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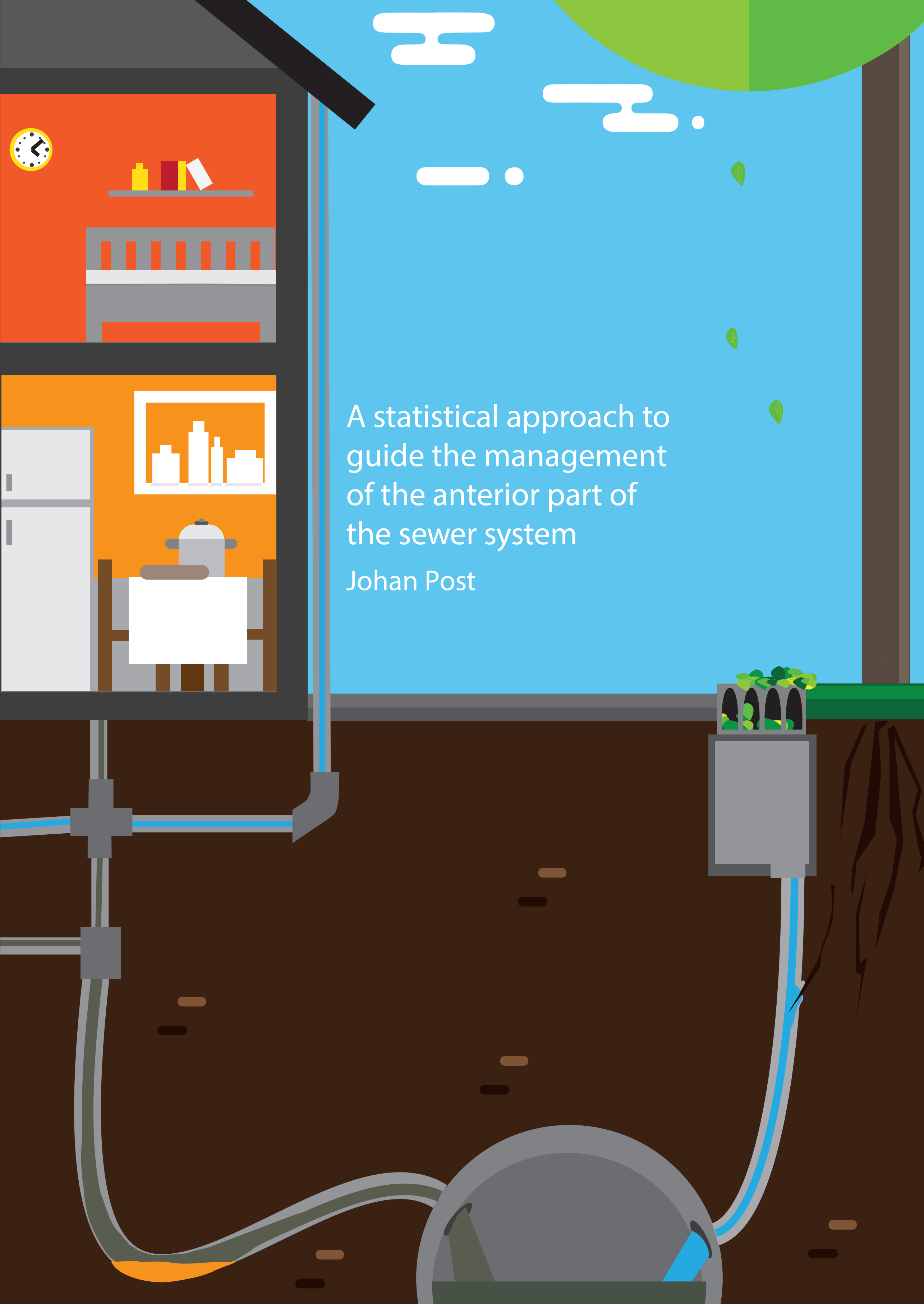

A statistical approach to guide the management of the anterior part of the sewer system

Johan Post

A statistical approach to guide the management of the anterior part of the sewer system

Proefschrift

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voorzitter van het College van Promoties
in het openbaar te verdedigen
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door

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to family & friends

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Johan Post, 2016

Contents

1 Introduction

1.1 Development of modern sewer systems

Sewer systems consist of a network of collection devices, pipes and pumping stations designed to collect and transport wastewater and excess stormwater from urban areas. Although the prevention of flooding and protection of the environment are fundamental objectives of sewer systems, protection of the public health was the main driver for the development of modern sewer systems. The link between infectious diseases and the urban water cycle was first established in 1854 by Dr John Snow, who found a cluster of cholera cases near a water well fed by groundwater contaminated with human excreta. The traditional barrel-system used to remove human excreta proved to be ineffective in preventing cholera outbreaks (Van Zon, 1986). Furthermore, the increasing popularity of flushing toilets and the introduction of artificial fertiliser resulted in increasing waste collection costs while revenues from compost sales decreased (Geels, 2006; Van Zon, 1986). At the end of the 19th century there was a shift towards constructing large-scale sewer systems for the disposal of wastewater (Geels, 2006; Preston and Van de Walle, 1978). Accelerated urban expansion after the second World War sustained a rise in the construction rate of sewers, lasting well into the 1970s.

1.2 Sewer asset management

In the 1970s there was a gradual shift in focus from the design and construction of new sewer systems towards the management of existing systems. Reactive strategies were common; responding to the condition of a sewer component only after the consequences of a failure became apparent. The progressively increasing number of sewer failures and corresponding consequences triggered a concerted move to more proactive strategies for man sewers in the 1980s (Hurley, 1994; Thissen and Oomens, 1991). Proactive strategies are characterised by activities that are undertaken before a failure occurs, to preserve the functionality of a component. Therefore, these strategies safeguard citizens from the undesired consequences of a service interruption, such as tangible flood damage (Ten Veldhuis and Clemens, 2010) and health risks (De Man et al., 2014).

Prioritising work on vulnerable sewers was considered necessary, as complete rehabilitation of sewer infrastructure was infeasible from an economic and social perspective. However, deterioration of sewer infrastructure is not solely determined by age (Fenner, 2000; Roberts et al., 2002) and may be influenced by local circumstances or practices at the time of construction. Therefore, age proved to be an unsatisfactory driver for decision-making. Development of the Sewerage Rehabilitation Manual (Water Research Centre, 1983) resulted in the identification of critical sewers in the UK, where the economic consequences of a collapse would be most severe. This strategy, however, did not take into account the likelihood of a collapse, a necessary element for risk assessment. The condition of these critical sewers was monitored by means of Closed Circuit Television (CCTV) inspections and used to direct proactive rehabilitation work. Inspecting the remainder part of the system was not deemed to be cost effective (Fenner et al., 2000), resulting in a continuation of the reactive approach for 80% of the system. In 1993 the Environmental Management Act became effective in the Netherlands. Although not as formalised, it required water authorities to develop strategic plans that described a framework for implementing and maintaining sewerage together with the resources necessary to achieve service objectives.

The 2011 Administrative Agreement on Water Affairs (Ministry of Infrastructure and the Environment, 2011) foresaw a reduction of 750 million euro in the Dutch water sector annually. This objective has challenged the sector to improve cost-effectiveness. Within the framework of asset management, maintaining the same level of service provision at minimum costs is achieved when work is prioritised on components based on their impact on system performance (Wirahadikusumah et al., 2001). Past research has recognised the role of blockages as the dominant cause of sewer service losses (Ashley et al., 2004). Considering the contribution of blockages to flood risks, proactive strategies to prevent blockages have found to be cost-effective (Ashley et al., 2000; Ten Veldhuis and Clemens, 2011). Currently, mostly main sewers are considered for proactive activities, while the rest of the system is subject to reactive strategies.

1.3 Anterior part of the sewer system

The anterior part of the sewer system consists of a system of gully pots, their lateral connection to the main sewer and lateral house connections (i.e. service laterals, lateral drains or lateral line) that connect building drainage systems to main sewers.

1.3.1 Gully pots and lateral connections

Gully pots, also referred to as catch basins, are inlet structures designed to collect and convey excess water from the urban surfaces. The name stems from the presence of a sump, that acts as a sand trap (see Figure 1.1). By capturing suspended particles in runoff, silting and wear of downstream sewer components are reduced. In addition, pollutants (e.g. heavy metals, hydrocarbons and organic matter) bounded to these particles are retained. These pollutants can disrupt the nutrient balance of receiving water bodies and cause harm to the aquatic life (Brinkmann, 1985). Smaller particles (<250 – 300 µm) are captured less efficiently and carry a larger fraction of the total pollutant load (Butler and Clark, 1995; Ashley and Crabtree, 1992). Furthermore, biochemical processes may increase dissolved pollutant concentrations during dry weather conditions (Morrison et al., 1988). Despite these limitations, the impact on the pollutant wash-off to the sewer system is considerable (Ashley et al., 2004; Butler and Clark, 1995). As a result, gully pots decrease the pollution load to receiving water bodies, especially for storm sewers.

