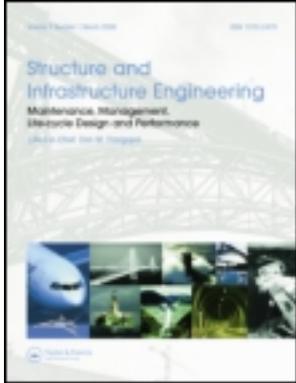


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Quantitative fault tree analysis for urban water infrastructure flooding

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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 article, we apply probabilistic fault tree analysis for the first time to assess the probability of urban flooding as a result of a range of causes. We rank the causes according to their relative contributions. To quantify the occurrence of flood incidents for individual causes we use data from municipal call centres complemented with rainfall data and hydrodynamic model simulations. Results show 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

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). Ashley *et al.* (2005) 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 for 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 to 7000 properties are flooded annually in England and Wales by sewage (Ashley *et al.* 2005). No quantitative estimations of urban flood risk in The Netherlands are known us, either in general or 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 failure and human error. Analysis of call centre data from three municipalities of 100,000 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 nuclear, aeronautic and chemical industries, to quantify risk, including risk analysis methods and probabilistic fault tree analysis (Kaplan and Garrick 1981, Haines 1998, Vesely *et al.* 1981, 2002). Risk-based decision making in water resources matured as a professional niche in the US in the 1980s (Haines 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 (Harremoës 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.

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A fault tree is a deductive model that links a systems failure via reverse paths to all subsystems, components, human error, etc. that can contribute to failure. It is very useful to detect potential causes of flood events, including both hydraulic overloading and component failure. 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.* 1981). 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, effect analysis and fault hazard analysis. Ang and Tang (1984) provide a short introduction for applications in the field of structural engineering.

In this article, we describe the application of quantitative fault tree analysis for 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 Prinsenbeek. 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, which 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. In addition, attention tends to focus on flood damage relief more than on data registration.

This article is organised as follows: in §2, data on flood incidents are described, followed by an explanation of the fault tree model for urban flooding in §3. Section 4 presents the results of the fault tree analysis and the article ends with a discussion and conclusions in §5.

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 registers 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. In addition, 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 more or less 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, 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 failure. Some examples are available where the vulnerability of model outcomes to component failure and data uncertainty 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, 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 2671 to 5540 cases of flooding yearly between 1994 and 2005. Of these cases, 80% concern flooding in buildings and 20% in 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. Newspaper 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?

3. Quantitative fault tree model for urban flooding

3.1. 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 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 riverbanks, 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, infiltrates or flows over the surface to an infiltration, 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 vulnerable to component failure. 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, such as 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.

3.2. 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). The top event of a fault tree is the failure that is the 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

