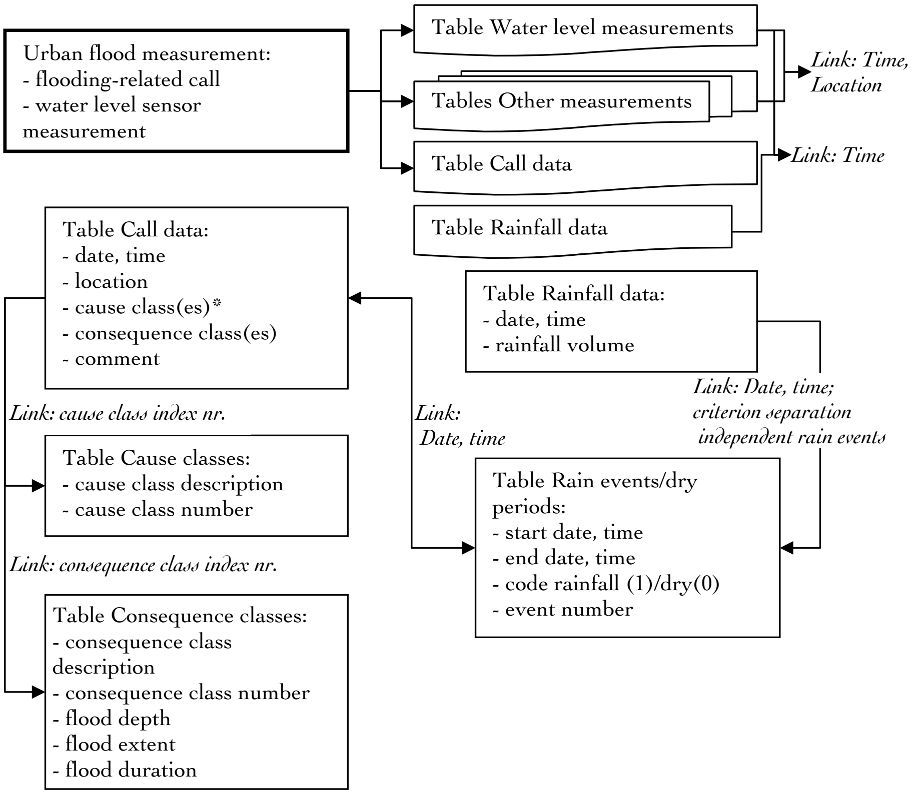

Figure 7.1 Schematic presentation of data collection for quantitative urban flood risk analysis

Rainfall data for flood risk analysis

In this thesis, daily rainfall measurements are used; as a result, relations between rainfall intensities and numbers of calls cannot be investigated. Urban drainage systems are especially sensitive to short-duration peak rainfall, therefore rainfall data are preferably collected at short time intervals: 5 to 10 minutes. If rainfall data are available, the effect of peak rainfall intensities on flood risk can be examined. Additionally, the interval of rainfall data influences the definition of independent rainfall events. In this thesis, a 24-hour dry period is used as a criterion to separate independent events. The use of daily rainfall data leads to rainfall events with long durations of up to 36 days, whereas in reality 24-

hour periods are likely to have occurred in between, yet not coinciding with daily rainfall measurement period. If rainfall data are available at shorter time intervals, the definition of rainfall events and dry periods can be made to represent reality more accurately.

Call data for flood risk analysis

Many municipalities collect call data; 109 out of 190 municipalities that took part in a questionnaire survey in the Netherlands (RIONED, 2007). Yet few use it to analyse the condition of their infrastructure, e.g. in a risk analysis. The reason is that call centres mainly aim at routing calls to a relevant department, where it is to be handled efficiently. Call centres are not oriented towards collecting information for an analysis of problem causes and consequences; thus valuable information is wasted. This situation can be improved by structuring the way call information is entered into a call database.

Current call databases usually have a time field, address field, main category and subcategory fields and one or more open text fields for comments on flood event characteristics. Main and subcategory fields are defined so as to facilitate call handling.

The address and comments fields in call databases used in this thesis are open text fields that contain a large diversity of texts. This complicates structured storage and analysis of the data. For instance, street names are spelled in different ways and comments vary from a few words to an almost literal transcription of call conversation. To prevent the need for manual call-to-call processing, text fields in call databases should be pre-structured as much as possible. For instance, street names are to be picked from a pre-defined list to prevent different spellings of the same street name. Similarly, other location details such as “at the corner of”, “at the entrance of” should be pre-defined and put in a different data field, separate from street name. Comment fields should be used only for information that is not essential for further analysis or that is too rare to be included in a predefined structure.

If call data are to be used for risk analysis, cause and consequence classes are to be added to the current categories for call handling. The more detailed classes are defined, the more information they can contain and the smaller the need for additional open text comments.

The list of cause classes used in this thesis is based on fault tree analysis; all basic events that appear in one or more call texts are included. The list of consequence classes is composed pragmatically, based on consequence descriptions found in the call texts from 2 databases. The lists of cause and consequence classes preferably contain a high level of detail from the beginning in order to avoid the need for adding new classes to the database at a large stage. Adding new classes leads to inconsistency in the database and discontinuity in time series, which can only be avoided by reclassifying all calls according to the new class definition, a large time investment that is to be avoided. The link between calls and classes can made via index numbers, or directly in the same database. The advantage of using index numbers is that the database remains more concise and that class descriptions can be adjusted without having to make changes in the database.

Reliability and accuracy of call data

Even if cause and consequence classes are predefined, the reliability of call classification at the call remains subject to uncertainty. Call centre employees handle a wide variety of problems of which they have no specialised knowledge, such as outfall of traffic lights, damage to street furniture and flooding. Additionally, call centre teams tend to change rapidly and as a result the effect of training employees on technical issues quickly erodes. As a result, causes and consequences of flood events are sometimes identified erroneously. A possible solution to this problem is to have technical personnel check every call on-site and enter cause and consequence classes accordingly, as is done for the two cases used in this thesis. In one of the cases, illustrations of urban drainage problem causes and consequences were made available at the call centre to support proper identification. Training and instruction, preferably in the field, is helpful and should be repeated at regular intervals. Even though training and on-site checking are time-consuming procedures, it is more efficient than manual classification afterwards or losing the information altogether.

Additional flood event measurements

Call data cover only a part of all flood events; to obtain a more complete register of flood events, additional data collection is needed.

Water level sensors can provide additional information on flooding: especially locations where flooding occurs and flood depth. Advantages of water level sensors are that they provide objective measurements and that they can provide continuous measurements of flood characteristics throughout a flood event. A disadvantage is that a sensor provides data of a single location: therefore sensors are useful to measure flooding at locations that are known to be flood-prone. The spatial density of a sensor network for blockage detection must be high to be able to detect all flooding due to blockage. It is estimated in this thesis that call data represent about 20% of true urban drainage problems, including failures of gully pots, pipes, pumps, infiltration facilities etc (see appendix 1). To obtain near 100% coverage for asset failure detection, sensors should be placed in every gully pot, i.e. about every 50 meters. Such dense sensor networks are not a feasible option, economically nor practically. To obtain higher sensor cost-efficiency, the number of sensors can be reduced to cover only vulnerable locations, such as entrances to hospitals and emergency centres, shopping streets, tunnels and residential areas at or below street level. Sensors can provide little information about causes and consequences of flooding. Configurations of two or more sensors can be used to identify the direction of flooding, e.g. by placing sensors inside a sewer, gully pot connection and in a gully pot, and to identify flooding consequences by placing sensors at various locations in a street profile, including sidewalks and gardens.

Health-risks of sewer flooding

Data collection on a larger scale is required to quantify health risk associated with combined sewer flooding with greater certainty. Collecting samples from flooding incidents is complicated by their unpredictability. Registration of flood incidents by responsible organisations will help to point out suitable locations for sampling; call data can be especially helpful in this respect. Sampling teams should be stand-by when weather forecast predicts heavy storms to reach flooded locations at rapidly as possible for sampling. Local representatives can be asked to call out as soon as they observe flooding or cameras or sensors can be installed to observe flooding at locations known to be flood-prone. Samples must be collected from a large geographical area or sample collection must be extended over long periods of time to collect a sufficient amount of samples to be able to draw reliable conclusions. Sampling from flooded locations is complicated by possible variations in pathogen concentrations in time and space due to ongoing rainfall and exchange between sludge and standing water. ISO guideline 5667, parts 1, 10 and 12 provide guidance on the design of sampling programmes and sampling of wastewaters and bottom sediments. More research is needed to define sampling programmes, necessary sampling frequencies and applicable techniques for health risk assessment of urban flood waters.

7.5 Recommendations for analysis and handling of asset failures

Asset failures prove to be an important cause of flooding. Data collection of asset failures and their consequences is essential in order to be able to assess their effect on urban drainage system performance, to adequately handle asset failures and to predict future failure likelihood. Data should be used in statistical analyses to estimate probabilities of occurrence of asset failures and in risk analyses to assess the effects of failures on flood risk. In addition, failure data can be used as input in hydrodynamic model simulations to predict how failures affect hydraulic processes, to identify locations that are vulnerable to flooding as a result of asset failures and to evaluate the effect of improved handling of asset failures. Data collection on asset failures in urban drainage systems in relation to flooding problems should focus on gully pot blockages (including blockage and breakage of gully pot connections), sewer pipe degradation leading to root intrusion, sedimentation and partial or full pipe blockage and on blockage of rainwater infiltration facilities. The role of pump failures was investigated by Korving et al. (2006); pump failures lead to increased combined sewer overflows, yet their influence on the occurrence of flooding is limited.

Currently, asset failures are handled by a combination of preventive, routine cleaning activities and reactive handling of problems. The results of this study suggest that improvements in the efficiency of asset management could be made, by shifting the balance further towards preventive handling of failures. Reactive handling of gully pot blockages and pump failures is expensive compared to preventive handling, either because travel times between individual cleaning actions are long compared to routine cleaning (gully pot blockage) or because repair actions take more time than routine maintenance (pump failures). Analysis results showed that higher sewer cleaning frequency leads to fewer pipe blockages, which suggests that cleaning frequency can be optimised further.

Since few data are available to assess the effectiveness of varying cleaning frequencies for sewer pipes, pumps and gully pots, experiments with varying cleaning frequencies should be conducted to test effectiveness with respect to flood prevention. Besides that, changes in the layout or the design of inflow devices could be investigated to prevent blockages. Gully pots often have a dual function of run-off water conveyance and sand trap. Anti-odour screens added in most type applied in the Netherlands. This combination of conveyance, sand trap and screen leads to high susceptibility to blockage. Sand traps aim to prevent blockage of pipes and damage to pumps; it is worth investigating whether this function can be accommodated in a different way.