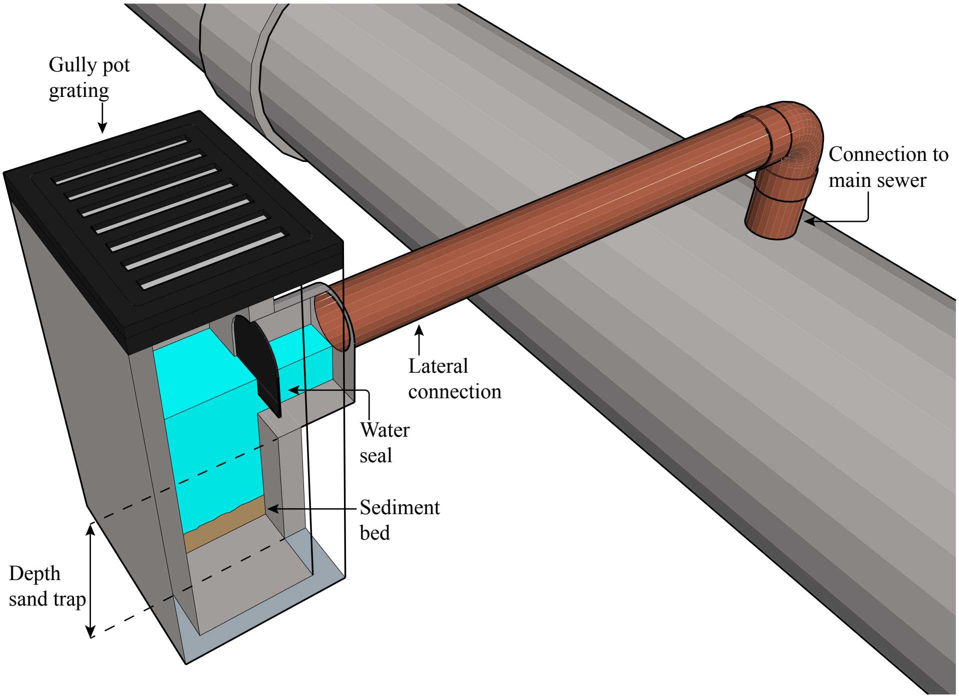

Figure 1.1: Schematisation of a gully pot and adjoining lateral connection.

Depending on the retaining efficiency of the sand trap, the supply of solids induces progressive silting over time. When the trap capacity is exceeded, the hydraulic performance of the gully pot is impaired. In the absence of alternative flow routes, the surface is flooded as water will pond and spread over adjacent areas. Recent research has shown that these components are responsible for the majority of all flooding events in public areas (Caradot et al., 2011; Ten Veldhuis et al., 2011).

Nevertheless, legislation on the design and use of gully pots is generally limited. Dutch standards only specify the amount of surface area of the grating available for the flow of water and the minimum diameter of the adjoining lateral connection (Nederlands Normalisatie Instituut, 2016). British standards (British Standards Institution, 2004) specify several design factors to ensure proper functioning, without providing any quantitative relation to the dimensioning.

1.3.2 Lateral house connections

A building drainage system relies on a lateral house connection to transport wastewater and excess stormwater from properties to the system of main sewers (see Figure 1.2).

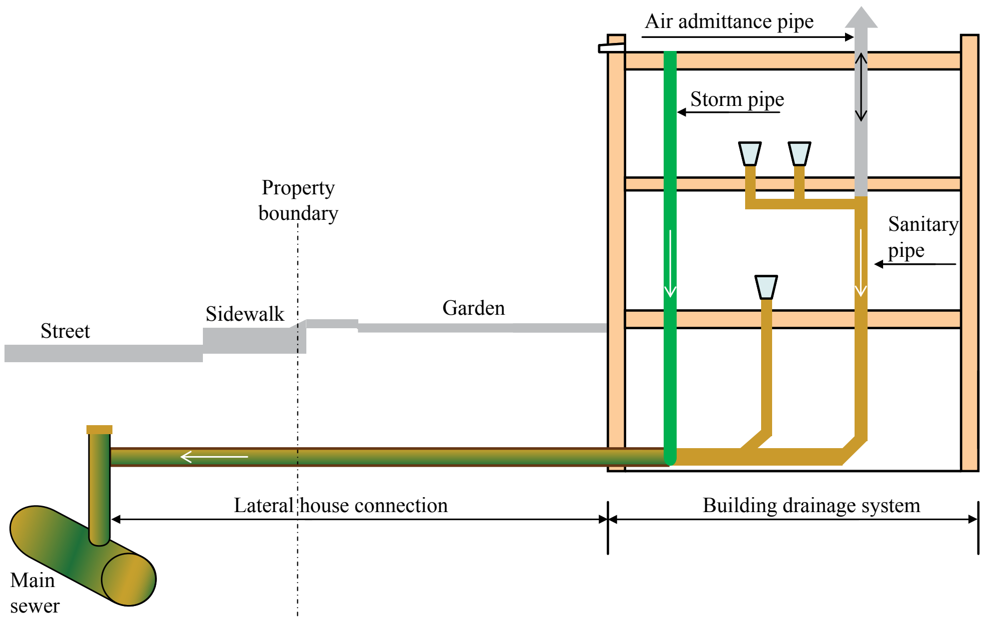

Figure 1.2: Schematisation of a lateral house connection.

Depending on the design of the sewer system, lateral house connections may also alleviate air pressure transients induced by surcharging of main sewers by storm events or discharging house appliances (Swaffield et al., 2004). The inability to cope with these pressure transients may result in odour ingress due to water seal depletion (Swaffield, 2006), the blow off of manhole covers and flood damage (Politano et al., 2007).

Main sewer networks can be looped, which allows for the re-routing of sewage to the pumping station given a blockage. In addition, main sewers are commonly equipped with an overflow construction. In contrast, residents rely solely on the performance of lateral house connections for the discharge of wastewater. Therefore, the operational condition of these connections has a direct impact on the level of service provision to residents. Potential consequences of a blockage may vary from the inability to discharge from appliances to tangible damage and health risks due to flooding in buildings. Although the contribution of lateral house connections to losses in sewer serviceability remains unknown, several studies (e.g. Arthur et al., 2009; Pohls et al., 2004) found small diameter sewers (<225 mm) to be more susceptible to blockages.

Responsibility for lateral house connections is not unambiguous. There are water authorities that take ownership up to the property boundary, while others consider the entire lateral house connection to be the responsibility of the home owner. Similar constructions are present in other countries (e.g. DeSilva et al., 2011), while in the UK ownership has recently been formalised (HMG, 2011) to improve management of the sewer system (Defra, 2011). In Germany, the DIN 1986-30 (2012) requires evidence of the water tightness of existing lateral house connections.

1.4 Sewer systems in the Netherlands

At present, 99.7% of all households in the Netherlands are connected to sewer infrastructure (Oosterom and Hermans, 2013). A vast majority of these connections (68.2%) drain to combined sewers, that transport both wastewater and excess stormwater from urban surfaces. A drawback of this robust system is that the dilution of wastewater during storm events results in a decreasing treatment efficiency of wastewater treatment plants (WWTP). In addition, a mixture of wastewater and stormwater is diverted to local surface water bodies when the treatment capacity is exceeded during intense storm events. In the Netherlands alone, 13,700 Combined Sewer Overflow (CSO) structures are available to relief sewer systems during storm events (Oosterom and Hermans, 2013).

In response, separate sewer systems were introduced in the 1970s. Separate sewers collect wastewater and stormwater separately and currently comprise 27.3% of all connections (Oosterom and Hermans, 2013). Next to providing a more stable flow to the treatment plant, this system mitigates drought issues by retaining stormwater in local surface water systems. A drawback of this system is the potential contamination of receiving waters by pollutants presented in runoff from urban surfaces (Zgheib et al., 2012) and the potential presence of illicit connections (Hoes et al., 2009).

Water boards are the regional government bodies responsible for wastewater treatment and surface water control in the Netherlands. Municipalities are the authorities charged with management of sewer systems. Costs for sewer management are covered by issuing taxes to business owners and residents.

1.5 The drive for data

Proactive strategies call for data on both the current and future condition to estimate the remaining time before intervention (Swanson, 2001). When the condition of a component reaches a specified deterioration level, work should be initiated. Traditionally, CCTV is the primary investigation method to estimate the condition of main sewers (Wirahadikusumah et al., 1998). Although these inspections provide an indication of the current condition, they provide no insight in the further deterioration over the course of time. Several studies have been devoted to supporting decision-making for sewer systems by formulating deterioration models to predict the structural condition rating of sewers (Ariaratnam et al., 2001; Baur and Herz, 2002; Duchesne et al., 2013; Egger et al., 2013; Kleiner, 2001; Le Gat, 2008). Applications vary from the estimation of pipe conditions in the presence of incomplete inspection data to the prediction of the future condition states. These models rely on the formation of groups with similar characteristics such as age and materials for inference. Next to being based on uncertain inspection data (Dirksen et al., 2013), these models generally focus only on structural defects that describe the physical condition of a component.

The operational condition describes a components capability to meet service requirements (Chughtai and Zayed, 2008; Hahn et al., 2002). Blockages can compromise the hydraulic capacity of a component, irrespective of its physical condition (Jin and Mukherjee, 2010). The recurrent nature of blockages (Fenner and Sweeting, 1999), encourages the identification of factors that distinguish these system components from the remaining stock. Second, returning blockages indicate that reactive interventions are not effective in removing the actual cause of a blockage.

The complex mechanisms that influence blockage formation processes limit the application of deterministic models (Jin and Mukherjee, 2010; Laplace et al., 1992). Instead, statistical models based on historical event data have proven to be more successful overall in modelling sewer blockages (Rodríguez et al., 2012). Calls concerning events are a measure of serviceability, a performance indicator that has received wide acceptance in sewerage provision (Arthur et al., 2009; Ashley and Hopkinson, 2002). As these data represent a direct measure of incidents deemed unacceptable by citizens, it is a potential valuable source of information.