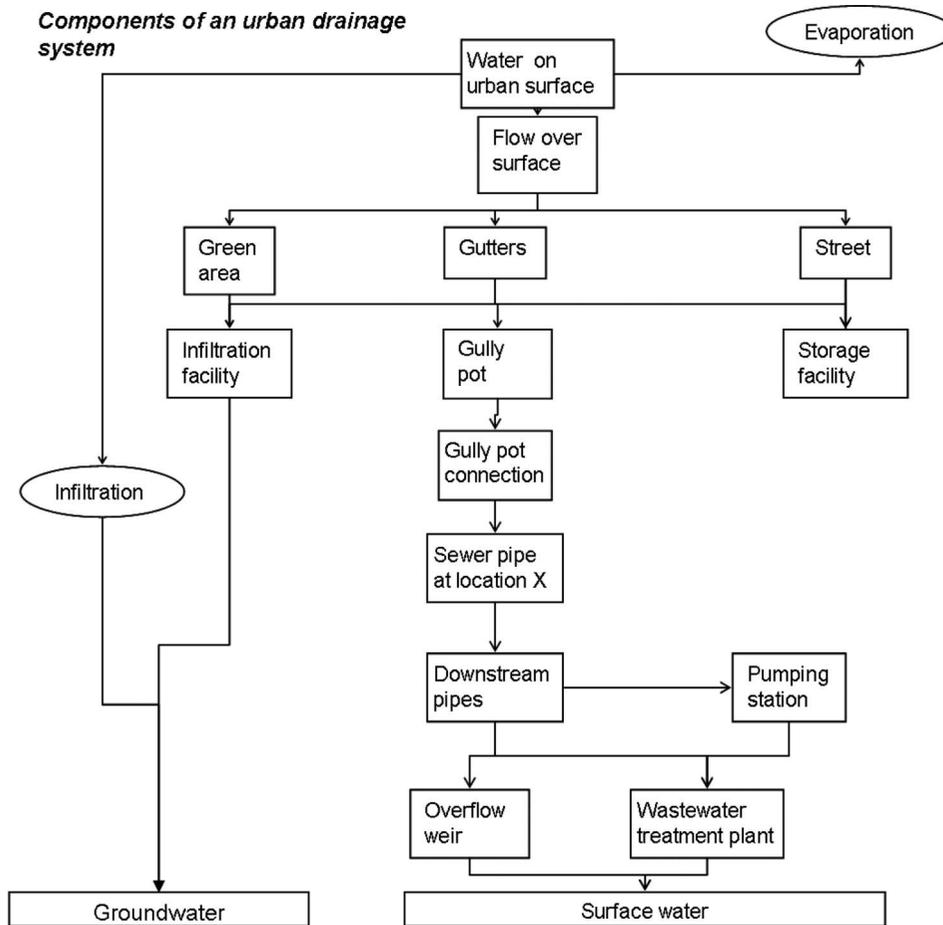


Figure 1. Block diagram for an urban drainage system. The diagram shows the system components that, by their failure, can lead to the occurrence of water on urban areas.

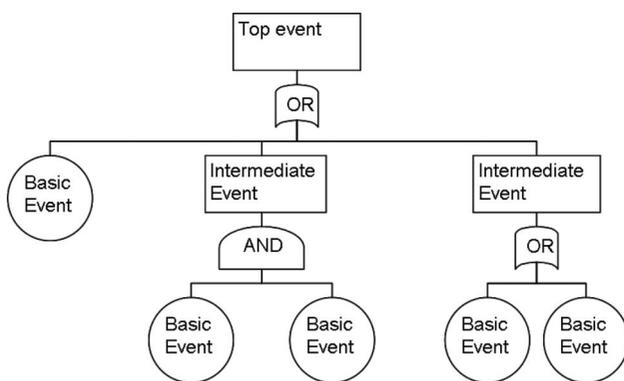


Figure 2. Elements of a fault tree model.

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.

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; and
- (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 3 shows a fault tree for urban flooding for these seven mechanisms. The intermediate events form a first level in the tree; they in 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.

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. Absence of gutters, gully pots or manifolds is also 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 in that water, which 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 a rise of the pressure level above ground level. Detailed fault trees for these failure mechanisms have been developed and are available upon request.

3.3. 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:

$$p_x(x) = \frac{(\lambda t)^x e^{-\lambda t}}{x!}, \quad (1)$$

where $p_x(x)$ is the probability of x occurrences in a period of time t and λ is the 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 non-homogenous 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

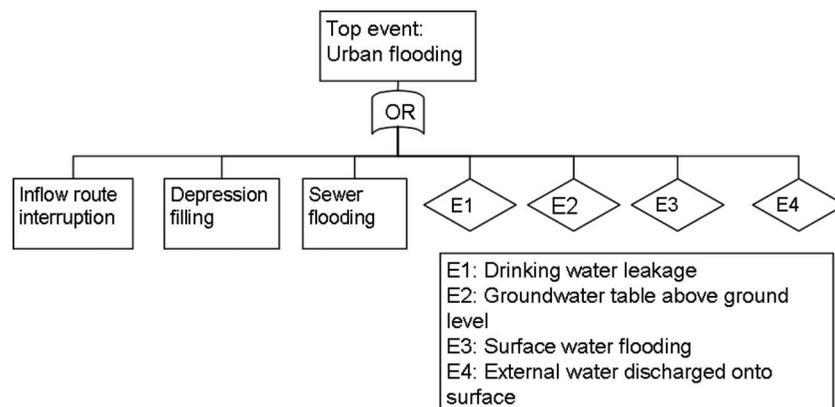


Figure 3. Example of a fault tree model for urban flooding, first level. Three events are to be developed deeper, to the level of basic events; four events remain undeveloped. The 'OR' gate indicates that each individual intermediate event can lead to the top event.

fault tree analysis, a constant failure rate has been assumed.

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

$$P(X \geq 1) = 1 - p_X(0) = 1 - e^{-\lambda t}, \quad (2)$$

where $P(X \geq 1)$ is the probability of one or more events and $p_X(0)$ is the 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 of 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 the occurrence of the basic events. The model can be developed further into a stochastic fault tree model such as reliability block diagrams (RBD) or dynamic fault trees (DFT), in which functional dependencies and fault-ordering is included, or state-event fault trees (SEFT) as an extension to fault trees based on state charts. More advanced stochastic extensions of fault trees could be obtained based on Markovian stochastics, such as generalised stochastic petri-nets (GSPN), or stochastic activity networks (SAN), which is a variation on stochastic petri-nets, which is geared more towards dependability modelling. These extensions will be the subject for future study. The focus of this study is primarily towards fault tree modelling.