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Appendix 1

Sensitivity analysis

This appendix specifically addresses uncertainty in the historical data series used in this study and analysis results: how does data uncertainty influence the validity of results and conclusions and can the conclusions be generalised to other lowland areas?

Influence of uncertainty in call data on quantitative urban pluvial flood risk results

Flood risk estimations are subject to large uncertainties, whether based on a combination of physical models or on a data-driven approach. Physical modelling approaches suffer from a lack of input and calibration data, model structure and parameter uncertainties and inherent uncertainties in natural phenomena like rainfall and run-off processes. Data-driven approaches suffer from data uncertainty, uncertainty due to phenomena that are not represented by available historical data and inherent uncertainties in natural processes.

A particular source of uncertainty for flood risk estimations based on call centre data is that call data represent a sample of the total number of flood occurrences, while the constitution of the sample cannot be controlled. It is unknown whether the characteristics of reported incidents are representative of the total collection of incidents nor how the number of report incidents relates to the total number of incidents. Also, call information can be subjective and comes from non-experts whose information can be incorrect. The latter source of uncertainty is greatly reduced when calls are checked on-site by technical experts as was the case of the data used in this study. The advantage of call data is that they directly convey citizens' experiences regarding adverse effects of flooding. Hence, call data indicate the acceptability of flooding problems to citizens.

To provide an estimate of the relation between the number of incidents reported in call data and the total number of incidents, a full coverage of a series of incidents would be needed for comparison to incidents reported in calls. Since flooding incidents, especially those associated with blockages are unpredictable, full registration of all flooding incidents would require a dense observation network in time and space. To set up a dense sensor network of 1 or 2 sensors per km of sewer length or a continuous video or radar registration just to validate data is not a feasible option.

References from customer research and complaint behaviour research provide an estimate of the percentage of people that expresses dissatisfaction out of the total number of people that is dissatisfied. Wiechen et al. (2002) compared characteristics of complainants and non-complainants about aircraft noise in the area around Schiphol Airport. They found that above a noise level of 55 dB, 2% to 7% of the total inhabitants in the noise exposed areas ever made a complaint to the responsible agency. Out of the group of people who expressed high annoyance by aircraft noise in a questionnaire, 19% had voiced their complaints to the responsible agency.

Devereux and Weisbrod (2006) investigated satisfaction levels with public services in Chicago, based on a telephone survey among 658 respondents. The respondents were asked for their satisfaction levels about garbage collection, street condition, police service and the quality of parks. Their results show that 3% to 9% of the respondents per category voiced a complaint. Of the group of respondents who are very or somewhat dissatisfied about garbage, streets or police, 23 to 26% voiced their most important complaint in this category. Of the other respondents, who expressed some degree of satisfaction, 5% to 11% voiced a complaint. Few people complained about parks: 3% of dissatisfied and less than 1% of satisfied respondents.

Phau and Baird (2008) investigated complaint behaviour among Australian consumers related to random service and purchase actions. They found that 50% of respondents will complain when they are dissatisfied with a product or service. Kau and Loh surveyed complaint behaviour of mobile phone purchasers in Singapore; 35% of respondents voiced a complaint to their mobile phone provider.

The reasons for consumers to complain have found to be diverse: dissatisfaction is an important though not always sufficient reason to complain. Other influencing factors are the expected benefit of complaining and time and energy spent in the complaint process.

Based on these aspects, an estimate is made of the percentage of citizens that is expected to make a call to a municipal call centre out of the total number of citizens who observe unsatisfactory urban drainage conditions. The examples of complaints about aircraft noise and public services are closest to the situation of complaints about unsatisfactory urban drainage conditions. Thus, the expected percentage of citizens who make a call is between 2% and 30%.

Higher percentages were found for customer complaints after direct purchase of goods or services; these situations are characterized by a higher direct personal involvement or investment of customers and a higher interest in obtaining a positive outcome. These percentages are therefore considered less representative for complaints about urban drainage conditions.

Additionally, risk assessment for urban flooding is preferably based on the real number of flood occurrences. This may include occurrences that were not observed by citizens, e.g. during the night. This is similar to the lowest percentage of 2% for noise complaints, where the 98% non-complainers includes citizens who experience noise and decide not to complain and citizens who are inside a noise range but do not experience noise.

Besides the size of the sample represented by citizens' calls from the real number of occurrences, the distribution of calls over cause and consequence classes forms an additional source of uncertainty. The question is whether all causes and consequences are equally represented in the sample. Representation of calls in cause classes depends on how easily a cause can be recognized by lay-people during the flood incident or by specialists who come to investigate the call afterwards. An evaluation of original classes, assigned to calls at the call centre upon reception of the call, compared to reassigned classes by a specialist based on the call text and information added after on-site inspection shows that gully pot blockage are easily recognized, whereas blocked sewers and gully pot manifolds are difficult to recognize as the cause of flooding. This implies that there may be hidden calls referring to these classes that were erroneously labeled in other classes. The same goes for detailed consequence classes like flooding at bus stops and flooding in front of shops. It is likely that many calls in the "flooding of residential road" class could be assigned to more detailed classes if more information were available. This problem was overcome by focusing on aggregated classes: flooding in buildings, flooding on roads and health-related flooding consequences. These classes are easily distinguishable even for lay-people.

In this study risks were quantified by multiplying probability and consequences of flooding events. The probability is quantified per class of causes or consequences, based on the number of events in which a particular class is mentioned; consequences are quantified based on the assumption that each call represents flooding at one location. Analysis results showed that this is true for 95% of all reported incidents. This implies that missed calls have the following effect on quantified risk:

- cause class entirely missed for an incident: cause class probability underestimated
- consequence class entirely missed for an incident: consequence class probability underestimated
- locations missed for an incident: magnitude of consequences (number of locations) underestimated

Likelihood of missing calls depends on the abundance of calls per class, visibility of specific cause and consequence classes and felt urgency of citizens to respond. Gully pots en heavy rainfall are likely to be overrepresented in call data compared to gully pot connection and sewer pipe blockages since these causes are more easy to recognise. For the same reason, flooding of buildings and roads is more likely to be reported than health-related consequences.

For quantitative flood risk estimates this implies that the probability of gully pot blockages and heavy rainfall is likely to be correctly estimated, while the probability of other causes of flooding is likely to be underestimated. The probabilities of road flooding and building are also likely to be correctly estimated. The magnitude of consequences likely to be underestimated; it is more sensitive to uncertainty because every flood event that goes unreported directly influences consequences magnitude. Contrarily, probabilities depend on only one report per class per event; they are not influenced if incidents within the same event are missed.

Decision problem: need for urban flood reduction for the case of Breda

The influence of data uncertainty on quantitative risk analysis results and the consequences for decisions based on these results is investigated by analyzing a typical decision problem for a case study of flood risk management. Acquired insights are used to assess the impact of uncertainty in call data on flood risk analysis and related decisions in general.

The urban drainage policy plan for the city of Breda states the following maximum acceptable flooding frequencies for roads: once or twice per year for residential areas, once per two years for commercial areas and the city centre (#Breda, 2007). Flooding of buildings is not explicitly distinguished from flooding of roads; protection levels of buildings therefore depend on the relation of their building level to street level: building levels above street level are likely to experience less flooding, those below street level more frequent flooding than roads. This aspect is not addressed in the urban drainage policy plan.

Call data analysis for the city of Breda has shown that flooding frequencies exceed these maximum prescribed values and indicate a need for flood reduction. Table A.1 summarises the results of call data analysis, distinguishing between flooding of roads and buildings. The contribution of the three most important causes of flooding is also quantified.

Table A.1 Outcome of call data analysis: flood risk in nr of calls/km sewer length/year, city of Breda, period 2003-2007

Flooded Locations/km/yr	Roads	Buildings
Total all causes	**0.3**	**0.03**
Sewer overloading	0.003	0.002
Sewer blockage	0.003	0.004
Gully blockage	0.2	0.02
Total	**0.206**	**0.026**

Under the assumption that calls represent 2% to 30% of all real flood occurrences, the uncertainty range in real flood risk in terms of the number of calls per km sewer length per year is summarized in table A.2.

Table A.2 Uncertainty range of quantified flood risk in nr of calls/km sewer length/year, city of Breda, under the assumption that calls represent 2% to 30% of real flood occurrences.

Flooded	**Roads**			**Buildings**		
Locations/km/yr	#calls	Min real occurr	Max real occur	# calls	Min real occurr	Max real occurr
Sewer overloading	0.003	0.01	0.15	0.002	0.007	0.10
Sewer blockage	0.003	0.01	0.15	0.004	0.013	0.20
Gully blockage	0.200	0.67	10.00	0.020	0.067	1.00
Total	0.206	0.69	10.30	0.026	0.087	1.30

If, based on these results it is decided that flood risk should be reduced, various actions can be taken to address these flooding causes. Table A.3 summarises actions that can be undertaken to reduce flood risk for three individual causes of flooding: sewer overloading, sewer blockage and gully pot blockage.

Table A.3 Actions to reduce flood risk, for each of the three analysed flooding causes. Costs are estimated based on investment and maintenance costs for 2 case studies; effect is estimated based on expert judgment

Flooding cause	Action to reduce associated flood risk	Estimated cost M€/km/year	Estimated effect: flood risk reduction outcome (locations/km/yr)
Sewer overloading	Enlarge sewer pipe:	0.05*	Reduction by 16.67% of sewer overloading-related events
Sewer blockage	Increase cleaning frequency	0.05	Reduction by 14% of sewer blockage-related events
Gully blockage	Increase cleaning frequency	0.05	Reduction by 10% of gully pot blockage-related events

* based on €1000/m sewer length replacement, 40 years amortization, interest rate 0.04

Sewer overloading is reduced by implementation of a structural measure, enlargement of a sewer pipe. Blockages are reduced by increasing maintenance frequencies. Three measures of similar yearly investment cost are used for comparison. The effect of each of the measures is estimated based on expert judgment. The following assumptions are made with respect to the effects of measures in relation to investment costs:

- Enlargement of sewer pipe to reduce flooding due to sewer overloading: 1 location at a time: 1000 m pipe enlargement by replacement with larger diameter; Investment cost: €1,000,000 or €50,000 per year; Effect: reduction of 1 flooded location per year (where capacity is enlarged) out of average 6 flooded locations per year: reduction 1/6 or 16.67%.
- Increase sewer cleaning frequency: yearly costs of sewer cleaning are €180,000. Increase cleaning costs with €50,000/yr: cleaning frequency increases by 28%. Effect: comparison of 2 cases with different cleaning frequencies shows that 2 times higher cleaning frequency corresponds with half the number of calls/year (50% reduction). It is assumed that 28% increase of frequency results in 14% reduction in the number of calls/year
- Increase gully pot cleaning frequency: yearly costs of gully pot cleaning are €150,000. Increase cleaning costs with €50,000/yr: cleaning frequency increases by 33%. Effect: no data are available to estimate the effect of

increased gully pot cleaning. The expected bandwidth of reduction induced by 33% frequency increase is 0-33%. It is assumed that 33% increase in cleaning frequency leads to 10% reduction in the number of calls.