1.6 Objective of the thesis

Omitting the anterior part of the sewer infrastructure from system assessments causes an overestimation of the level of service provided by sewer systems. As lateral (house) connections and gully pots are the sewer system components closest to the users, users are directly affected by performance losses. The Netherlands has approximately 7 million gully pots with corresponding lateral connections and close to 7.2 million lateral house connections (Oosterom and Gastkemper, 2012). In comparison, the total length of lateral house connections may be similar to the entire length of the downstream sewers (Sullivan et al., 1977).

Despite spending around 26 million euros on cyclic gully pot cleaning in the Netherlands annually, gully pot blockages remain responsible for the majority of public flood events (Ten Veldhuis, 2010). In addition, management strategies for lateral (house) connections are generally reactive, owing to the scarcity of data on the condition of these components and the lack of knowledge on the effectiveness of proactive strategies. For example, only 1.9% of these studies on sewers concern lateral (house) connections or gully pots (Scopus, 2016).

Safeguarding the performance of the anterior part of sewer systems calls for the optimisation of management strategies, where proactive and reactive activities are balanced to improve cost-effectiveness. A prerequisite for the appropriate allocation of available resources is knowledge on the effectiveness of proactive strategies and information on blockage prone components to prioritise management decisions. The objective of this thesis is to **provide a methodology that supports the development of management strategies for the anterior part of the sewer system**. Several research questions have been formulated in order to meet this objective:

1. What mechanisms contribute to a blockage?
2. What is the overall contribution to serviceability losses?
3. What factors differentiate blocked components from the rest of the stock?
4. Are proactive strategies effective in improving sewer serviceability?

1.7 Thesis outline

The work presented in this thesis is divided in three parts, as presented in Figure 1.3. The first part establishes a theoretical basis by providing an overview of the available literature on blockage mechanisms of gully pots and lateral (house) connections (Chapter 2). As literature on these sewers is scarce, the scope has been expanded to include sewers with similar characteristics.

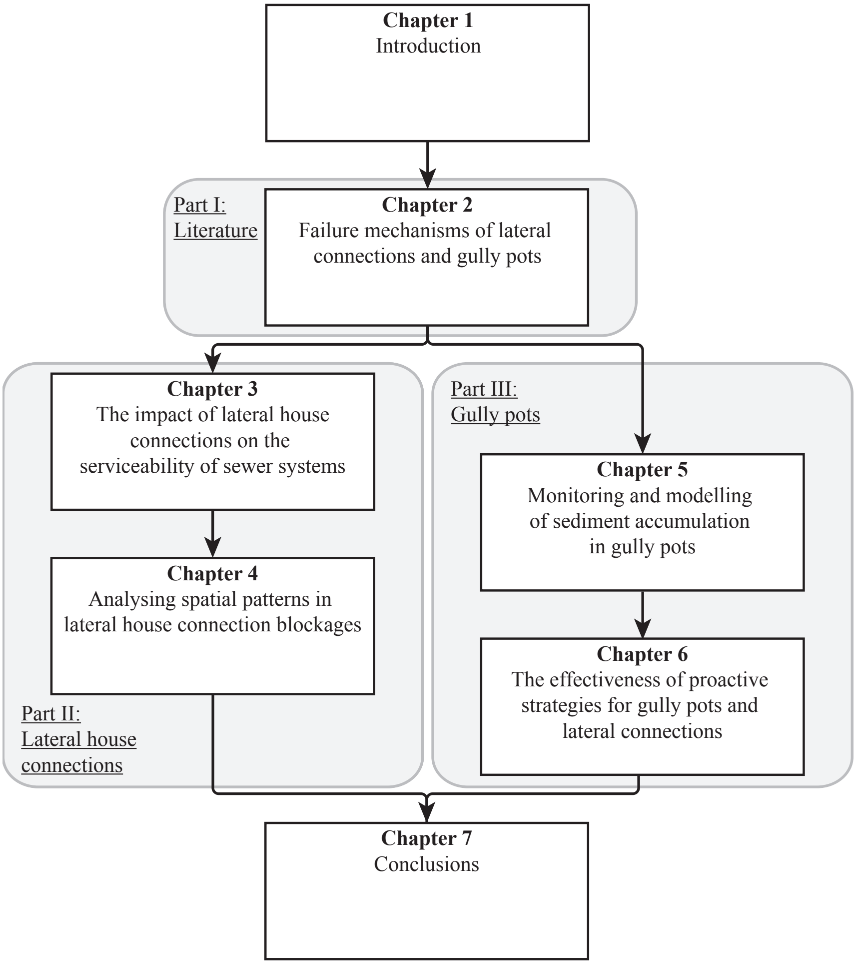

Figure 1.3: Relation between the different parts in this thesis .

The second part is dedicated to lateral house connections. Chapter 3 quantifies the contribution of different failure mechanisms to the overall probability of a lateral house connection blockage. Emphasis is put on the comparison with failure rates of other sewer components to determine the impact of lateral house connections. Chapter 4 describes a statistical approach to identify blockage prone lateral house connections. The modelling approach considered factors that explain observed blockage incidences. Scarcity of data on these factors is acknowledged and accounted for.

The third part discusses gully pots and lateral connections. First, Chapter 5 discusses the accumulation of sediment in gully pots, that may result in a blockage. This chapter contains a comprehensive monitoring campaign and a statistical model to determine the impact of different factors on the propensity to block. Subsequently, Chapter 6 investigates the effectiveness of proactive strategies to improve the serviceability of gully pots and corresponding lateral connections. To this end, Bayesian methods and methods from survival theory are explored.

Chapter 7 summarises findings from this thesis and draws conclusions. Recommendations for decision-makers and future research are made.

2 Failure mechanisms of lateral connections and gully pots

On the premise of a static hydraulic load, operational sewer failures occur when the cross-sectional area of flow reduces to such an extent, that the system is unable to meet the functional requirements. Commonly referred to as blockages, these operational failures can occur irrespective of the structural condition of the components comprising the system. Past research has identified a variety of mechanisms that can lead to the operational failure of a main sewer (e.g. Hahn et al., 2002; Stanić et al., 2014). Understanding potential failure mechanisms is an essential aspect of effective decision making in maintenance and rehabilitation (Ben Daya et al., 2016).

This chapter consists of two parts. The first part considers failure mechanisms of lateral (house) connections, while the second part focusses on the processes that influence the occurrence of gully pot blockages. In addition to identifying failure mechanisms, reviewing literature may also uncover the underlying root causes (see Figure 2.1) that promote the occurrence of blockages. Understanding these processes can aid to improve component design or focus proactive maintenance efforts. This chapter ends with a discussion and concluding remarks.

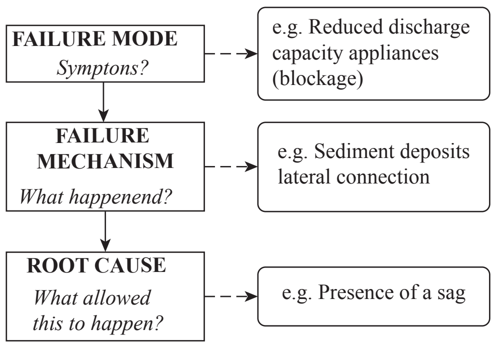

Figure 2.1: Hierarchy in root cause failure analysis.

This chapter is based on: Post, J.A.B., Pothof, I.W.M., Ten Veldhuis, J. A. E., Langeveld, J.G., and Clemens, F.H.L.R. (2016). Analysis of lateral house connection failure mechanisms. *Urban Water Journal*, 13(1):69-80, doi: `http://dx.doi.org/10.1080/1573062X.2015.1057175` and Post, J.A.B., Pothof, I.W.M., Langeveld, J.G., and Clemens, F.H.L.R. (2016). Monitoring and statistical modelling of sedimentation in gully pots. *Water Research*, 88:245-256, doi: `http://dx.doi.org/10.1016/j.watres.2015.10.021`

2.1 Lateral connections

Literature on both small diameter main sewers and lateral (house) connections located outside buildings have been considered, as these are strongly related. Despite this relation, susceptibility to failure mechanisms may vary from main sewers. Lateral connections differ from main sewers with respect to diameter size (<200 mm) and the governing flow regime. The flow responsible for transport in small sewers located at the upper ends of sewer networks varies in time, depending on both the number and types of appliances discharging (Littlewood and Butler, 2003). Consequently, the transport of solids in these sewers is often intermitted, as solids are deposited and subsequently re-suspended (Ashley et al., 2004; Brown et al., 1996; Butler and Graham, 1995).

2.1.1 Pipe collapse

Deterioration of a sewer pipe may eventually trigger a collapse of the pipe. Loose pipe material, as well as ingress of soil can also restrict the effective cross-section. Lillywhite and Webster (1979) mentioned that collapsed pipes make up 10% of all faults found in a survey concerning lateral connections in the UK. All collapsed service laterals concerned vitrified clay pipes and although the exact cause could not be identified for all cases, high loadings or ground subsidence could be related to some of the cases. Liserra et al. (2008) showed a higher break rate for house connections of a distribution network, compared to the main network. The authors suggest that the difference in break rate stems from an increase in likelihood of interfering with other underground services.

