Evaluation of operational strategies for sewer flooding based on failure data

J.A.E. ten Veldhuis*, J. Dirksen* and F.H.L.R. Clemens*

**Department of Water Management, Delft University of Technology, PO Box 5048, 2600 GA Delft, the Netherlands (E-mail:j.a.e.tenVeldhuis@tudelft.nl)*

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 and handling gully pot blockages should therefore be a priority for sewer operators. 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.

Keywords

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 a recent study (ten Veldhuis et al., 2009), quantitative fault tree analysis, a powerful risk analysis tool (Vesely et al., 2002), has been applied to urban flooding in order to detect and quantify causes of urban flooding. The study has shown that the contribution of component failures to flood incident frequency is 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 paper 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 1 summarises types of strategies and scheduling of operational activities.

Table 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 paper focuses on 3 sewer failure mechanisms that are main contributors to sewer flood risk (ten Veldhuis et al., 2009): 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 no 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 only 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). This paper aims to find out whether failure data this common agreement about the efficiency of current strategies and if analysis of failure data can point out directions for improvement.

METHOD

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 two municipalities were analysed to detect characteristics of failure processes for the three failure mechanisms described in the introduction of this paper. Relative contributions of these 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.

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.

$$R = P\left(flooding \right) * \overline{C} \quad (1)$$

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

A failure probability model must be chosen that suits the type of failure processes. In this analysis the occurrence of events was assumed to be a Poisson process. This implies that the probability of occurrence of an event is approximately proportional to the length of the

observed time period, occurrences of events in disjoint time periods are statistically independent and events do not occur exactly simultaneously.
Under these conditions, the number of occurrences *x* in some fixed period of time is a Poisson distributed variable:

$$p_X(x) = \frac{(\lambda t)^x e^{-\lambda t}}{x!} \tag{2}$$

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 this analysis a constant failure rate was assumed, because the analysed data do not give an indication of changes in occurrence rate over time.
Since failure occurs due to the occurrence of 1 or more events, the probability of failure can be calculated from:

$$P(X \geq 1) = 1 - p_X(0) = 1 - e^{-\lambda t} \tag{3}$$

Where: $P(X \geq 1)$: probability of occurrence of one or more events in period of time t
$p_X(0)$: probability of no events in period of time t

The time period t can be chosen at will; the length of the time period that is chosen for analysis does not influence the outcomes of event occurrence frequency analysis. A longer time period t results in higher outcomes of calculated frequencies and corresponding probabilities of occurrence. The time scale is preferably chosen so as to fit the frequency of events in order to avoid very high or low probability outcomes. A time period of 1 year has been chosen for this analysis.

Independent events
Since the occurrence of rainfall incidents was assumed to be a Poisson process, successive events must be independent. This means that the total urban drainage system must have returned to its initial condition before a second event starts. In practical cases insufficient data are generally available to check whether initial conditions have been restored for all system components. A safe and practical assumption was made for a period of at least 24 hours without rainfall to separate independent events. This period was chosen because it is sufficiently long for the drainage system to come back to its initial condition, even though initial soil conditions may not have been entirely restored. If a longer dry period were chosen, this would lead to numerous extremely long events which exceed the minimum return period of flood events and would distort probabilistic analysis.

Case studies: cities of Haarlem and Breda
Haarlem is situated in the northwest of the Netherlands, in a transition area between sea dunes up to about 30 m above sea level and polder areas below sea level. It has 147.000 inhabitants. Breda is situated in the south of the Netherlands, on the confluence of two small rivers. It has 170.000 inhabitants.
Rainfall data from local rain gauges were used to define independent rain events Table 1 summarises some characteristics of the sewer systems of Haarlem and Breda and available data. Figure 1 shows maps of the cities of Haarlem and Breda.