Table A.4 Uncertainty range of quantified flood risk in nr of locations/km sewer length/year, city of Breda, as a result of 3 different flood reduction measures, for road flooding and for building flooding.

Locations/km/yr Road flooding	Enlarge sewer pipe		Increase sewer cleaning frequency		Increase gully pot cleaning frequency	
	Min occur	Max occurr	Min occur	Max occurr	Min occur	Max occurr
Sewer overloading	0.008	0.125	0.010	0.150	0.010	0.150
Sewer blockage	0.010	0.150	0.009	0.129	0.010	0.150
Gully blockage	0.667	10.000	0.667	10.000	0.600	9.000
Total	0.685	10.275	0.685	10.279	0.620	9.300

Locations/km/yr Building flooding	Enlarge sewer pipe		Increase sewer cleaning frequency		Increase gully pot cleaning frequency	
	Min occur	Max occurr	Min occur	Max occurr	Min occur	Max occurr
Sewer overloading	0.006	0.083	0.007	0.100	0.007	0.100
Sewer blockage	0.013	0.200	0.011	0.172	0.013	0.200
Gully blockage	0.067	1.000	0.067	1.000	0.060	0.900
Total	0.086	1.283	0.085	1.272	0.080	1.200

The relation between actions and reduction of call numbers is summarized in table A.4. Comparison of the results in table A.4 with those in table A.2 shows that increasing gully pot cleaning frequency is most effective of the 3 strategies to reduce flood risk. Sewer pipe enlargement and increasing sewer cleaning frequency have only marginal effect on total flood risk. This follows from the small number of calls, thus flooded locations, related to sewer overloading and sewer blockage compared to gully pot blockage.

Table A.5 summarises investment costs and minimum and maximum flood risk estimates in terms of the number of flooded locations per year for the current situation and after execution of each of the three flood reduction measures. Figure A.1 gives a graphical representation of the data in table A.5. It shows that for the same investment level, increasing gully pot maintenance is the most effective measure to reduce flood risk. The effect of increased gully pot cleaning frequency is about 10 times higher than that of enlarging sewer pipe capacity or increasing sewer cleaning frequency. Uncertainty in flood risk results derived from call data does not influence this conclusion. It only influences absolute values of quantitative flood risk outcomes.

Table A.5 Summary of yearly investment costs and resulting flood risk in terms of the number of flooded locations/km sewer length/year, for 3 flood reduction measures. Uncertainty margins are based on the estimated representation of flood-related calls compared the real number of flooded locations

Effect of investments; nr. of flooded locations/km/yr	**Do nothing**	**Enlarge sewer pipe**	**Increase sewer cleaning frequency**	**Increase gully pot cleaning frequency**
Investment	€0/yr	€50,000/yr	€50,000/yr	€50,000/yr
Road flooding				
Min (calls represent 30% of real occurrences)	0.687	0.685	0.685	0.620
Max (calls represent 2% of real occurrences)	10.300	10.275	10.279	9.300
Building flooding				
Min (calls represent 30% of real occurrences)	0.087	0.086	0.085	0.080
Max (calls represent 2% of real occurrences)	1.300	1.283	1.272	1.200

Sensitivity of decisions to data uncertainty and data need for risk-based decisions on urban flooding

1. Identify most vulnerable components in sewer system with respect to causing flooding. Vulnerable components with respect to flooding are those components that are most likely to fail and contribute most to flood risk. Call data have shown to provide sufficient accuracy to identify gully pots as the most vulnerable component in sewer systems, with respect to flooding. Gully pot blockages stand out against other causes to such an extent that uncertainties in call data do not influence this conclusion. In order to distinguish between component vulnerabilities that differ less

conspicuously from others, more accurate and more complete data sets are needed. In particular the relative contributions of sewer blockages and heavy rainfall should be supported by additional data, since this distinction cannot be made by call data based on above-ground observations and ex post analysis by experts.

2. Identify most vulnerable locations to flooding in catchment. The vulnerability of locations to flooding can be interpreted in various ways: locations that suffer flooding most frequently, those that suffer most severe consequences or those that raise most protest from citizens. The first two aspects are summarised in quantitative flood risk assessment, the latter is revealed in call texts and letters and petitions to local authorities. Flood risk assessments are typically aiming to be objective; citizens' protests are subjective. The use of call data for flood risk analysis implies introduction of a degree of subjectivity into quantitative risk assessment outcomes. This effect is diminished by the large number of call data: the call database shows that the maximum number of calls per street represents 1% of the total number of calls. This indicates that the data are not susceptible to bias introduced by excessive calling of one or a few individuals and that call data are sufficiently representative to identify most vulnerable locations in a catchment.
3. Evaluate urban drainage systems respect to urban flooding standards. Urban flooding standards mostly define a maximum flooding frequency or a maximum surcharge frequency; some distinguish between different occupational land uses. Call data analysis results in an estimate of flooding frequencies and of flood risk; they provide a sufficient level of detail to distinguish between occupational land uses and even between road types and buildings uses. Call data provide a better basis to check compliance with standards than hydrodynamic model simulations or singular-event-based evaluation, because they include a wider range of flooding causes and consequences. The main drawback of call data for risk quantification is that they represent a sample of unknown size of real flooding incidents. This means that quantitative flood risk based on call data always underestimate

the true flood risk, while the degree of underestimation is unknown. Still, it provides a risk estimate that is closer to reality than model simulations that focus on heavy rainfall events and do not include asset failures as a cause of flooding.

4. Decision to prioritise locations for investments to reduce flood risk. This decision problem is similar to decision 2, if prioritisation takes place according to flood risk. If other aspects are taken into account, like possibilities to combine investments with other maintenance or construction activities in order to gain efficiency, additional data regarding these respects is needed.
5. Decision in what flood reduction measure to invest, for a certain location or area, in order to most efficiently reduce flood risk. Call data analysis can identify the main causes of flooding for a particular location. Besides this, information about the effect of flood reduction measures is needed. The effect of structural measures can be estimated based on model simulations; little information is available to estimate the effect of different maintenance frequencies. If differences between cause incidences are large, call data are sufficient to decide how flood risk can be most efficiently reduced. If differences are small, call data do not provide sufficient accuracy to distinguish between causes. Additional data must be collected to assess flood risk more accurately and to estimate the effect of flood reduction measures, especially varying maintenance frequencies.

Most decision problems require data collection in addition to call data to provide more accurate risk assessments and to allow distinctions between options that differ little. Ideally, data would provide a full sample of flood occurrences, including cause and consequence details. This would require a high temporal and spatial resolution of data collection. A dense sensor network, e.g. one that is constituted of sensors in gully pots and house connections could provide such information. The installation and operational costs of such of network are high and the reliability depends on the quality of the sensors, data transfer, storage and analysis. Alternatively, satellite images can provide high-resolution spatial data, yet the temporal resolution is low, typically weekly or monthly data collection. Another drawback is that satellite images are disturbed by clouds, while satellite radar images are not well fit for interpretation of flooded surfaces, especially at the level of detail require for the urban scale.

Since the aim of urban flood protection is to protect citizens and their possessions from the harmful effects of flooding, citizens' observations are a valuable source of information to be used in flood risk analysis. The use of call centres to register citizens' observations and complaints is widely spread among authorities; public, e.g. municipalities, as well as private, e.g. water companies. The quality of call data can be enhanced in several ways to improve the reliability of flood risk analyses. Additionally call data can be complemented with data from other sources.

Call data have several advantages over other types of flood data, like data from water level sensors and ex post interviews with people affected by floods. Sensors have the advantage of providing more objective measurements; yet to collect details on flooding causes and consequences, a combination of sensors would be needed which results in an expensive monitoring set-up. Ex-post interview have the drawback of collecting information with a certain delay, which inevitably result in information loss, since interviewed people may have forgotten details of not have paid attention to certain information details.

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Appendix 2

Automatic classification of call data for quantitative urban flood risk analysis

Introduction

In the past, comprehensive flood risk analyses have been limited by a lack of data or a lack of knowledge of the complex interactions between rainfall conditions and flooding consequences (Apel et al., 2006). Although it is widely recognised that hydrodynamic models are indispensable tools for successful flood management, the development of such models is to date limited by a lack of spatially distributed evaluation data (Werner et al, 2005; Schumann et al., 2008). Monitoring networks in urban drainage systems can provide the required information, if they have sufficient spatial density to detect all flood events throughout urban areas. In practice, monitoring locations are limited to pumping stations, overflow weirs and some additional points e.g. at special constructions. This density is largely insufficient to register in detail all flood incidents in an urban area. Additionally, monitoring networks in urban drainage suffer from data loss due to sensor failure, communication failures etc. (Dirksen et al., 2009).

Municipal call centres register information on urban drainage problems observed by citizens. The network of callers is potentially dense since every citizen can be assumed to have access to a telephone. Though calls do not necessarily give complete coverage of flood incidents, because there is no guarantee that a call is made for every event, it is one of the best sources to provide indication of events unacceptable to citizens: citizens make calls to point out abnormal situations that they citizens want to see solved.

Calls related to urban drainage cover a variety of details on problem causes and consequences that traditional monitoring and modelling find difficult to address, such as details on in-house flooding and maintenance-related problems like pipe blockages. The drawback of this type of data is their unstructured nature: call texts vary in the level of detail and type of information provided, depending on what is provided by the caller and how much of that is reported at the call centre. To be able to use call information in flood risk analysis, calls must be screened and classified to obtain consistent output that can be used in quantitative analysis.

Even though many municipalities have a call register, 109 out of 190 municipalities that took part in a recent inquiry in the Netherlands (RIONED, 2007), few use it to analyse the occurrence of problems in their infrastructure. One reason is that manual classification of calls is time-consuming due to the large numbers of calls: hundreds or thousands per year per municipality. Yet call data have proven to provide valuable information to detect causes and consequences of urban flooding that cannot be provided by other types of monitoring data (Arthur et al., 2009, ten Veldhuis et al., 2009).