Savic et al. (2006) analysed an asset database containing an inventory of all blockage events and collapse failures for a sewer network in the UK with pipe diameter sizes ranging from 50 - 1500 mm. Applying the evolutionary polynomial regression (EPR) method, the authors found that the likelihood of collapse increases when the pipe diameter decreases. The proposed regression equation includes an inverse relation between the mean pipe length and the number of collapses. Although this dependency specifies that shorter pipe segments are more prone to collapse, confirming the results of Britton (1982), no relation with the pipe material was identified. It is, however, possible that the influence of the pipe material is incorporated implicitly, since brittle vitrified clay pipes generally have a relatively short length compared to other materials (Environmental Protection Agency, 2000).

The Environmental Protection Agency (2000) discusses pipe diameters ranging from 50 mm to 1000 mm and stresses the importance of proper installation for vitrified clay pipes and a suitable bedding for PVC pipes. Britton (1982) extends this notion by claiming that bad construction workmanship is the primary cause of main sewer collapse. Besides high temperatures, trench loadings when installed improperly was mentioned by the Army Corps of Engineers (1984) as a possible cause for excessive pipe deflection of PVC pipes.

As part of a review, Davies et al. (2001) investigated the effect of the cover depth on the sewer structural condition. They found several studies that reported a decrease in the number of failures with an increasing depth. Fenner et al. (2000) used a Bayesian statistical model to identify priority zones for maintenance and concluded that foul sewers with a cover depth of 0 - 1 m and a diameter less than 150 mm are responsible for a high proportion of failures. O'Reilly et al. (1989) attributed this phenomenon to the influence of surface factors such as road traffic and utility maintenance activity. In addition, the authors reported more structural failures in sewers situated beneath gardens than roads and suggested this to be result of disturbances during construction or later.

Figure 2.2: Damage to a lateral connection by a cross drill (Langeveld and De Haan, 2014).

The interaction with other utilities was investigated by Oosterom and Gastkemper (2012). By analysing CCTV inspections, the damage to main sewer pipes by horizontal directional drilling of utility lines in the southern part of the Netherlands was researched. An example of a cross drill is shown in Figure 2.2. The authors concluded that there were 18 cross drills per 100 km main sewer, with an estimated total repair cost of more than 35.5 million Euro. Based on a survey among different municipalities, the authors estimated the number of cross drills in lateral connections to be several times greater than the amount found for main sewers. This presumption is confirmed by Ariaratnam (2014), who reported cross drills in 2% of the 11,000 inspected lateral connections.

Davies et al. (2001) mentioned several studies that have recognised the influence of leaking or broken pressure mains on the stability of sewers. Amongst others, they reviewed a study by Sparrow and Everitt (1977), who elaborated how a near void created by the transport or compaction of soil due to water from a pressure main, can result in the collapse of a sewer pipe.

Infiltration may threaten the structural integrity of sewer pipes when the surrounding soil is transported by leaking water (Davies et al., 2001). The Environmental Protection Agency (2000) mentions that even when pipe materials are more resistant to acids and chemicals, the joints are not. This makes joints more susceptible to leakages. Several authors reported that the connection with the main sewer is the weakest point (Ellis et al., 2004; Princ and Kohout, 2004). For instance, even though literature indicates that lateral house connections cover 21 - 47% of the total length of the entire sewer system (Gonwa et al., 2004; Princ and Kohout, 2004), these components contribute 30 - 55% of the total infiltration (Curtis and Krutsch, 1993; Ellis, 2001; Sullivan et al., 1977; Water Environment Federation, 1999). This contribution is attributed to a lack of direct benefits of investing in maintenance for building owners (Ellerkamp et al., 2010) and a variable standard of workmanship of house connections (Reynolds and Barrett, 2003).

2.1.2 Tree roots

The penetration of tree roots into sewage lines can directly cause blockages and affect the structural integrity of sewers (Östberg et al., 2012). The latter is caused by the ingress of soil through an entry point expanded by roots, which may deteriorate the pipe to such an extent, that collapse is inevitable (Schrock, 1994). The direct occurrence of blockages is induced by the reduction of free flow by dense roots and the entrapment of suspended solids (Sullivan et al., 1977).

Root intrusion has been recognised as an underestimated problem, associated with nuisance and an increasing financial burden to society (Ridgers et al., 2006; Stål, 1998). A survey among 64 U.S. cities identified root penetration to be a major sewer maintenance problem (Sullivan et al., 1977). This notion is supported by Geyer and Lentz (1966) who studied four U.S. communities and reported tree roots to be the main cause of blockages in main sewers. A larger survey carried out by Stål (1998) among 232 municipalities in Sweden reported that 99% of the public sewer systems were affected by tree roots. The National Water Commission (2008) concluded that lateral sewers are also susceptible to tree root intrusion. They found that up to 85% of the annual lateral sewer breaks and blockages are caused by tree roots in Australia.

Tree roots are attracted to sewer pipes due to the high moisture gradient. This gradient is not only due to the exfiltration of water but is also the result of condensation on the pipe walls, which the roots follow until a vulnerable location is found where the sewer line is invaded (Rolf and Stål, 1994). This is also reflected in the seasonal variation. Marlow et al. (2011) reported an increase in blockages during drought periods. This is in line with the observations made by Beattie and Brownbill (2007) who published results for an Australian municipality, stating that the increase in blockage events can be fully attributed to the seasonal variation in tree root related blockages.

Several authors reported that the resistance to roots among different pipe materials is not similar. Rolf and Stål (1994) claim that PVC and glass-reinforced plastic pipes are nearly unaffected by root intrusion, as long as mistakes during construction are disregarded. This is contradicted by Ridgers et al. (2006); Stål (1998) who stated that even though older types of clay and concrete pipes are more sensitive to root intrusion compared to modern pipes, modern concrete and PVC pipes are not unaffected by roots. Via a survey in Denmark, Randrup (2000) found that 78% of the intrusions found were in main sewers made of concrete, compared to 16% for PVC. The author also reported a significant drop in root intrusions in pipes constructed after 1970 and noted that joints constructed before 1960 were filled with material that makes the connection stiff, therefore causing cracks when subjected to ground settlement. This view on pipe age is supported by Östberg et al. (2012); Rolf and Stål (1994). Ridgers et al. (2006), however, argue that it is 'difficult to distinguish the effect of time of exposure, from joint designs prevalent in earlier times'. Therefore comparison of different joint types or materials is not straightforward. In newer main sewer lines, roots are primarily found in the joints between pipes of different material which can likely be attributed to frequent mistakes during construction (Randrup, 2000; Rolf and Stål, 1994). This is confirmed by Ridgers et al. (2006) who built a full scale installation consisting of concrete and PVC pipes with trees planted directly above, to test the sensitivity of modern rubber junctions. After the first inspection, the joint between the concrete and PVC pipes already suffered from root intrusion. Moreover, ten years later most of the joints showed signs of root intrusion, indicating that these points are the most susceptible to root intrusion.

Data on root intruded pipes from two Swedish cities were collected by Östberg et al. (2012). In contrast to other studies, they reported a significant higher intrusion rate for PVC pipes compared to concrete pipes. A possible explanation mentioned is that a large amount of these PVC pipes are lateral connections, which are generally close to trees. This notion shows that the authors suspect lateral connections to be more vulnerable to root intrusion compared to main sewer lines. Several authors mention the vulnerability of lateral sewers with respect to root intrusion directly or indirectly. Based on data of root intrusions collected in Malmö, Sweden, Rolf and Stål (1994) reported that although the severity of the intrusion was generally limited to small roots, the majority of roots were found in small dimension pipes. Pohls et al. (2004) reached similar conclusions and added that 60% of all tree related blockages were found in pipes laid at shallow depths ranging from <1 m to 2 m. Sewer depth and insufficient inspection during construction are suggested to be the main cause of the higher maintenance requirement for root intrusions in lateral connections (42%) compared to main sewers (27%) in the United States (Sullivan et al., 1977). This survey also disclosed that lateral connections in foul systems are mentioned twice as often as being susceptible to tree root intrusion, compared to combined lateral connections. Besides this survey, several studies report the majority of all root related blockages to occur in lateral connections (Randrup, 2000; Randrup et al., 2001; Ridgers et al., 2006).

2.1.3 Fat, oil and grease (FOG)

Butler and Davies (2004) define fat, oil and grease (FOG) deposits as ‘a collective term for deposits consisting of fats, oils, greases and waxes of plant or food-based origin present in sewage’. These compounds hardly degrade and coagulate to form deposits that adhere to pipe walls, thereby reducing the effective cross-sectional area (DeSilva et al., 2011). In addition Bowen (2006) stated that FOG will often adhere to tree roots suspended from the top side of a sewer, increasing the likelihood of a blockage. The author even denoted this combination to be responsible for the majority of the mainline blockages.

Lillywhite and Webster (1979) reported large quantities of FOG deposits in the sags of lateral house connections for a sample of 70 service laterals. This is likely due to solidification after the temperature of the warm suspension decreases due to contact with stagnant water in the sag. These deposits were, however, never found to be the direct cause of a blockage unless only kitchen sinks were draining to the lateral in question. These findings contradict Dirksen (2013), who reported that FOG deposits in main sewer sags were the main contributor to blockages in Amsterdam.

Marleni et al. (2012) stated that it is likely that the presence of FOG deposits in sewers depends on the wastewater characteristics. The composition of wastewater in a lateral house connection is, however, dependent on the spills of only a few of users. This adds to the sensitivity of laterals house connections to appropriate use by residents.