3.4. Independent events

Probabilistic fault tree analysis is more straightforward if successive events are independent because probability distributions such as 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. As the main source of urban floodwater is rainfall, a criterion has first been defined for the independence of rain events. It is based on the length of the intermediate dry period that must be sufficiently long to allow the drainage system to come back to the initial conditions. This period is typically of the order of 10 to

15 hours. The intermediate period must not be longer than 24 hours because extremely long events, of 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 which give rise to flood incidents are removed before the start of a new event, to ensure independence of successive blockage events. Given that call data are used as data sources 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 this case, the fault tree model provides probabilities of flood incidents on a 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.

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

4.1. Case study characteristics and available data

The quantitative fault tree model has been applied to two case studies: Prinsenbeek and Haarlem. A municipal call register, local rainfall measurements and a hydrodynamic sewer model are available for both cases. Table 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. Figures 4 and 5 show the layout of the case study areas and the location of the rain gauges.

Call data are the most important data source to provide estimates of flood incidents as a result of basic

Table 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 years)	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 where 1 st flush pumped to combined system)	km ²	0.15	2.22
	%	60	–

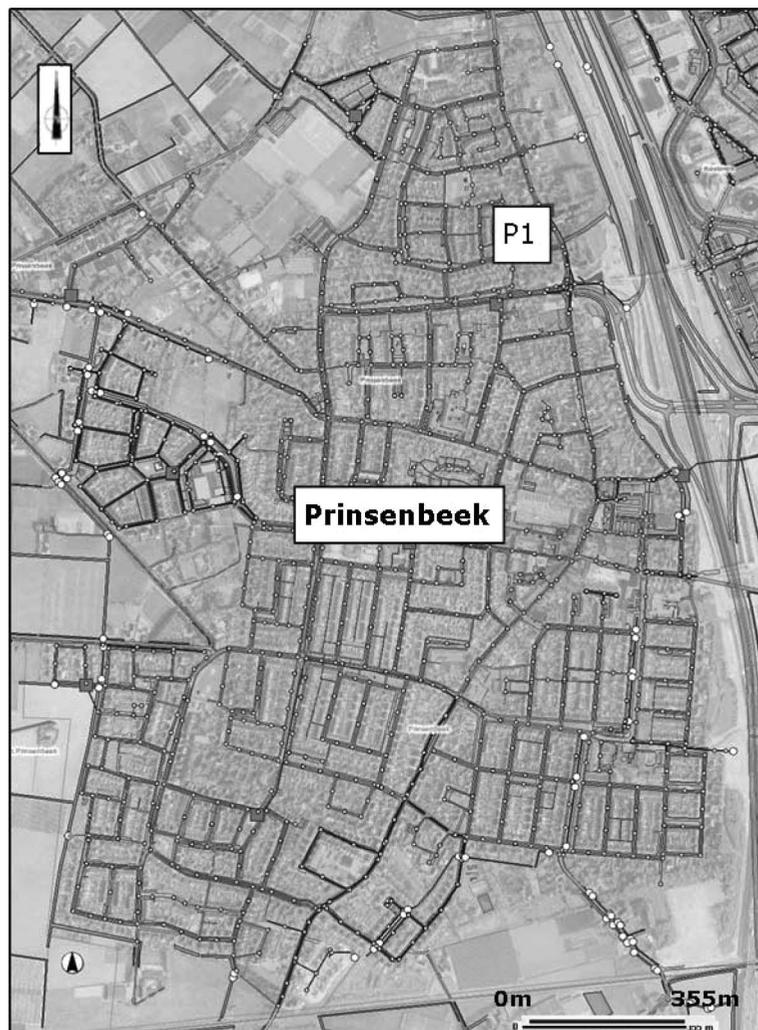


Figure 4. Map of Prinsenbeek indicating the layout of the sewer system and the location of the rain gauge P1.

fault tree events. Call texts are analysed manually and every call is assigned to 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

one 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

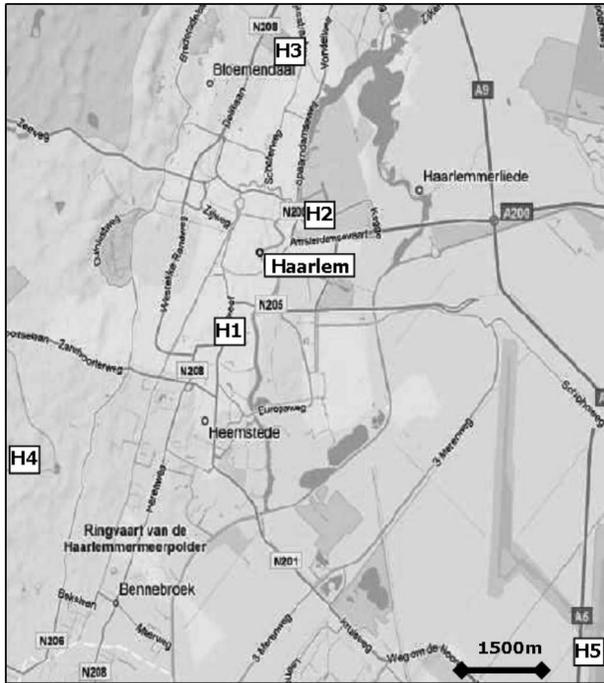


Figure 5. Map of Haarlem that shows the location of rain gauges H1, H2 and H3 within the city area and the location of rain gauges H4 in Leiduin and H5 at Schiphol.