This chapter examines the possibility of automatic call classification based on call texts for the purpose of urban drainage system analysis and quantitative risk assessment. To this end, some well-known classification routines are tested by application to two call databases containing about 6300 calls each.

Automatic classification of municipal calls may be compared call routing where a call is routed to a destination based on words or grammar fragments in call texts (Garfield and Wermter, 2006; Gorin et al., 1997). The task of call classification differs from call routing for helpdesk applications where routing is preferably based on a minimum of information, e.g. only the first caller's utterance. Call classification for application in risk assessment tries to retrieve as much information as possible from a call. Municipal calls typically contain natural spoken language (Gorin et al., 1997) that comes from one or two sources: call centre employees write down in telegram style what callers have actually said and in part of the databases technical employees enter text on how they handled calls. The information content of both texts differs and the second text may even contradict what was stated in the first, because a problem was found to be different from the one described upon on-site investigation.

This article is structured as follows: first, principles of classification pattern recognition are discussed in brief, followed by a description of the datasets that are used for automatic classification experiments. After that, the set-up is given of some initial automatic classification experiments that have been conducted.

The results are outlined, followed by a discussion and some additional notes and observations. Finally, conclusions derived from the outcome of our experiments are presented.

Materials and methods

Pattern recognition

Call classification is a special case of pattern recognition, a research field that aims to assign observations to classes based on observations' characteristics, expressed as a number of features.

There are numerous books and other texts that provide a good introduction to the field of pattern recognition (e.g. Duda et al. (2001), Jain et al. (2000) and Bishop (2006)), while various more dedicated texts concerned with text categorization are also available (e.g. Sebastiani, 2002). Here we only provide a brief sketch of some of the essentials that should enable the reader to understand the illustrations given and the basic experiments carried out in this work.

One of the main questions in pattern recognition studies is how, and to what extent, one can decide on the class label of a new object, based on a comparison of object characteristics with those of objects with known labels? The basic idea is that particular, typically statistical patterns in the characteristics of an object provide weak or strong clues about the true class label of this object. E.g. a relatively high number of occurrences of the words "yellow" and "submarine" lowers the probability that a text is about Elvis. The initial collection of observations for labelled objects is used to try to find general patterns and relations that can subsequently be used to predict the label of new objects.

In pattern recognition language a label predictor is referred to as a classifier, the act as classification, the overall error made in this prediction is called the classification or generalization error (in a way this is the probability that a new object will be labelled with the wrong label), while finding the patterns and relations in the training data is called learning or training. In addition, the different labels are called classes and the characteristics chosen to describe the objects are features. One important step in pattern recognition can accordingly be stated as devising features based on which successful classification can be performed. Another is the choice of the actual classifier that is to be trained using these features and the associated class labels. There is an immense amount of literature on various types of classification approaches and procedures. We discuss two simple schemes, first nearest neighbour (1NN) classification and nearest mean classification (NMC), that should give a good initial impression of how such classification could be performed.

Having measured N features for every object -- this could for example be word counts of “submarine”, “yellow”, “haze”, “purple” or any other word that might help us to distinguish different classes from each other -- we can represent every object as a vector in an N-dimensional space (the section on word counts, which can be found below, details our particular choice of features). Now, the 1NN classifier operates in this vector space and labels new objects with the same label as the object that is nearest to the new one and for which one knows the label. Nearest is in terms of the distance between the feature vectors in the vector space. The idea behind 1NN is simple and intuitive: the nearer features are to each other, the more similar the original objects probably are, and therefore chances are high that their labels are also the same. NMC, on the other hand, relies on more global statistics, but is no more complicated than 1NN. In the classifier training phase, one determines the mean of every class, i.e., the average feature vector for every category is computed, which again is an N-dimensional vector. In the classification phase, every new object is assigned to the class mean that is closest, i.e., it gets the label belonging to that class.

A final concept that needs to be introduced is the learning curve. Learning curves plot the generalization error with varying training set size or feature set size. The first type of curves investigates how much there is to gain from adding more and more data to the training set and can be used to decide whether it is worth the effort to collect more labeled data. The latter type of curves provides insight into how a classifier behaves under a varying number of features for a particular fixed number of training objects. As it turns out, adding more and more features, and hence more and more information about the individual objects, does not necessarily mean that classification performance will improve. This maybe counterintuitive behavior of classification schemes is often coined the curse of dimensionality (Duda et al., 2001; Jain et al., 2000; Bishop, 2006).

Available datasets for classification

Two call databases were available for this study, including all calls related to urban drainage for 2 municipalities in the Netherlands: Haarlem and Breda. The datasets consist of 6991 and 6361 calls respectively over a period of 5 and 10 years (Table 1).

Table A2.1 Summary of data for two cities with available datasets: sewer system characteristics, call data in municipal call register

Data case study	Haarlem	Breda
Number of inhabitants	147000	170000
Length of sewer system (% combined)	460 km (98%)	740 km (65%)
Total surface connected to sewer system	1110 ha	1800 ha
Total number of gully pots	42500	80000
Period of call data	12-06-1997 to 02-11-2007	31-01-2003 to 23-10-2007
Total number of calls on urban drainage	6359	6980
Length of data series	3788 days	1726 days

Table 2 gives some examples of call texts from the call datasets. The examples illustrate how the type of information and details vary between call texts. Features are selected from these call texts to be used for automatic classification.

Table A2.2 Example of call texts

Date	Call text
2-5-2002	On the Karel Doormanlaan near the apartment complex Spaarnhoven, much water remains on the street after a storm. Elderly people have trouble entering the building. Can this be solved? Action: 10/05, Gully pot cleaned.
25-10-2005	At the busstop on the Zuiderzeelaan and the busstop to the west 2 or 3 gully pots are blocked. The busstop is flooded. Action: 2 gully pots cleaned and flushed
15-5-2007	This caller on the Veenbergstraat nr 20 has problems with moisture under his residence. There are also rats in the residence. She thinks it has to do with the bad condition of the sewer in the street; the street is full of pits and holes. Please contact caller and take a look in this street. Action: Solved by owner.
22-5-2007	Flooding of bicycle tunnel. 14-06-07 situation ok, problem solved

Definition of classes

We used sets of manually classified data from a quantitative flood risk analysis study (ten Veldhuis et al., 2009). Class definitions were defined based on a fault tree analysis; this resulted in six classes that correspond with potential causes of urban flooding (table 3). The calls were manually classified by technical specialists based on the information in the call texts. The manually classified datasets provide the training and test sets for the development of an automatic classification procedure.

Table A2.3 Class definitions used in manual classification and manual classification results

	Class definition	# entries/class Breda	# entries/class Haarlem
1	Blocked inflow process (gutters, gully pots, manifolds)	1767	2455
2	Sewer overloading by heavy rainfall	20	12
3	Blocked sewer pipe or pump	222	32
4	Blocked or broken house connection	131	61
5	Problem related to other urban water system components: groundwater/surfacewater/drinking water	47	124
6	Not relevant	1301	493

Selection of features

The basic features employed in this work are based on individual words in the call texts, a typical choice in text classification. More complex word combinations and grammatical constructions were not used.

To start with, call texts are split into separate words. This gives 216231 separate words spread over 8544 vocabulary units, i.e., unique words. In order to reduce the size of the database, all words that occur only once have been removed. This reduces the number of different words to 4489. Words of only 1 or 2 characters have been removed as well since most of these are words with low information content like the Dutch definite article “de”. This results in a list of 4378 words that are used to compile an initial dataset of word count features in the following way. Every single call text, of the total of 6359 and 6980 call texts, is represented by a 4378-dimensional feature vector in which every dimension, every feature, corresponds to the number of times a particular word, from the 4378 words, occurs in the call text. This feature set size is very large, which implies that a very large number of training records is needed for training and calculation times for classifier training and testing are long. Additionally, a high-dimensional feature space may result in the earlier-mentioned curse of dimensionality. Therefore, latent semantic analysis was applied to reduce the initial number of features before starting the experiments. Latent semantic analysis is a multivariate analysis technique that is very similar to well-known principal component analysis and it selects and combines features based on their (relative) importance (Manning et al., 2008). The result is a reduced list of 1024 features that are ranked according to decreasing importance.

Classifiers for automatic call classification experiments

Three classifiers were tested to give a first idea of the applicability of automatic classification of municipal calls. Two of them have been introduced above, i.e., the nearest mean classifier (NMC) and the first-nearest neighbor (1NN) classifier. A third classical and well-known classifier we used in our experiments is Fisher's linear discriminant (FLD), also referred to as linear discriminant analasis (LDA) (Bishop, 2006, Duda et al., 2001, Webb, 2002). These classifiers were chosen because of their straightforward structure and associated short calculation times, which facilitates our experiments. Moreover, results obtained employing these relatively straightforward classifiers, which can be seen as representatives from different parts of the classifier spectrum (Mansilla and Ho, 2004)., should give an indication of their potential use of pattern recognition in automatic call classification.

Experimental set-up: Learning curves

For practical application of automatic call classification, classifiers are to be trained anew for each new call center dataset. The natural way to proceed is to provide a training set from the dataset for which calls have been classified manually. The smaller the size of the dataset that is needed for training, the fewer calls need to be classified manually and the less time-consuming application to new datasets will be. This in turn enhances the usefulness of automatic call classification for practical applications. Dataset size depends on the number of features needed for classification and on the number of records needed for classifier training. Classifier performance for different dataset sizes is tested in learning curve experiments. Three experiments have been conducted with the available datasets of 6359 and 6980 call records and 1024 features.

- Learning curve for feature set size

A learning curve of classification error as a function of the number of features shows how many features are needed to obtain a minimum classification error. As features set size increases, more information is available for classification; more features also require a higher number of training records

- Learning curve for training set size

A learning curve of classification error as a function of the number of training objects provides information to determine the required dataset size, for a given number of features, to obtain sufficient accuracy of the classification results. In practical applications, sufficient accuracy depends on the sensitivity of applications to classification errors. For new datasets the required dataset size determines the number of records that is to be trained manually.

Application of automatic call classification results for quantitative fault tree analysis

The applicability of automatic call classification results in quantitative risk analysis is tested in a quantitative fault tree analysis for urban flooding. Figure 1 shows the fault tree model that was used, including four failure mechanisms that can give rise to urban flooding. Three failure mechanisms are related to urban drainage systems and are represented as basic events in the tree: blockage of inflow processes, e.g. blockage of gully pots gully pot connections, hydraulic overloading as a result of heavy rainfall and blockage of sewer pipes and pumps. Problems in other water systems are not analysed in detail; failure related to these water systems are lumped into an undeveloped event, represented by a diamond symbol instead of a circle. More information on the construction of the fault tree can be found in (Sebastiani, 2002). The fault tree analysis results obtained based on automatically classified calls are compared to the results based on manual classification of the calls.