2.1.4 Deposition of solids

Flows in lateral connections are intermittent, owing to the variation in rainfall intensities and use of different appliances throughout the day. Even though during dry weather the volume per discharge is largest for baths and washing machines (60 - 120 litres), the largest dry weather flow rates are associated with toilet flushes (Wise and Swaffield, 1995). Since the flow peak transporting solids attenuates as the wave progresses, solids may be deposited and resuspended by subsequent flushes (Brown et al., 1996). When resuspension does not occur, subsequent deposits build up, eventually clogging the lateral connection completely.

Transport of solids in these intermittent flows is governed by two mechanisms or a combination of the two (Littlewood and Butler, 2003). The authors found that for a large flush volume, compared to the solid size, solids are transported with a velocity proportional to the wave velocity. For larger solids, water will build up behind the object serving as a main driver for transport. The latter transport mechanism is more sensitive to minor obstructions such as pipe misalignment, which may disrupt the force balance by delaying the solid while letting by water, resulting in the deposit of solids (Swaffield and Wakelin, 1976). This presumption is confirmed by Lillywhite and Webster (1979) who investigated 70 laterals house connections with regularly recurring blockages and found that 30% of the cases involved defective pipe joints. These faults were believed to be the result of bad site construction rather than manufacturing errors. It should be noted that only one of these cases concerned a PVC system whilst the other systems consisted of cast iron or vitrified clay pipes, indicating the sensitivity of these materials for recurring blockages. In the same study results of laboratory work regarding the number of flushes required to transport solids through a pipe showed that a pipe with poor joints required more flushes. Moreover, many solids were reported to be stuck.

Littlewood and Butler (2003) reported an increase in the solid transport distance for a larger flush volume or a reduction in pipe diameter. The relation with the flush volume seems to be supported by Marlow et al. (2011). They found a significant relation between the water consumption and the number of blockages, supporting the hypothesis that water conservation efforts increases the likelihood of a blockage.

The influence of the pipe gradient on the number of flushes needed to transport solids was investigated by Lillywhite and Webster (1979). They did not ascertain a clear relation between the gradient and the number of flushes needed. This is consistent with a survey carried out in 194 vitrified clay pipes laid at different gradients with a diameter of 100 mm. The authors reported no significant relation between the pipe gradient and the number of blockages. These results are contradicted by Memon et al. (2007), who reported a positive effect of the gradient. An increase in the solids transport distance of over 50% was found by means of an experimental setup.

2.2 Gully pots

The accumulation of sediments in gully pots is governed by various processes. Depending on the retaining efficiency of the gully pot sand trap, the supply of solids induces progressive silting over time. This process is illustrated in Figure 2.3. When the trap capacity of a gully pot is exceeded, a blockage occurs. This section discusses the processes that influence the propensity to block.

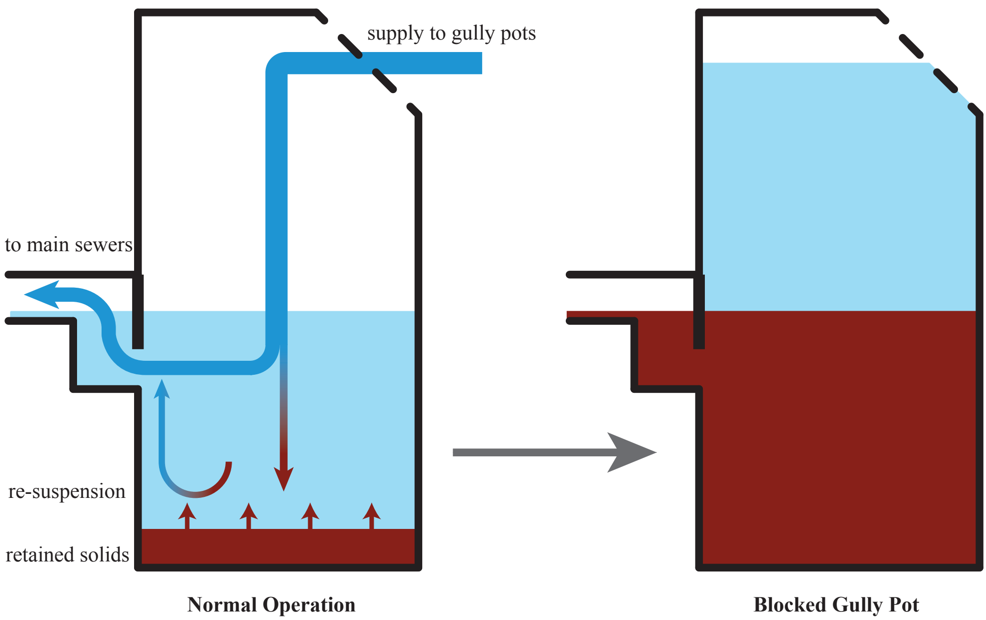

Figure 2.3: Solids transport processes in a gully pot that eventually lead to a blockage.

2.2.1 Supply to gully pots

Particles present in the urban environment are predominately inorganic, comparable to sand and silt (Lager, 1977; Sartor and Boyd, 1972). These particles originate from different sources, such as local traffic (Deletic et al., 2000), construction activities (Ashley and Crabtree, 1992), weathering of buildings (Jartun et al., 2008), animal wastes, litter, and de-icing materials (Brinkmann, 1985). Particles that are transported to gully pots during storm events are generally not well removed by street sweeping (Brinkmann, 1985; Sartor and Boyd, 1972). Material available for wash-off to gully pots may vary spatially, as the presence of potential sources is subject to local circumstances. Pratt and Adams (1984) reported a relation between characteristics of the contributing area (e.g. size, drainage path length) and the mean mass of the measured sediment wash-off in the field. These data did, however, originate from the same gully pots, indicating a potential dependence between successive measurements over time. In addition to spatial variation, the supply to gully pots may also vary temporally. Grottker (1990) analysed the organic content of sediment samples and found a higher organic loading (5 - 10%) in autumn. Peaks in the material supply in June, autumn and after snowmelt were mentioned by Pratt et al. (1987), indicating seasonal variation. On a shorter timescale, flow characteristics dominate the temporal variation. Ellis and Harrop (1984) found that the antecedent dry period was only weakly correlated with the sediment loading to gully pots. Rainfall intensity was, however, strongly correlated. Similar results lead Pratt and Adams (1984) to the conclusion that the shear force required to suspend material is limiting, rather than the availability of material. The overall variation in particle loading results in models that typically calls for several site specific calibration parameters (Memon and Butler, 2002).

In addition to the bulk of particulate matter, Butler and Karunaratne (1995) reported that 10% of the mass collected from 50 field samples consisted of non-particulate matter such as street litter from human activities. Armitage and Rooseboom (2000) reported the amount of litter varies both in time and space. The presence of vegetation and land use were identified as spatial variables, while the type of rainfall was mentioned as a variable explaining temporal variation.

2.2.2 Retaining efficiency

The fraction of solids captured by gully pots has been studied extensively. Field studies reported retaining efficiencies ranging from 20 to 50% (Deletic et al., 2000; Pitt and Field, 2004). Both Butler and Karunaratne (1995) and Grottker (1989) conducted lab experiments where the solids supply to gully pots was varied. They found that the retaining efficiency was independent from the solids concentration, which support model results from Butler and Memon (1999). Butler and Clark (1995) found the build-up rate to vary between 14 and 24 mm/month for urban areas. This variation may well be related to the substantial variation in grain size distributions of samples from different gully pots (Jartun et al., 2008), as solids with a smaller diameter are captured less efficiently (Butler and Karunaratne, 1995; Lager, 1977). The retaining efficiency for litter and debris range from 95 to 100% (Sartor and Boyd, 1972)

Laboratory tests by Butler and Karunaratne (1995) with varying sediment bed levels up to the level of the outlet pipe of a gully pot show a marginal increase in the retaining efficiency with increasing sediment depths. This is contradictory with experimental results reported by Lager (1977), who found that solids removal efficiencies decreased when a threshold of 40% of the gully pot storage was exceeded. The latter is supported by the increase in the retaining efficiency with an increasing cleaning frequency (Memon and Butler, 2002; Mineart and Singh, 2000). Field measurements from Butler and Clark (1995) indicate that equilibrium sediment bed levels were reached at the level of the outlet pipe. Conradin (1989) reported similar results for 63 gully pots monitored for 16 months; sediment bed levels did not exceed the level of the outlet pipes and equilibrium depths were generally reached in 6 months. Pitt and Bissonnette (1984) found bed volumes to stabilise after a year. These results are, however, not in line with recent research (e.g. Caradot et al., 2011; Ten Veldhuis et al., 2011) that concluded gully pot blockages to be the dominant cause of flooding events.

2.2.3 Re-suspension of sediments

There is a general consensus that the sedimentation rate is inversely proportional to the rainfall intensity (e.g. Morrison et al., 1988; Deletic et al., 2000; Ciccarello et al., 2012). Depending on the particle size, the jetting effect induces erosion of the gully pot sediment bed (Butler and Memon, 1999). Sartor and Boyd (1972) applied flushing tests equivalent to heavy storms and found only 1% of the sediment bed to be re-suspended. This confirms earlier results reported by Fletcher and Pratt (1981), who mentioned that the majority of solids discharged from gully pots are due to a lack of sedimentation rather than re-suspension. As the top layer of the sediment bed is more unstable, these solids may be eroded (Pitt and Field, 2004). However, bed erosion decreases substantially as these particles are depleted and the bed becomes graded (Butler and Karunaratne, 1995).