resulting from model simulations. In addition, frequent flood locations are compared. Every heavy rainfall incident that results in flooding, according to model simulations, is reported by at least one call, in the call register. Most locations that suffer frequent flooding in model simulations are also reported in the call register. Only a number of locations in Haarlem, which 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 provides a summary of available call data and rainfall data for the two case studies.

Two different analyses have been conducted for the two case studies: for Prinsenbeek, the sewer flooding failure mechanism has been analysed (Figure 2, second 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.

4.2. 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. The rainfall series that is used as input for model simulation entirely overlaps the period of call data. Incidents are counted for independent events; the total rainfall period is thus 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.

In the call register, 15 incidents of sewer flooding are found; model simulations result in four flood incidents. These four 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 per week or 0.9 per 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.

4.3. 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.

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

four 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 3 gives six 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 causes other 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

Table 2. Data sources and characteristics of 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 number of calls* in urban-water call category	996	6361
Length of data series	1720 days	3795 days
Rain gauges		
Location of rain gauges (see also figures 4 and 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: 14.4, 21.6, 25.2, 28.8, 32.4 mm/hr Design storms: $T = 1$ year, $T = 2$ years 3 storms from data series gauge H1
Correlation rain gauges Haarlem		
Correlation between H4 and H5 (2003–2007)		0.635
Correlation between H1 and H4 (18/11/04–23/07/05)		0.81 (daily rainfall from 8H to 8H for H1)
Correlation between H1 and H5 (18/11/04–23/07/05)		0.59 (daily rainfall from 8H to 8H for H1)

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

Table 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: including or excluding calls with no explicit consequence mentioned and including or excluding calls during dry periods.

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

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.

Gully pot blockages and gully pot manifolds cause the highest numbers of flood incidents (Table 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 4). This is to be expected since, in many cases, floodwater 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 failure, cause more flood incidents than sewer overloading by heavy rainfall, not only for flooding in public areas, but also for flooding in buildings.

4.3.1. Quantitative analysis: Monte Carlo simulations 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 simulations: 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. Monte Carlo simulations for the case of Haarlem result in 7000 failures out of 10,000 simulations. The probability of the top event is 0.7 per week. Table 5 shows the contribution of five basic events to the overall probability of failure.

4.3.2. 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 crosschecking with rainfall data is small. Maximum estimates are based on the number of basic events that could occur under unfavourable conditions, with a minimum of maintenance and a maximum of human errors. Estimates are made by expert judgement. For instance, the maximum expected probability for gully pot blockages 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 4. Basic event incident numbers and probabilities in urban flooding fault tree for four scenarios of flood consequences: (1) sum of all flood consequences, (2) flooding in buildings only, (3) flooding in basements only and (4) flooding of public areas only. Incident numbers of scenario 1 can be lower than the 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, four flood consequence scenarios for the period 1997–2007	Number of basic event incidents (/ 10 years)	Probability of at least 1 occurrence per week (/ week)	Number of basic event incidents (/ 10 years)	Probability of at least 1 occurrence per week (/ week)
	Scenario 1	1	Scenario 2	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	3	Scenario 4	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

Table 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

Table 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 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.

5. Discussion and conclusions

In this article, we provide a methodology to conduct quantitative fault tree analysis for urban water infrastructure systems and present results of applications to two cases. To our knowledge, this is the first

application of probabilistic fault tree analysis to urban water infrastructure flooding. The results show that component failure contributes significantly to urban flood probability: gully pot blockages contribute 71%, gully pot manifold blockages 25% and pipe blockages 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 blockages contribute 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 parts of potential incidents are 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. In practice, a test should be conducted 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 and 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 article 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 of 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 (e.g. Penning-Rowell *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, of the order of once in 10 years, to undertake adequate preventive actions. Other components, such as 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 such as fault tree analysis can actually reduce incident frequencies compared to traditional approaches is yet unanswered. Fault tree analysis provides an insight into relative contributions of failure mechanisms and can draw attention to failure mechanisms that were previously overlooked or underestimated. If preventive maintenance to prevent blockages, or at least to prevent flooding caused by blockages, 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. In addition, 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. However, modelling of flood causes related to blockages and errors and quantification of associated flood probabilities requires complex manipulations and can be done in a more straightforward manner 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 in 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 into 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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