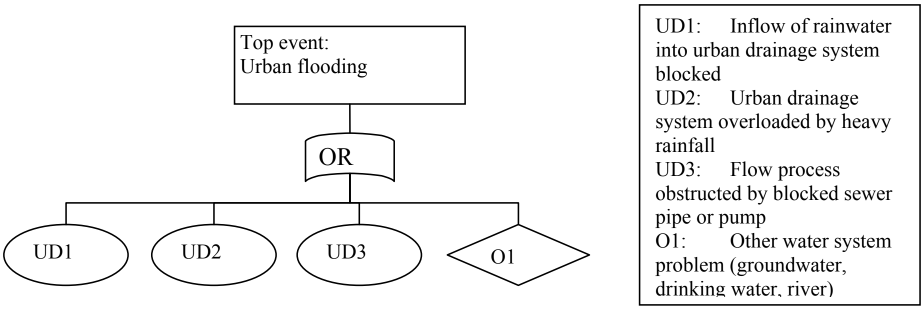

Figure A2.1. Fault tree model for urban flooding used to test sensitivity of quantitative fault tree analysis results to errors in automatic classification results.

Results

Learning curve number of features

Figure 2 shows learning curves for the Breda and the Haarlem datasets, for the three classifiers LDA, NMC and 1NN, for increasing feature set size. The classification error rate, i.e. the rate of wrongly classified calls out of the total number of calls, has a clear minimum for LDA and NMC as a results of the counter-intuitive effect of increasing error-rate with increasing feature set size. The error-rate in the 1NN curve is almost insensitive to the size of the feature set; error rates for all feature set sizes are above the minimum errors for LDA and NCM. The optimum number of features, based on these learning curves, is 200 for LDA and 300 for NMC. The plots also show that the minimum error rate for Breda is higher than for Haarlem. This will be explained later in this chapter.

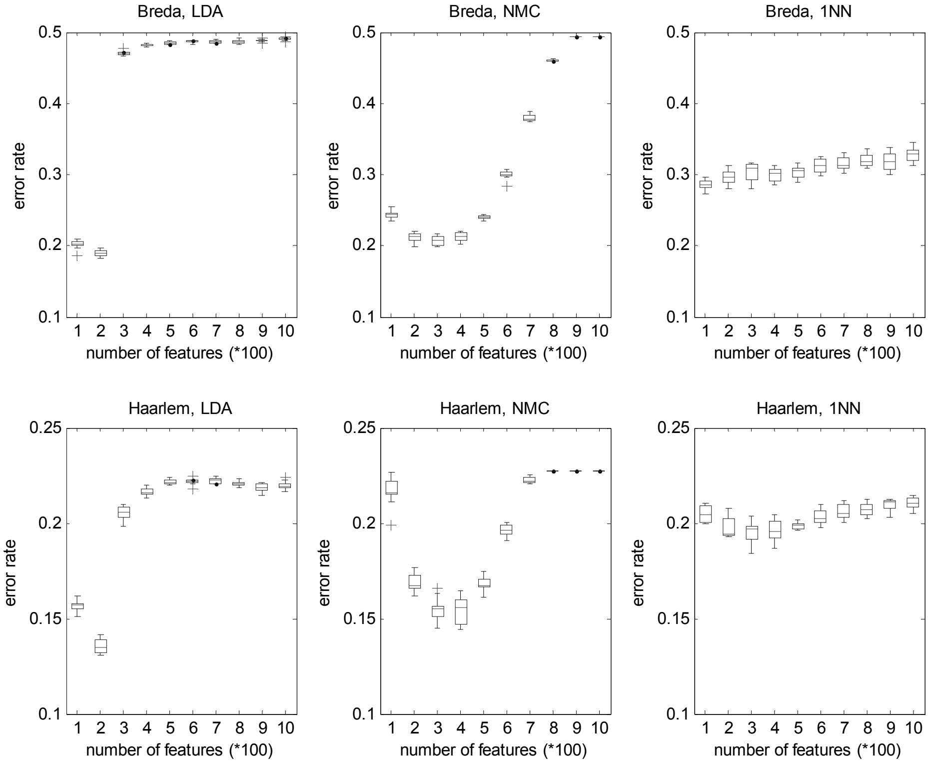

Figure A2.2 Learning curves for feature number increasing from 100, with steps of 100 to 1000, for the Breda and Haarlem datasets. 50% of the dataset is used for training and 50% is used for testing. Boxplots are based on 10 repetitions of the training and testing procedures of the classifiers.

Learning curve training set size

Learning curves for increasing training set size were created by successively using 10% up to 90% of the dataset for training and the other 90% down to 10% of the dataset for testing. Feature set sizes of 200 for LDA, 300 for NMC and 300 for 1NN were applied, based on the learning curves for feature set size.

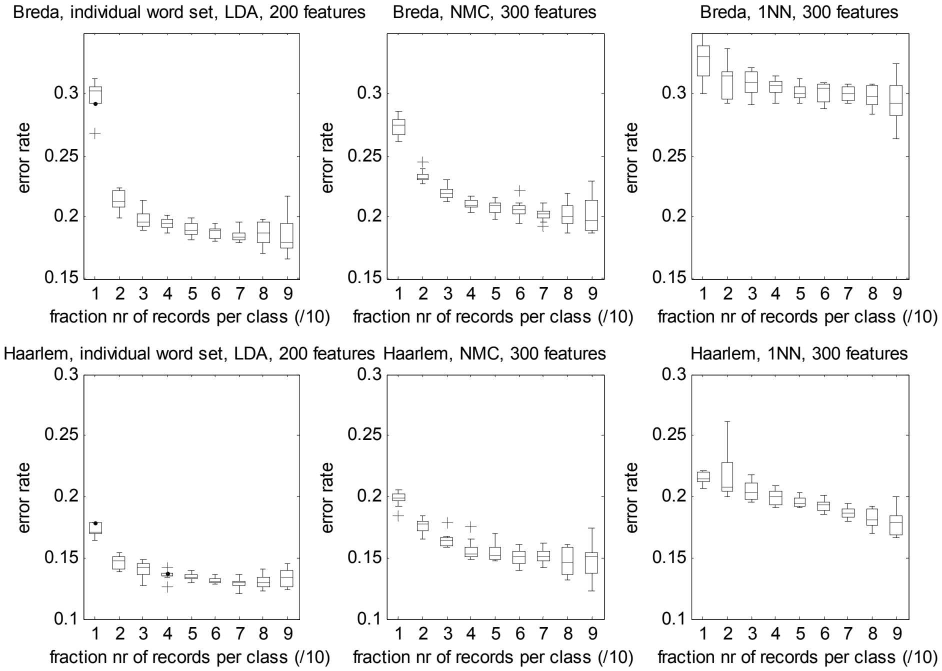

Figure A2.3 Learning curves for increasing fractions 0.1 to 0.9 of the dataset used for training; the remainder of the dataset is used for testing. Boxplots are based on 10 repetitions of the training and testing procedures of the classifiers.

Figure 3 shows how error rates decrease with increasing training set size; the uncertainty in error rate increases as a result of smaller test sets as training set sizes grow. The lowest mean error rate for the Breda dataset is 0.18 and is obtained applying LDA, when 90% of the dataset is used for training, i.e. 6282 training records. The lowest mean error rate for the Haarlem dataset is 0.13 and is obtained applying LDA, when 60% or more of the dataset is used for training or at least 3815 training records. The lower error rate for the Haarlem dataset is explained by the presence of one large class that contains 77% of the call records. This implies that if all records were erroneously assigned to this largest class, the error rate would be 0.23. The Breda dataset is more balanced; the largest class contains 51% of the call records, corresponding with an error rate of 0.49 if all records were assigned to this class.

In order study the nature of the classification errors in more detail, class confusion matrices were created that show the results for all classes for both the true (manually classified) labels and the labels assigned through automatic classification. Table 4 shows the confusion matrix for LDA, for the Breda dataset; correctly labelled records are on the matrix diagonal, erroneously labelled records are off-diagonal.

Table A2.4 Class confusion matrix for the results of LDA, for 200 features and 50% of the dataset used for training and for testing. Classification error rate: 0.20

True labels		**Assigned labels**						**Sum**	**Σcorrect**
		1	**2**	**3**	**4**	**5**	**6**	**True**	**/Σtrue**
1	Inflow process blocked	**1503**	19	30	27	2	186	1767	0.85
2	Overloading by heavy rainfall	7	**7**	0	1	0	5	20	0.35
3	Blocked sewer pipe or pump	36	1	**108**	9	2	66	222	0.49
4	House connection problem	12	6	11	**79**	0	23	131	0.60
5	Other water system problem	5	0	0	2	**29**	11	47	0.62
6	Not relevant	132	5	55	20	12	**1077**	1301	0.83
	Sum assigned	1695	38	204	138	45	1368	**3488**	0.80

The matrix shows that the classifier has special difficulty in distinguishing records for the smallest class, class 2, which has the lowest correct/true ratio of 0.35. This is probably due to the lower number of available records for training in this class. Surprisingly, class 5, which also has a small class size, has a correct/true ratio of 0.62, higher than the ratio for the larger classes 3 and 4. The confusion matrix for NMC (not shown here) has a correct/true ratio above 0.5 for all classes except class 2. For the Haarlem dataset, LDA gives a low ratio for class 2 of 0.08, while NMC gives a ratio of 0.58. Class 5 scores are good for LDA and NMC for both datasets, which implies that class 5 is easy to recognise for these classifiers. Classification results for class 1 are robust: correct/true ratios are above 0.85 for LDA and NMC for both datasets. This is a result of the large size of class 1 compared to other classes.

Sensitivity of fault tree analysis results to errors in automatic call classification

Probabilities of occurrence of events in the fault tree were calculated based on manual and automatic call classification results for the events in the tree. Automatic classification results for LDA, 200 features are used. Probabilities are derived from the number of calls in each class, divided by the number of independent flooding events. Quantitative fault tree analysis is based on Monte Carlo simulation: the occurrences of basic and undeveloped events are simulated with the use of a random number generator. Each simulation that results in failure is stored, with the combination of causes that led to flooding.