2.3 Discussion and conclusions

With the exception of solids deposition, literature on lateral (house) connection failures is limited. Since failures of main sewers and lateral connections are strongly connected (e.g. joints, materials, etc.), inference of studies concerning failure mechanisms of small diameter sewers is appropriate.

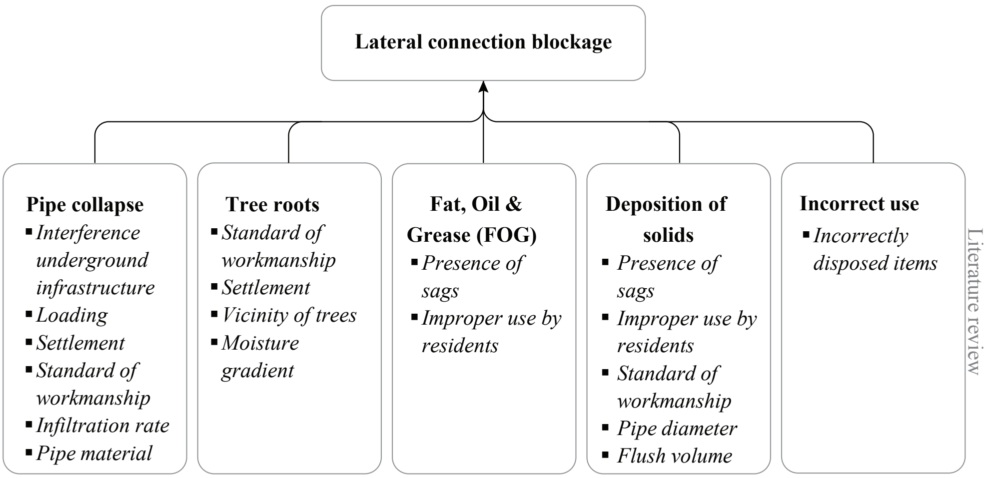

Figure 2.4: failure mechanisms identified in literature. Root causes reported for small diameter sewers are in italic.

Identified failure mechanisms are depicted in Figure 2.4. In addition, this figure provides an overview of the root causes that support these mechanisms according to literature. In conclusion, multiple studies indicate that lateral (house) connections are more susceptible to these failure mechanisms than main sewers. Incorrect use by citizens is mentioned repeatedly as a factor that influences the probability of occurrence of blockages. The structural condition of an asset (e.g. the presence of sags or state of the joints) seems to determine the extent to which a lateral connection is able to cope with incorrect use, before a blockage occurs. Moreover, the structural condition also determines the ease with which roots can intrude sewer pipes.

Gully pots are subject to successive storm events over time, where sediment bed levels increase or decrease depending on the rainfall regime. As the height of the bed increases over time, the trapping efficiency reduces. As a consequence, it is possible that the sediment bed reaches an equilibrium level and a blockage is precluded. This does, however, mean that particles and attached pollutants are transported to the downstream system. The hypothesis of equilibrium bed levels is contradicted by other studies that found gully pot blockages to be the dominant contribution to the risk of urban flooding.

3 The impact of lateral house connections on the serviceability of sewer systems

Lateral house connections are currently omitted when assessing the sewer systems ability to meet service requirements. The literature review in Chapter 2 suggested that lateral connections may be more susceptible to sewer failure mechanisms than main sewers. Yet, a quantitative assessment of the blockage propensity to support this assertion have not yet been considered.

Quantifying the blockage propensity of lateral house connections is pivotal in evaluating the impact on the serviceability of sewer systems. Analysing the contribution of different failure mechanisms provides an indication to which extent blockages appear to be random due to complex triggering mechanisms (Rodríguez et al., 2012) or are affected by progressive structural deterioration. This differentiation allows to further tailor maintenance strategies to be more effective.

Nomenclature

Symbol	*Description*
t	time to an event
T	duration of the observation period
n	total number of events
U	test statistics for trend detection
λ	event rate
x	operating time since an event
ψ_n	integrated distribution function
T_n	test statistic according to Klar (1999)
r_1	first order correlation coefficient

This chapter is based on: Post, J.A.B., Pothof, I.W.M., Ten Veldhuis, J. A. E., Langeveld, J.G., and Clemens, F.H.L.R. (2016). Analysis of lateral house connection failure mechanisms. *Urban Water Journal*, 13(1):69-80, doi: `http://dx.doi.org/10.1080/1573062X.2015.1057175`

The first section of this chapter introduces a database of the Dutch market leader in the maintenance of gravity drainage systems in and around buildings. This database contains close to two years of blockage data. As Lateral house connections are often (partly) under responsibility of the property owner, these data complement data from municipal call centres. Subsequently, a statistical procedure to analyse blockage data is discussed. Results and discussion are presented in Section 3.3, followed by conclusions in Section 3.4.

3.1 Blockage database

Quantitative data on lateral house connection blockages were obtained by interrogating the database of a commercial sewer maintenance company. This company serves mainly private property owners, businesses and housing associations. They specialise in resolving blockages in small diameter sewers on private property.

3.1.1 Data collection

The working procedure of the sewer company involves (1) driving a powered sewer router through the blocked pipe. This device consists of a slightly flexible metal cable with chains attached to the tips. As these tips reach a blockage, the rotation speed is increased. The resulting centrifugal force provides tension to the chains, which removes the blockage. Residues accumulate to the chains during operation and are used to establish the composition of the blockage. When the operator observes a decrease in the resistance and household appliances are able to discharge freely, the problem is considered solved. In other cases (e.g. debris or construction error), the pipe in question will be (2) excavated or (3) closed circuit television (CCTV) will be used to find the blockage cause.

Database records contained the following information for each case: A date when the event was registered by the call centre, a date when reactive maintenance was completed, the address, the observed composition of the blockage by the repair worker onsite and the object where the defect occurred. Data on the failure mechanism was collected by means of a multiple choice question with a single answer. The operator was instructed to denote the primary failure mechanism from a list of possible mechanisms. The relation between this list and the failure mechanisms discussed in Chapter 2 are shown in Figure 3.1. Classification was based on the composition of the blockage, of which examples are given in this figure. When the operator perceived the blockage to be caused by an act of the consumer, incorrect use was denoted as the main failure mechanism.

The call date was considered as the date at which the defect occurred. Data on lateral house connections were isolated by selecting cases with the proper object type while the failure mechanism was deduced from the recorded direct cause of the blockage.

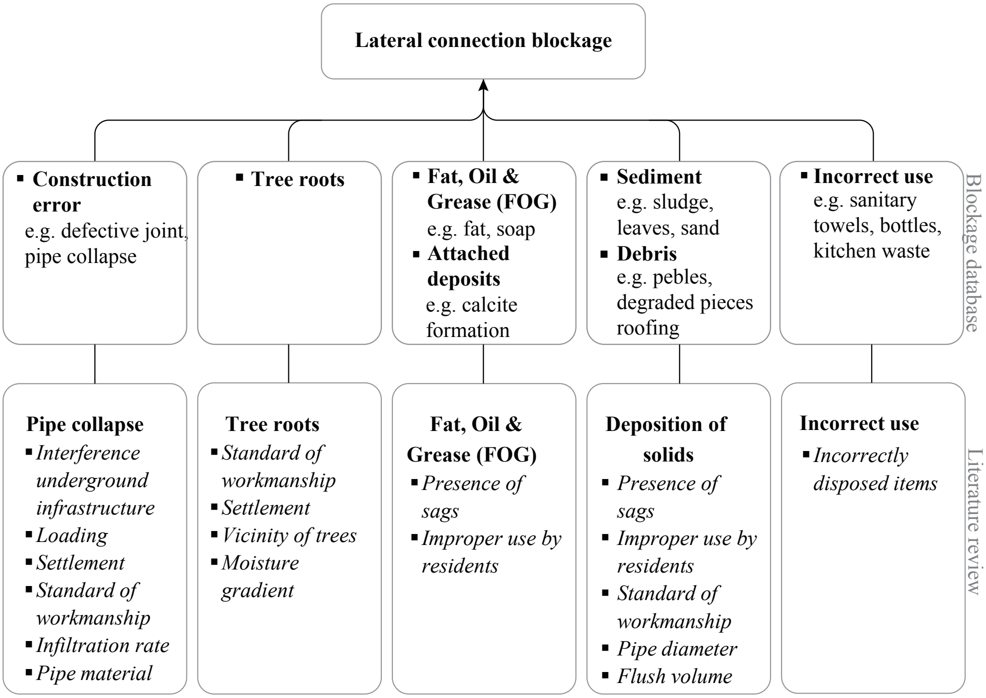

Figure 3.1: Relation between the available failure mechanisms in the interrogated database and the failure mechanisms identified in literature (see Chapter 2). Root causes reported for small diameter sewers are in italic.

3.1.2 Subsetting data

In total, the database comprises over 355,000 cases in the Netherlands in the period 2011-2013. As this database only covers the blockages solved by one company, it is not directly possible to derive a typical event rate, as their market share is uncertain. However, the company also serves housing associations with service contracts. In these contracts, the company is the sole service provider and, as a consequence, an blockage rate can be calculated for those areas where no other companies have been active. Therefore, a subset pertaining to a housing association was selected, which allows for normalisation of the blockage rate with respect to the total number of residential units. These normalised blockage rates were compared with other quantitative studies on other failure mechanisms of sewer systems, such as gully pot blockage and main sewer blockage.