Table 1. Summary of data for the cities of Haarlem and Breda: sewer system characteristics, call data in municipal call register, rainfall data

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
Rain gauges		
Period of rainfall data	12-06-1997 to 02-11-2007	31-01-2003 to 23-10-2007
Location of rain gauges	H4: Leiduin H5: Schiphol	P1: Prinsenbeek
Call register		
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	6361	6991
Length of data series	3788 days	1726 days
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)

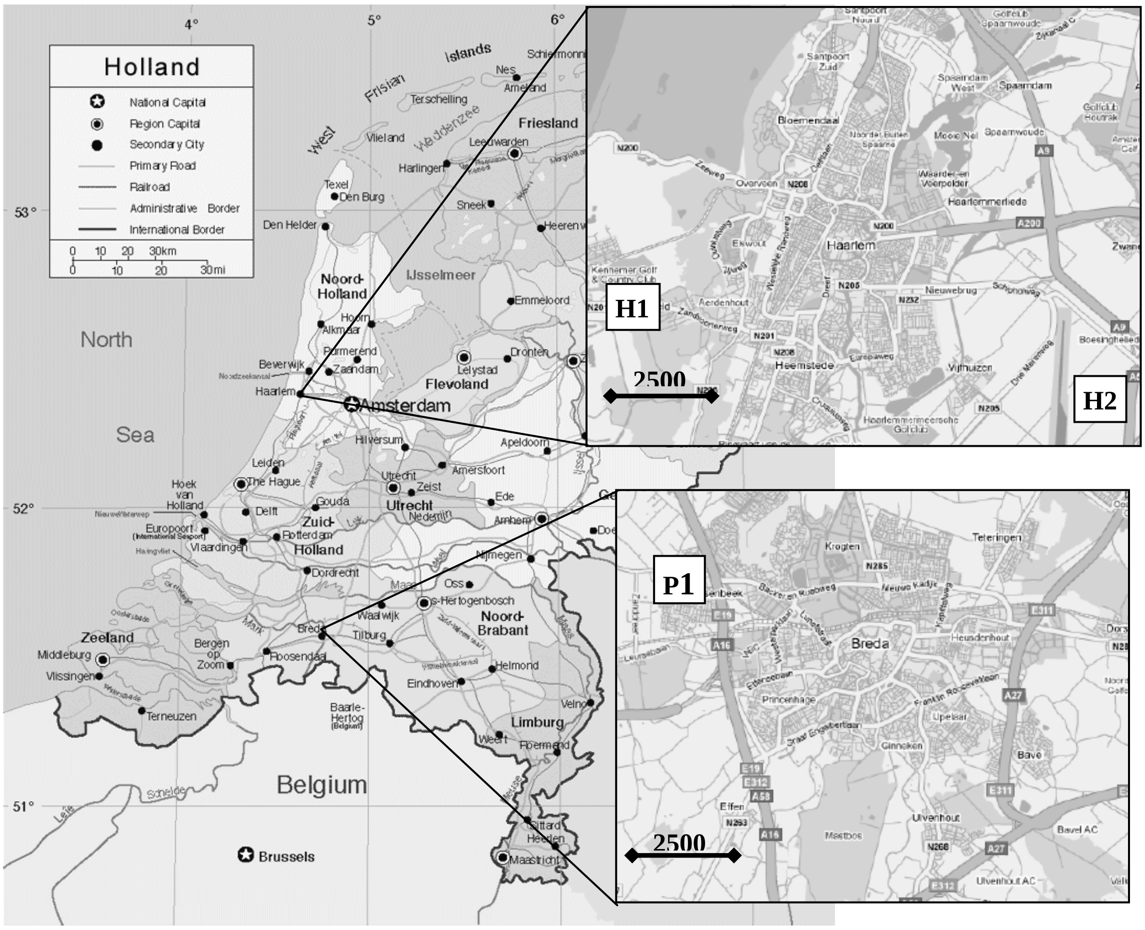

Figure 1 Map of the Netherlands, Haarlem and Breda; locations of rain gauges in Haarlem, H1 (Leiduin) and H2 (Schiphol) and in Breda, P1 (Prinsenbeek). Source: Google maps, 2009

RESULTS

Tables 2 and 3 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 2 and 3 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 2 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 3 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 2 and 3 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 2 shows incident frequencies for Haarlem and Breda per 100 km of sewer length and per year, for rain incidents.