A Monte Carlo simulation for the case of Breda with manually classified calls results in a probability of flooding of 0.68 per event per 100 km sewer length. A Monte Carlo simulation with automatically classified calls results in a probability of flooding of 0.66/event/100km. Tables 5 and 6 show the contributions of the basic events to the overall probability of flooding for the 2 simulations. The results show that errors in the automatic classification procedure have only limited influence on the outcomes of the fault tree calculations. The overall probability of flooding remains approximately the same: the contribution of the main failure mechanism, blockage of inflow processes is 92% for both manual and automatic classification results. The contribution of the smallest failure mechanism, overloading, changes by 1%, from 2% for manual classification to 3% for automatic classification.

Table A2/5. Results of 10,000 Monte Carlo simulations with the fault tree model for Breda, manual classification

Flood causes	Contribution to overall probability of failure
Inflow process blocked	9212 out of 10,000 (92%)
Overloading by heavy rainfall	156 out of 10,000 (2%)
Blocked sewer pipe or pump	1654 out of 10,000 (17%)
Other water system problem	344 out of 10,000 (3%)

Table A2.6. Results of 10,000 Monte Carlo simulations with the fault tree model for Haarlem, automatic classification

Flood causes	Contribution to overall probability of failure
Inflow process blocked	9153 out of 10,000 (92%)
Overloading by heavy rainfall	314 out of 10,000 (3%)
Blocked sewer pipe or pump	1572 out of 10,000 (16%)
Other water system problem	339 out of 10,000 (3%)

Discussion

Learning curves for varying feature set sizes show that LDC and NMC suffer from the "curse of dimensionality": minimum error rates are obtained for feature set sizes of 200 and 300 and error rates rise rapidly for larger feature set size. 1NN is less sensitive to feature set size and error rates vary only little with varying feature set sizes.
Error rates decrease as the training set grows, up to half the total dataset; larger training set sizes give only limited improvement of the error rate. This implies that a training set size of about 3000 records is needed for application of the LDA and NMC classification schemes to new call datasets. The 1NN classification scheme performs poorly for this classification task: it results in high error rates compared to LDA and NMC. In this case, error rates decrease more slowly with increasing training set size and have not yet reached a minimum when 90% of the dataset is used for training. Potentially, the addition of more records could bring the performance of 1NN to the level of LDA or NMC, but in the current situation one of the latter classifiers is clearly to be preferred over 1NN.

Confusion matrices for LDA and NMC show that small classes are most sensitive to classification errors. This implies that classification accuracy for these classes could improve if data sets with larger numbers of calls in these classes were available. In practical applications, call numbers increase with time as a call centre stays in operation. As data set size grows, larger training and test sets become available and classifiers can be retrained to obtain higher accuracy. It is more efficient, and possibly equally effective, to purposefully acquiring examples of the smaller classes only in order to improve their accuracy. Obviously, overall performance improvements might be obtained by choosing yet another classification technique from the large number of approaches that have already been proposed in the literature (see [referenties naar PR en ML literatuur]). What is potentially more powerful is to develop classifiers and construct features that are more dedicated to handling municipal call data as the integration of the correct prior information should generally be beneficial. Nonetheless, the power and potential of the presented methods and their variations should be apparent from the initial study we offered.

Minimum error rates of 0.18 and 0.13 are obtained for the datasets of Breda and Haarlem, for the LDA classification scheme. Application of classification results in quantitative fault tree analysis shows that error rates of 0.18 and 0.13 for Breda and Haarlem do not distort the outcomes of the analysis: the ranking of failure mechanisms and their contributions to the overall probability of flooding change by at most 1%.
For other applications in risk assessment absolute probabilities of occurrence of individual classes may be needed; in that case error rates of more than 30%, as obtained in the presented applications for small classes, are likely to be unacceptable. For such applications, larger data set sizes for smaller classes are required or alternative, more elaborate classification schemes could be explored to obtain lower error rates. The same is true if calls are used to identify vulnerable locations for flooding, for specific failure mechanisms. In that case, correct labelling of individual calls is important which is more sensitive to classification errors than the total number of calls per class.

Instead of training a classifier for anew for each individual call database, the trained classifier of one database can be directly applied for classification of a new database. If the classifier has good portability from one database to another, it will provide acceptable classification results for the new database. This means no new classifier needs to be trained to classify new databases. This offers opportunities for broad application of automatic call classification: once a classifier with good portability is found and trained, many databases can be trained with the same classifier. Whether classifiers with good portability can be found and trained is a topic for further research.

Conclusion

The results of this study show that simple automatic classification schemes like LDA and NMC can classify call datasets with error rates below 0.2. Classifiers perform better for large class sizes than for small classes, probably due to the larger number of available training objects. The presence of one large class in the Haarlem dataset, containing 77% of the call records results in a low error rate of 0.13; for the Breda dataset with a more balance distribution of calls over classes, an error rate of 0.18 can be obtained. Application of automatically classified datasets in quantitative fault tree analysis shows that obtained classification accuracy is sufficient to correctly rank failure mechanisms according to their contributions to the overall probability.

Acknowledgement

The authors want to thank Breda and Haarlem municipalities for making available the data in their call centre database. We also would like to thank the people that develop and maintain the Matlab pattern recognition toolbox PRTools (prtools.org; van der Heijden, F. and Duin, R. and De Ridder, D. and Tax, DMJ (2004). Classification, parameter estimation, and state estimation: an engineering approach using MATLAB. John Wiley & Sons Inc), especially Dr. R.P.W. Duin.

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Appendix 3

Risk curves for urban pluvial flooding

This appendix presents risk curves for all consequences of urban pluvial flooding used in the analysis of data from the municipal call centre of the city of Haarlem, over the period 1997 to 2007.

Introduction

Risk assessment studies often present the expected value of risk as a summary value for a range of probabilities and consequences or they give a risk value for a given scenario, e.g. a certain return period. Risk curves go one level deeper and present risks for a range of probabilities and consequences (Kaplan and Garrick, 1981). Risk curves for urban flooding depict flood damages on the horizontal axis and their associated exceedance probabilities on the vertical axis. Figure A3.1 gives an example of a risk curve, for a flood damage x_i varying from 0 to 100 on the horizontal axis and associated exceedance probabilities on the vertical axis.

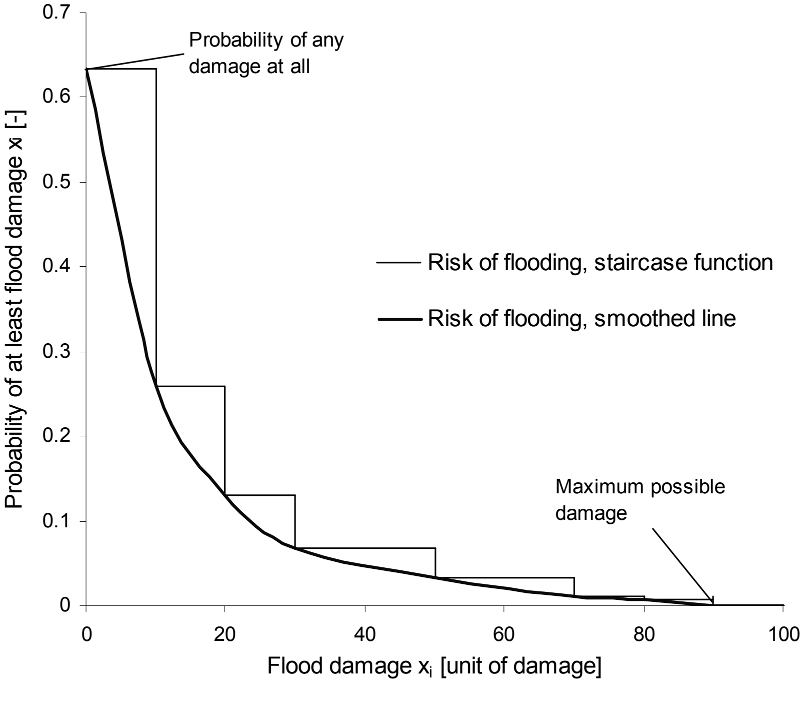

Figure A3.1. Example of a risk curve (based on: Kaplan and Garrick, 1981): a complementary cumulative distribution function (CCDF), i.e. the probability of exceeding a given damage

Risk curves for urban flooding depict flood damages on the horizontal axis and their associated exceedance probabilities on the vertical axis. The intersection of the curve with the vertical axis gives the probability of any damage at all; the intersection with the horizontal axis gives the maximum possible damage, with zero probability of exceedance. Values in between are interpreted as probabilities of at least damage x_i; this probability increases or remains constant for decreasing damages. The staircase function is the plotted result of a series of points representing damage for scenario i and the exceedance probability for each scenario. The staircase function can be regarded as a discrete approximation of a continuous reality, represented by the smooth curve. The area below the risk curve is a measure of total risk; the further risk curves shift to the top-right-hand corner of the graph, the higher their associated total risk. The advantage of risk curves compared to one value for expected risk is that risk curves give insight into the contributions of small and large damages to flood risk. If flood risk is mainly associated with small damage incidents, the curve decreases steeply for small damages and more gently for high damages, as is the case of the example in figure A3.1. If large damages mainly compose risk, the curve is more or less flat for small damages and steeply decreases at large damage values.

Preparation of call data to construct risk curves

Table A3.1 summarises results of call classification for consequence classes of urban pluvial flooding, for the case of Haarlem. Sixteen consequence classes are distinguished, based on information in the call texts. Classified calls are subsequently assigned to independent rainfall events, as described in chapter 2 of this thesis. This results in a matrix of events and consequence classes; each cell in the matrix gives the number of calls received per event per consequence class. For each consequence class, the incidence of numbers of calls per event is determined. The result is illustrated in table A3.2, where X is the number of call per event per consequence class. A small number of calls per consequence class per event means that the amount of associated flood damage is small. Table A3.2 shows that this is the case of most events: call incidence 1 per event per

class (X=1) occurs most frequently. Call incidence of more than 10 per event (X>=10) occurs only for 3 consequence classes.
The results in table A3.2 are used to calculate probabilities of occurrence of consequence classes. The occurrence of events is assumed to be a Poisson process, which implies that the probability that an event will occur in any specified short time period is approximately proportional to the length of the time period. The occurrences of events in disjoint time periods are statistically independent. Under these conditions, the number of occurrences *x* in some fixed period of time is a Poisson distributed variable:

$$p_X\left(x\right)=\frac{\left(\lambda t\right)^x e^{-\lambda t}}{x!} \qquad \text{(A3.1)}$$

Where: $p_X\left(x\right)$: probability of *x* occurrences in a period of time t
λ : average rate of occurrence of events per time unit

Since failure occurs due to the occurrence of 1 or more events, the probability of failure can be calculated from:

$$P\left(X\geq 1\right)=1-p_X\left(0\right)=1-e^{-\lambda t} \qquad \text{(A3.2)}$$

Where: $P\left(X\geq 1\right)$: probability of one or more events
$p_X\left(0\right)$: probability of no events

The time period t can be chosen at will; the longer t, the higher the probability of occurrence. The time scale is preferably chosen so as to fit the frequency of events. In the case of urban flooding flood events typically occur up to several times per month and the duration of events is in the order of several days. A time period of 1 week fits the event occurrence frequency and has been chosen for the construction of risk curves.