A housing association located in the municipality of Rotterdam served as a case study. This city is the second largest in the Netherlands, with the majority of the buildings being constructed in the 20^{th} century. The sewer system is almost completely combined. The housing association in question represented close to 15% of the residential properties in Rotterdam, constructed mainly after 1920. The associated subset contained over 11,000 cases. To ascertain whether the relative contribution of each failure mechanism was representative for the Netherlands, it was compared with the contribution of each failure mechanism derived from the entire dataset containing 355,000 cases.

Although non-governmental ownership renders geometrical data of lateral house connections scarce, bounds for certain characteristics are known. Pipe gradients vary between 1:50 to 1:200 (Nederlands Normalisatie Instituut, 2011). Based on the year of construction of the premises, approximately 45% of all laterals is PVC and 55% vitrified clay. Moreover, the maximum design length is 20 meters (Ganzevles and Oomens, 2008), with pipe diameters vary between 117-200 mm.

3.1.3 Data validation

Data validation was conducted in order to remove any errors, inconsistencies or outliers that may affect the quality of the data. Registered events that met at least one of the following criteria were removed.

- Geocoding algorithms failed to find geographic coordinates associated with an address.
- The blockage occurred in the in-house drainage system instead of a lateral house connection.
- The property owner was never home.
- Failed date registration.
- Subsequent cases related to the same event.
- No blockage was found.

Figure 3.2 shows that from the initial 11,000 cases pertaining to the housing association, 4305 cases passed validation. By far the most cases were discarded based on the fact that the actual cause of the blockage was found to be in the building drainage system instead of the lateral house connection.

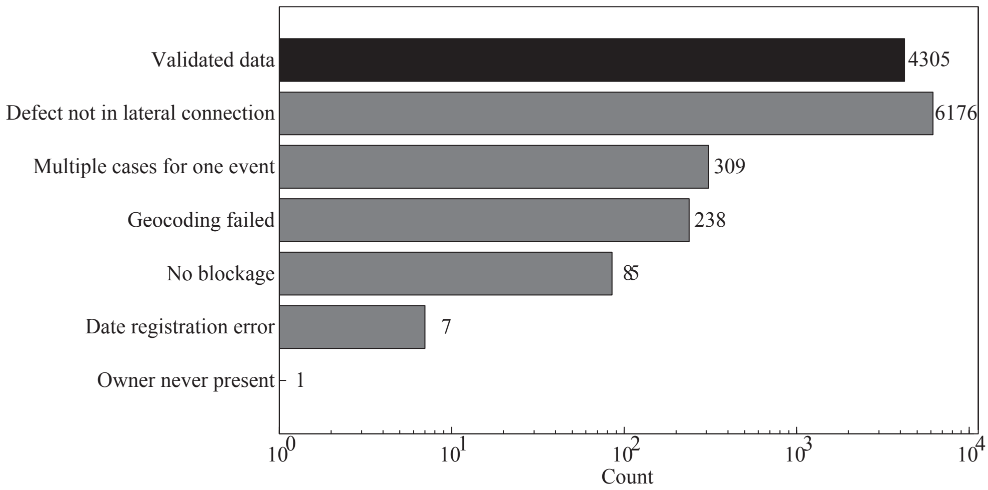

Figure 3.2: Validated event data for a housing association in Rotterdam.

3.2 Methods

Reliability theory specifies various approaches to model failure events. Reliability is defined as the probability that an item will meet functional requirements within a specified period of time. This chapter applied a statistical approach by assigning an appropriate probability distribution to model lateral house connection failure mechanisms.

A probability distribution that describes the event rate of a repairable system was established by adapting the procedure proposed by Ascher and Hansen (1998). This procedure is presented in Figure 3.3 and involves: (1) a trend analysis to identify a possible monotonic trend and (2) the identification of a process model to describe the time between successive events.

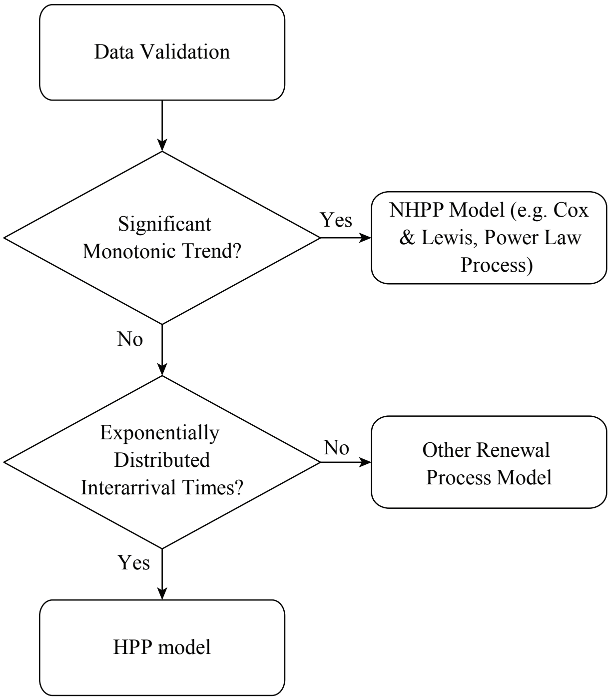

Figure 3.3: Procedure for analysing event rates of a repairable system, adapted from Ascher and Hansen (1998)

3.2.1 Trend analysis

First, a distinction was made between models with a constant (time independent) event rate and models with a time dependent event rate. In the presence of a Monotonic trend, events are described by models with a time varying rate. In the absence of a trend in the event rate, the times between successive events, also referred to as interarrival times, are independent and share a common probability distribution. This means that the probability of occurrence is not influenced by the systems history of events or the operating time. A decrease in the event rate is associated with errors in the production or installation process, whereas an increase indicates aging. These phases are part of the bathtub shaped failure pattern frequently suggested in literature (see e.g. Davies et al., 2001; Jin and Mukherjee, 2010; O'Connor and Kleyner, 2011) and illustrated in Figure 3.4.

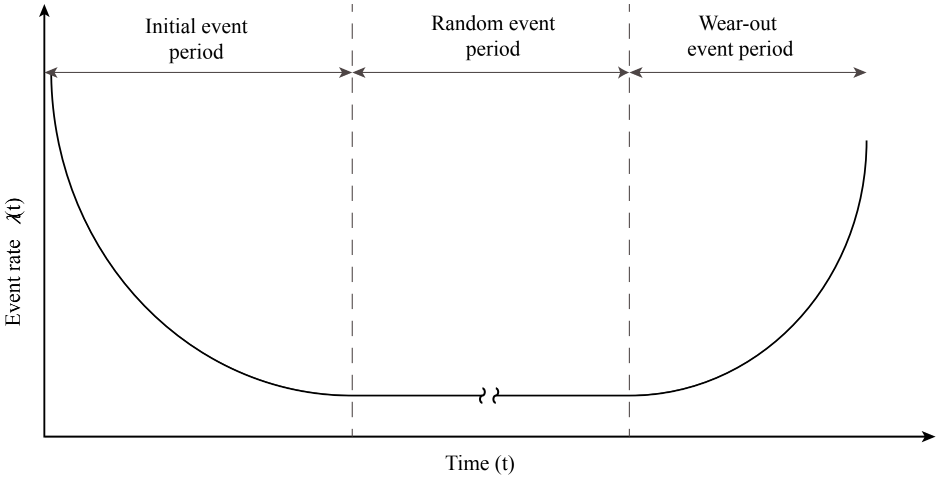

Figure 3.4: Schematisation of a bathtub shaped failure pattern.

Most of the useful life of a component takes place in the flat region of this curve, where the event rate is constant and repair restores the component to a state similar to the one before the event occurred. Therefore, it is referred to as a renewal process. A test statistic, which can identify a monotonic trend is given by

$$U_F = 2\sum_{i=1}^{n} \ln\left(\frac{T}{t_i}\right) \tag{3.1}$$

where $t_1, t_2, \ldots, t_i, \ldots, t_n$, are the times of events, T is the end of the observation period, and n is the total number of events. If the time series end after n events, instead of a fixed observation period, n becomes n-1 and T is T_n. When events are uniformly distributed over the interval 0 to T, this test statistic has a $\tilde{\chi}^2$-distribution with $2n$ degrees of freedom (Birolini, 2014).

An alternative test statistic is the Laplace test. This test is found to be appropriate for trend detection (Bain et al., 1985) and has been applied in the field of urban drainage (Korving et al., 2006; Rodríguez et al., 2012). Lewis and Robinson (1973); Lawless and Thiagarajah (1996) reported the following adjustment of the Laplace test statistic in order to improve performance for more general renewal process models. This test statistic is defined as

$$U_{LR} = \frac{\sum\limits_{i=1}^{n} t_i - \frac{nT}{2}}{T\sqrt{\frac{\frac{1}{n-1}\sum\limits_{i=1}^{n}(x_i-\bar{x})^2 n}{12\bar{x}^2}}} \tag{3.2}$$

where x_i is the operating time since event $t_{i\text{-}1}$. If no trend is present, all interarrival times are described by a common distribution.