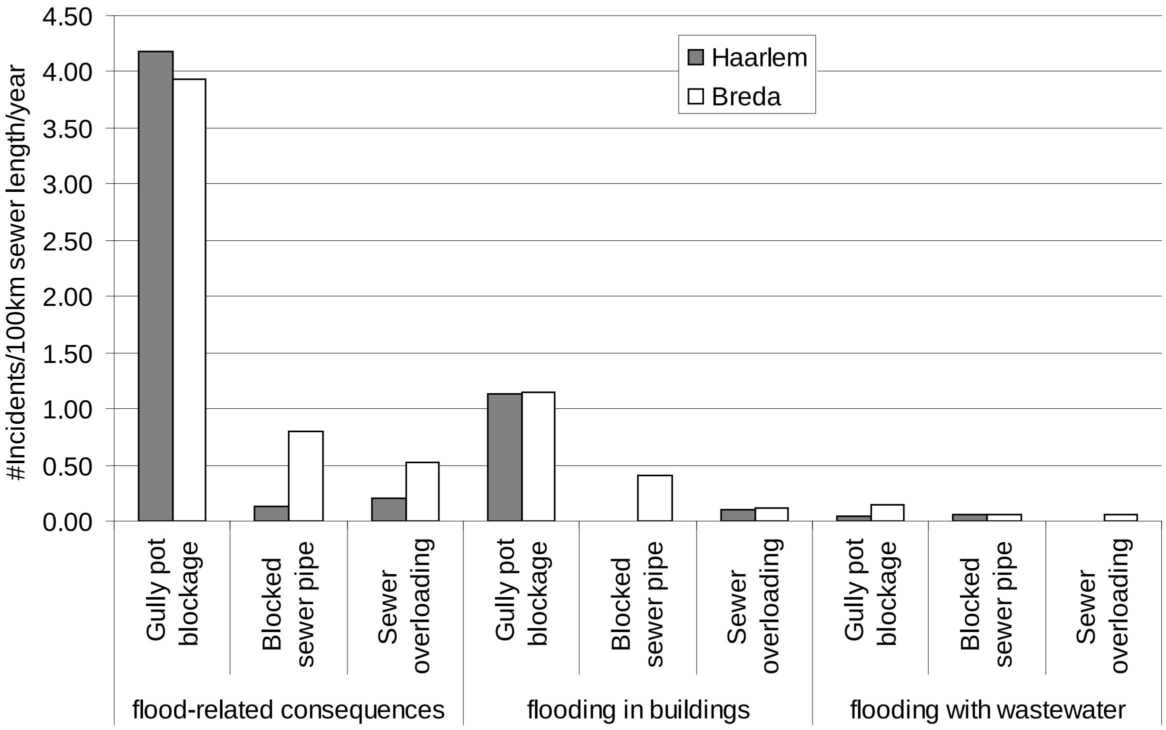

Figure 2 Comparison of the number of incidents per kilometre sewer length per year for between Haarlem and Breda for 3 different selections of flood consequence classes, for rain incidents

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 occurs 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 1). 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.
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 4 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 4 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 2 and 3 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.

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.

ACKNOWLEDGEMENT

The authors would like to thank the municipalities of Haarlem and Breda for making available the data in their cal registers.

REFERENCES

Bedford, T., Cooke, R. (2001). Probabilistic risk analysis: foundations and methods. Cambridge University Press, Cambridge

Dirksen, J., Goldina, A., ten Veldhuis, J.A.E.Clemens, F.H.L.R. (2007). The role of uncertainty in urban drainage decisions: uncertainty in inspection data and their impact on rehabilitation decisions. In: Proc. of 2nd Leading Edge Conference on Strategic Asset Management, Lisbon, Portugal

Gemeente Breda (2008). Verbreed GRP Breda 2009-2013 (in Dutch). Extended municipal sewer management plan 2009-2013. Gemeente Breda, the Netherlands.

Gemeente Haarlem (2008). GRP Haarlem 2007-2011 (in Dutch). Municipal sewer management plan 2007-2011. Gemeente Haarlem, the Netherlands.
RIONED Foundation (2004). Leidraad Riolering, Module C2100, 17-20 (in Dutch). ISBN 978-90-73645-68-4. Stichting RIONED, Ede, the Netherlands.
RIONED Foundation (2007). Leidraad Riolering, Module D1100, 43-70 (in Dutch). ISBN 978-90-73645-68-4. Stichting RIONED, Ede, the Netherlands.
Tuhovčák, L., Ručka, J., 2007. Hazard identification and risk analysis of water supply systems. In: Proc. of 2nd Leading Edge Conference on Strategic Asset Management, Lisbon, Portugal
Vesely, W., Dugan, J., Fragola, J., Minarick, J., Railsback, J. (2002). Fault Tree Handbook with Aerospace Applications. Version 1.1. NASA Headquarters, Washington.