Table A3.1 Call classification results for aggregated and for detailed flood consequence classes, for the cases of Haarlem, for a period of 10 years

Primary functions	**Consequence classes**	**Nr. of calls/ class:Haarlem**	
		(nr)	(%)
Human health: physical harm or infection	Flooding with wastewater	61	3.4
	Manhole lid removed	7	0.4
Protection of buildings and infrastructure: damage to public and private properties	Flooding in residential building (house/garage/shed)	116	6.5
	Flooding in commercial building (shop/storage hall)	34	1.9
	Flooding in basement	173	9.7
	Water splashes onto building	26	1.5
	Flooding of gardens/park	74	4.1
Prevention of road flooding: traffic disruption	Flooding in tunnel	13	0.7
	Flooding at bus stop/taxi stand	18	1.0
	Flooding in shopping street/place/commercial centre	117	6.5
	Flooding in front of entrance to shop/bar/library/hospital	55	3.1
	Flooding in front of entrance to residential building	65	3.6
	Flooding on residential/main street	655	36.5
	Flooding on cycle path	133	7.4
	Flooding on sidewalk/footpath	73	4.1
	Flooding on parking space	173	9.7
Total number of calls relevant for flooding		1793	100%
No consequence mentioned		3563	
Consequence other than flooding		1005	
Total number of calls		6361	

Table A3.2 Incidence of events with X calls per class, for consequence classes E0, E101 to E116. Call incidence above 0 is shaded in grey.

X: number of events with X (for X 1 to 30) calls per class; E101: Flooding in residential building; E102: Flooding in commercial building; E103: Flooding in basements; E104: Flooding on streets; E105: Flooding of tunnel; E106: Flooding on cycle path; E107: Flooding on footpath; E108: Flooding on parking space; E109: Flooding at bus stop; E110: Flooding with wastewater; E111: Manhole lifted due to flooding; E112: Flooding of green areas (parks/gardens).

X	E0	E101	E102	E103	E104	E105	E106	E107	E108	E109	E110	E111	E112
1	100	38	15	33	75	9	42	37	46	17	25	4	27
2	61	6	5	12	35	0	11	4	7	0	2	1	5
3	41	1	0	3	19	0	7	0	8	0	1	0	2
4	22	1	1	1	12	0	1	2	5	0	0	0	1
5	27	0	0	2	6	0	2	0	3	0	0	0	0
6	17	1	0	1	4	0	0	0	2	0	0	0	2
7	18	2	0	3	2	0	1	0	1	0	0	0	0
8	9	0	0	0	1	0	0	0	1	0	0	0	0
9	8	1	0	0	6	0	0	0	0	0	0	0	0
10	7	1	0	0	0	0	0	0	0	0	0	0	0
11	6	0	0	1	1	0	0	0	0	0	0	0	0
12	1	0	0	1	2	0	0	0	0	0	0	0	0
13	3	0	0	0	0	0	0	0	0	0	0	0	0
14	6	0	0	0	0	0	0	0	0	0	0	0	0
15	3	0	0	0	1	0	0	0	0	0	0	0	0
16	2	0	0	0	1	0	0	0	0	0	0	0	0
17	2	0	0	0	0	0	0	0	0	0	0	0	0
18	2	0	0	0	1	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0
20	4	0	0	0	1	0	0	0	0	0	0	0	0
21	1	0	0	0	0	0	0	0	0	0	0	0	0
22	3	0	0	0	0	0	0	0	0	0	0	0	0
23	1	0	0	0	0	0	0	0	0	0	0	0	0
24	2	0	0	0	0	0	0	0	0	0	0	0	0
25	2	0	0	0	0	0	0	0	0	0	0	0	0
26	1	0	0	0	1	0	0	0	0	0	0	0	0
27	3	0	0	0	0	0	0	0	0	0	0	0	0
28	1	0	0	0	1	0	0	0	0	0	0	0	0
29	1	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0
>30	17	0	0	0	0	0	0	0	0	0	0	0	0

Risk curves for consequence classes of urban pluvial flooding

Figures A3.2 and A3.3 give 2 examples of risk curves for individual damage classes. Flood consequence severity on the horizontal axis is expressed as amount of calls per incident. The risk curves show that the maximum amount of calls for flooding on streets is more than twice as high as for flooding in residential buildings. The probability of at least 1 call is more than 3 times higher for flooding on streets than flooding in residential buildings.

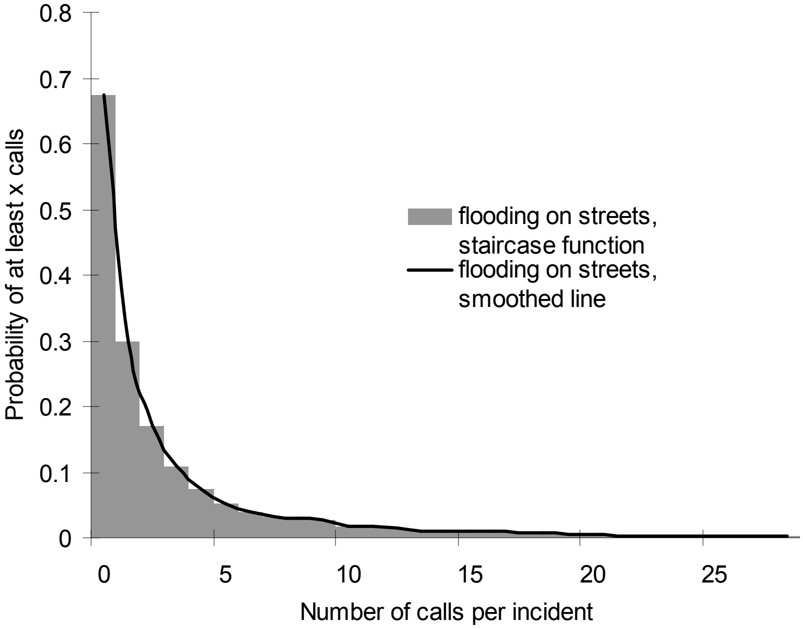

Figure A3.2. Risk curves (smoothed lines) and staircase functions for consequence class 'flooding on streets', based on call amounts per incident as a measure for consequence severity

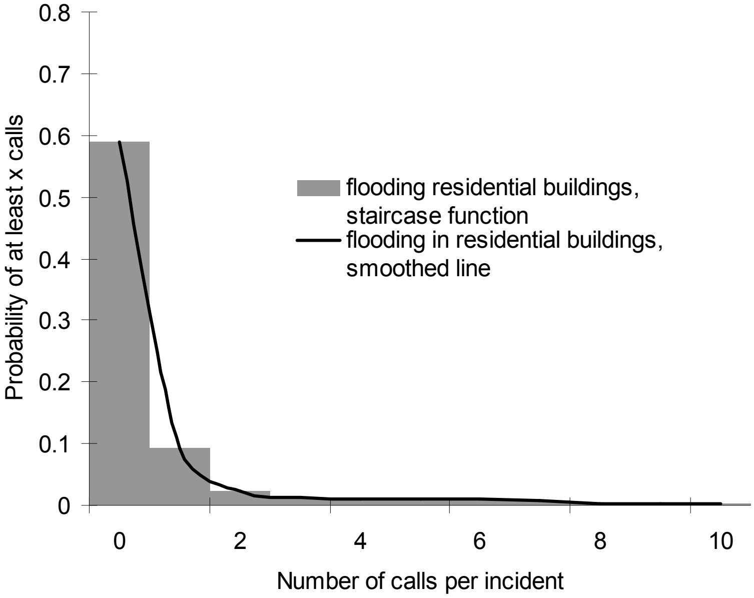

Figure A3.3. Risk curves (smoothed lines) and staircase functions for consequence class 'flooding in residential buildings', based on call amounts per incident as a measure for consequence severity.

Risk graphs for other consequence classes (figures A3.4 to A3.7) show that for most consequence classes, the maximum number of calls per incident is below 5. Probabilities of at least 1 call per event vary from 0.009 per week for lifted manholes to 0.13 per week for flooding on parking spaces. Most risk curves decrease steeply for increasing numbers of calls per event, indicating that flood risk for most consequence classes is associated with small events.

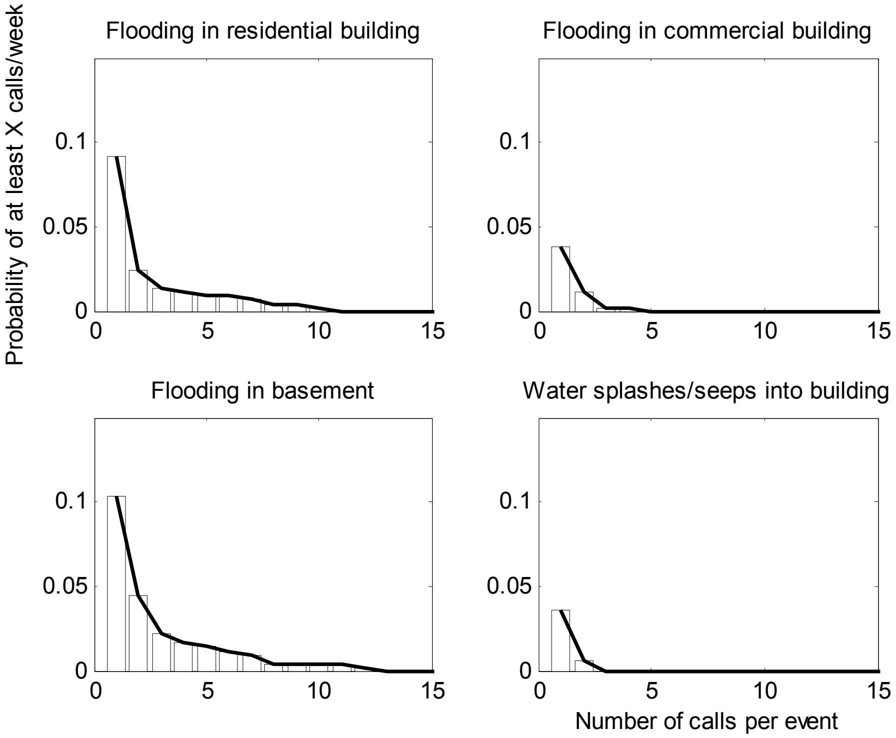

Figure A3.4. Risk curves for consequence classes related to flooding in buildings, based on call amounts per incident as a measure for consequence severity.

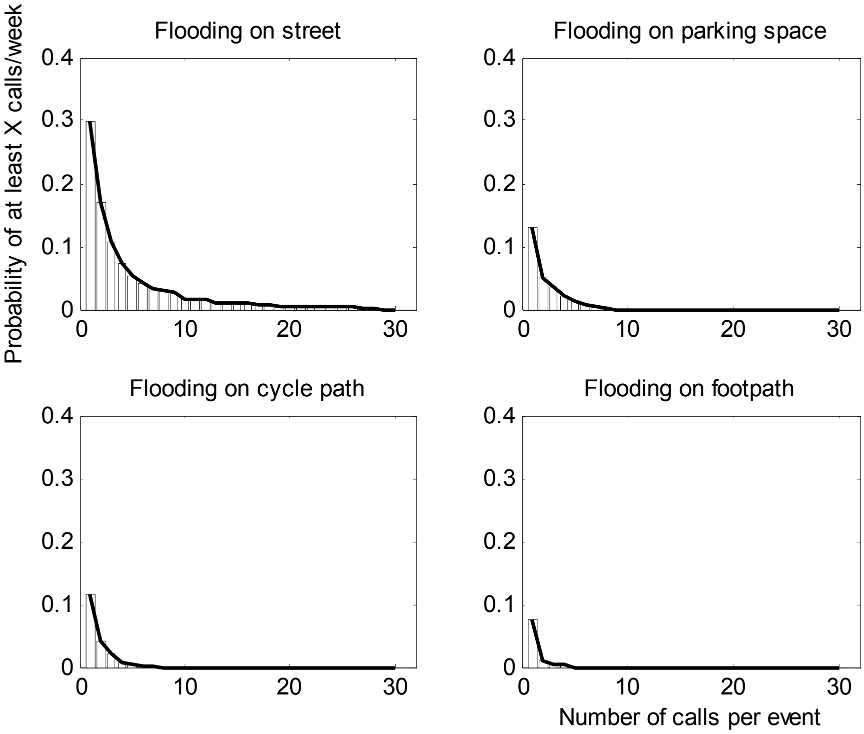

Figure A3.5. Risk curves for consequence classes related to flooding of streets, based on call amounts per incident as a measure for consequence severity.

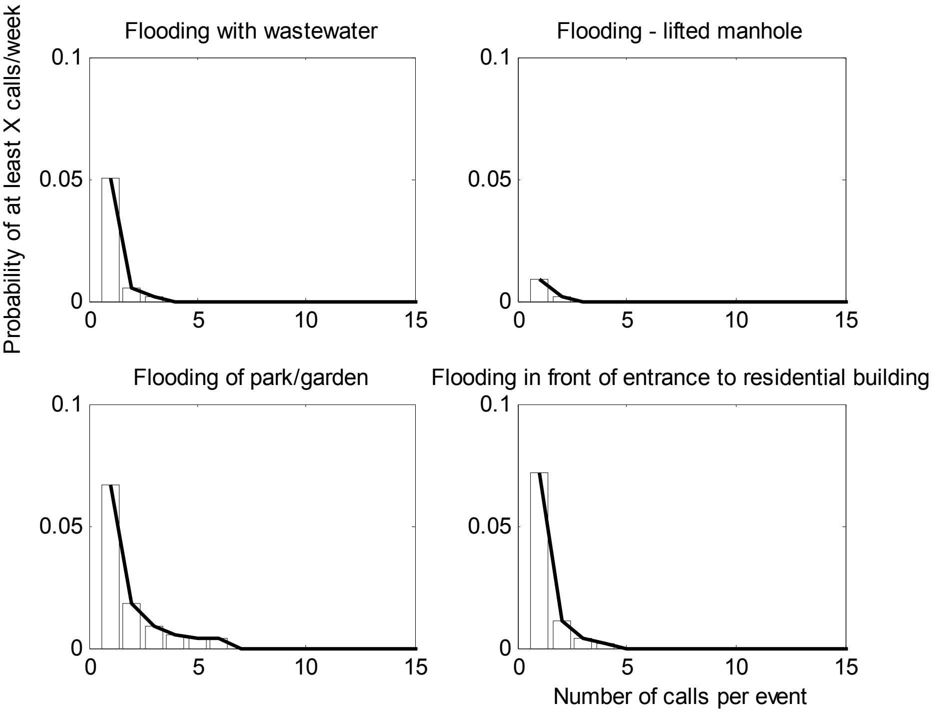

Figure A3.6. Risk curves for consequence classes related to flooding with wastewater, lifted manholes, flooding of green spaces and flooding in front of entrances to residential buildings, based on call amounts per incident as a measure for consequence severity.

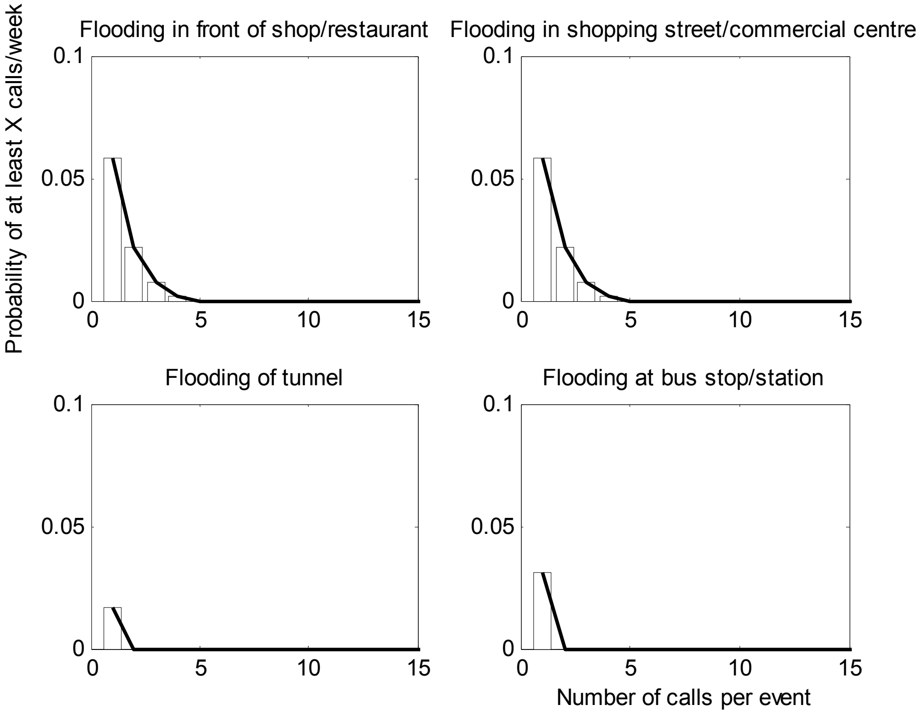

Figure A3.7. Risk curves for consequence classes related to flooding in front of entrances to commercial facilities, flooding in shopping streets, flooding of tunnels and flooding at bus stops, taxi stands and bus and train stations, based on call amounts per incident as a measure for consequence severity.

List of publications

International peer-reviewed journals

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Publication Date: 15 Sep 2009 • ISBN: 9781843391869

Editorship

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doi: 10.2166/WPT.2009.018

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This thesis is the result of three and a half years of research investigating problems of urban flooding in lowland areas. The main reason for undertaking this work is that I felt that the existing approach of urban flooding analysis that strongly focuses on hydrodynamic modeling was not addressing urban flooding problems appropriately. According to my experience as an urban drainage manager in Breda, models were unable to simulate reality: they showed flooding locations that had no record of flooding and they missed locations where people had to protect themselves from recurrent flooding by installing barriers in front and back doors. An important reason was that we lacked monitoring data to calibrate the hydrodynamic models, as is the case of many cities throughout the world. Even if cities have a monitoring network installed, it takes a lot of energy to obtain reliable data and large data gaps are more of a rule than an exception. That is why I felt alternative methods should be developed to obtain information on urban drainage system functioning. Not to replace hydrodynamic models, but to complement data from monitoring networks. Preferably this complementary information should come from data sources that are widely available: data that is collected anyhow and can be put to use for analysis. Call centre data proved to be such a data source and analyzing these data has been an enriching experience and great fun, too, at times.

This thesis could not have been completed without the help of people that I have had the pleasure to work with over the past few years. After I left university I have been in doubt whether or not I should pursue a PhD degree. To do this while working on a full time job is not evident and going back to university as PhD student never seemed a realistic option. Until the option of a university job combining research and education popped up. François, I'm grateful to you for suggesting this opportunity to me and for guiding me into the scientific world. My colleagues in urban drainage research provided a stimulating working environment and were a great support in busy times. Rémy, I have good memories of the time we organized the SPN-conference together; Ivo, thanks for upgrading my knowledge of hydraulics; Jojanneke, you were always ready to read through my texts critically. My work load was much relieved by Robin Harder, who helped me for several years to develop accessible call databases that were a prerequisite to be able to make sense of the data. I enjoyed working with Boyd Berends and Frans van Knapen at IRAS, who introduced me into the particulars of microbiological risk assessment. Gerdien Sterk's graduation work provided the data that allowed me to add this component to my research study.

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Curriculum vitae

Marie-claire (Johanna Antonia Elisabeth) ten Veldhuis was born on October 15, 1969 in Roosendaal, the Netherlands. She followed her secondary education at St.-Oelbertgymnasium, from 1982 to 1988. In 1988 she started her study of Civil Engineering at Delft University of Technology, from which she graduated in 1995. Her MSc-graduation focused on an analysis of water quality problems in a pond in Amsterdam that was fed by water from a separate storm water system. After graduation she went to Belo Horizonte in Brasil to work on a research project studying flooding problems in low-income areas of the city. Upon her return in 1996 she started to work at IWACO BV as a water systems consultant. She worked on various water quality and water management studies and was sent abroad several times to work on a European project in Israel, Jordan and the Palestinian Territories. In 2002 she moved to the city of Breda to become manager of urban water and sewerage, which she did in cooperation with a team of engineers and operators. Building on this experience she started PhD research at Delft University in 2006. She combined this research with a position as assistant professor, teaching master courses on urban drainage. Her present research interests are data acquisition by monitoring and data mining of existing data sources for analysis and operation of urban drainage systems.