3.2.2 Renewal process model

Subsequently, an appropriate distribution to model event data was determined (e.g. a Weibull or Gamma distribution). A special case of the renewal process is the homogenous Poisson process (HPP). Based on this process, the event count follows a discrete Poisson distribution with an equal variance and expected value. If a system consists of multiple components that can fail, there is a superposition of multiple renewal processes on a system level. Although in general the sum of multiple renewal processes is not a renewal process, the sum of several Poisson processes is (Tobias and Trindade, 2011). This allows for events of different lateral sewers to be analysed on a system level. A property of the HPP is that interarrival times are exponentially distributed. It follows that the probability of at least one event within a specified period of time t is described by

$$\Pr\left(n \geq 1\right) = 1 - e^{-\lambda t} \tag{3.3}$$

where λ is a positive real number. An unbiased estimate of this parameter is given by the following maximum likelihood estimate

$$\hat{\lambda}_{MLE} = \frac{n}{T} \tag{3.4}$$

which is equal to the event rate. The inverse of this estimate is the average interarrival time and is commonly referred to as the mean operating time between events (MTBE). Goodness of fit tests can be used to test whether the interarrival times are distributed according to the exponential model. To this end, the classical Kolmogorov-Smirnov test was selected. Moreover, a test for discrete distributions proposed by (Klar, 1999) was considered as a comparison, for the Poisson distribution. This statistic was found to be universally consistent by Gürtler and Henze (2000). The method is based on the deviation between the integrated distribution function and the empirical integrated distribution function and is given by

$$T_n = \sup_{t \geq 0} \sqrt{n} \left| \psi_n\left(t\right) - \widehat{\psi}_n\left(t\right) \right| \tag{3.5}$$

in which $\psi_n\left(t\right)$ is the empirical integrated distribution function and $\widehat{\psi}_n\left(t\right)$ is its estimated counterpart. By means of a parametric bootstrap procedure, the p-value is approximated. Unlike most test statistics, this test is asymptotically distribution-free (ADF) and consistent for discrete distributions. ADF refers to the fact the test does not depend on the probability distribution of the statistic when the null hypothesis is true. Consistency ensures that for a sufficiently large sample size, the test makes no error concerning the null hypothesis and its alternative.

The presence of temporal correlation in data hampers the application of hypothetical testing, as the number of independent observations is reduced (De Solla et al., 1999). Since correlated observations do not bring a full degree of freedom, confidence bands are incorrectly narrowed (Legendre, 1993). This inflates the probability of a type 1 error (incorrect rejection of a true null hypothesis). Temporal correlation can be regarded as a special form of persistence, the tendency of an observation with a small interarrival time to be followed by an observation with similar arrival times (e.g. during storm events). By correcting the number of degrees of freedom for temporal correlation between sequential observations, the probability of a type 1 error is reduced. Bartlett (1935) proposed an equation to correct the sample size based on the temporal correlation for many orders. By assuming a first-order Markov process, Dawdy and Matalas (1964) obtained the following equation for the effective sample size given by

$$n' = n\frac{1-r_1}{1+r_1} \tag{3.6}$$

in which r_1 is the first order correlation coefficient. The data are considered random if its first order autocorrelation is not significant at the 95% level. Confidence bounds of the goodness of fit tests were corrected for temporal correlation in other cases.

3.3 Results and discussion

After data validation 4305 recorded events spanning 85 weeks were available. First, Section 3.3.2 compares the derived event rates for lateral house connections with rates for other system component. Subsequently, Section 3.3.3 quantifies the contribution of different failure mechanisms and compares these with the distribution derived for the Netherlands. Section 3.3.4 goes into more detail on the implications of lateral house connection blockages for the level of service provided by sewer systems.

3.3.1 Trend analysis

The time of registration of a call was used to approximate the time of the event and the failure mechanism was deduced from the recorded blockage composition by the worker onsite. Figure 3.5 shows the registration over time to be linear (R-squared: 0.991), indicating a constant event rate.

A close-up of the data in Figure 3.5 shows both a daily and weekly pattern. Even though the customer call centres operate 24 hours a day, property owners appear less reluctant to report events in weekends or nights. This phenomenon also results in an increase in calls on Mondays. Locally weighted scatterplot smoothing was applied to reduce the effect of the discrepancy between the actual time of occurrence and the time of registration on the trend analysis. This procedure uses neighbouring points to smooth arrival times.

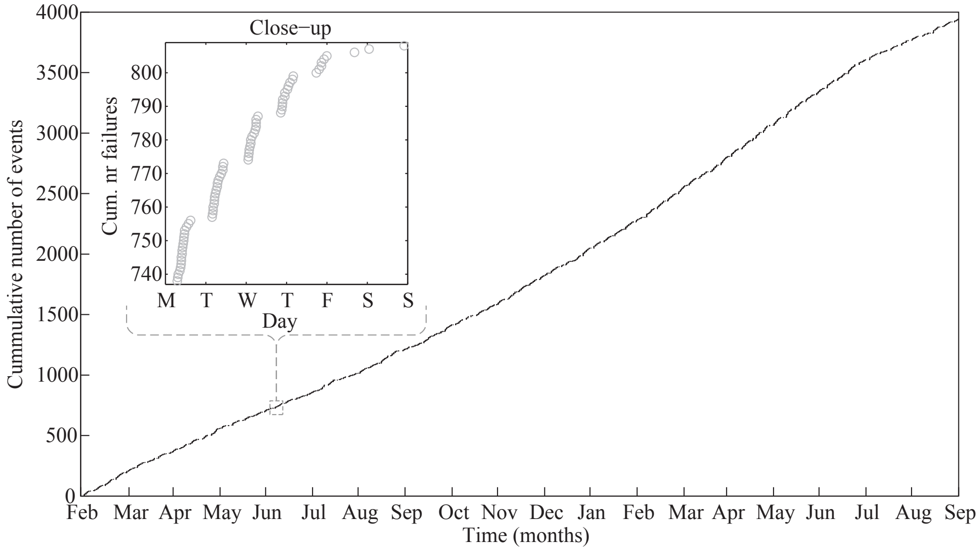

Figure 3.5: Cumulative number of reported blockage events over time.

The data were divided into nine subsets according to the recorded failure mechanism. Following the procedure outlined in Section 3.2.1, possible trends in these subsets were identified. The results for the test statistics given by Equations 3.1 and 3.2 respectively, are presented in Table 3.1. This table shows that on a 95% confidence interval, none of the subsets hold any significant monotonic trend in the event rate. Consequently, the occurrence frequency of each of the failure mechanisms is constant during the observation period. This is not unexpected, when considering the length of the observation period compared to the mean lifespan of sewer pipes.

3.3.2 Quantitative analysis of blockages

Analysis of the interarrival times reveals whether a renewal process can be described as a Poisson process. To this end, it was tested whether the interarrival times were exponentially distributed according to Equation 3.3. Power estimates for the test statistic proposed by Klar (1999) and the Kolmogorov-Smirnov test are given in Table 3.2. The mean time between events (MTBE) for FOG deposits was the smallest, thereby making this the dominant failure mechanism.

Table 3.1: Values of the test statistics for trends in event rates due to different failure mechanisms.

Failure Mechamism	$\tilde{\chi}^2$ distribution Lower crit. value	U_F	Upper crit. value	N(0,1) Lower crit. value	U_{LR}	Upper crit. value
FOG	171.76 <	181.97	<252.03	-1.96 <	1.63	<1.96
Debris	119.76 <	128.92	<188.03	-1.96 <	0.02	<1.96
Unknown	121.53 <	125.99	<190.25	-1.96 <	1.77	<1.96
Incorrect use	139.37 <	161.24	<212.42	-1.96 <	-0.66	<1.96
Sediment	95.07 <	104.84	<156.71	-1.96 <	0.65	<1.96
Attached deposits	157.32 <	170.78	<234.46	-1.96 <	1.15	<1.96
Construction error	63.94 <	79.11	<115.84	-1.96 <	-0.26	<1.96
Tree roots	6.91 <	27.87	<28.85	-1.96 <	-1.75	<1.96

Table 3.2: Power estimates of goodness of fit tests for Poissonity and associated characteristics.

Failure mechanism	P-value K-S test	T_n	Characteristics λ(week^{-1})	MTBE(week)
FOG	0.18	0.16	19.13	0.05
Debris	0.19	0.14	1.58	0.63
Unknown	0.22	0.25	9.63	0.10
Incorrect use	$4.84 \cdot 10^{-2}$	0.11	4.80	0.21
Sediment	0.08	0.07	3.89	0.26
Attached deposits	0.07	0.16	5.14	0.19
Construction error	0.40	0.36	0.96	1.04
Tree roots	0.58	0.56	0.11	9.40

Based on the data presented in Table 3.2, the hypothesis of a Poisson process was rejected on a 95% confidence interval for the failure mechanism 'incorrect use'. All other failure mechanisms showed a p-value ≥ 0.05, indicating a HPP. However, a few values were outside the bounds in the case of 'incorrect use'. The sensitivity of the Kolmogorov-Smirnov test to deviations from the hypothesized distribution occurring in the tails, is clear from Figure 3.6. This Figure shows the exponential probability based on Equation 3.3 versus the interarrival times. The narrow bounds on the lower part of the graph demonstrate the sensitivity of the Kolmogorov-Smirnov test. Moreover, the power estimate of the statistic proposed by Klar (1999) provided insufficient evidence ($p = 0.11$) to reject the hypothesis of a HPP.

A stochastic process can be modelled as a HPP when events occur continuously and independently of one another. Since the majority of individual properties experienced less than two events in the observation period, independency with respect to the time of the last event is evident. Moreover, lateral house connections commonly operate independently from one another, thereby contributing to the notion that the sum of these processes is also independent.

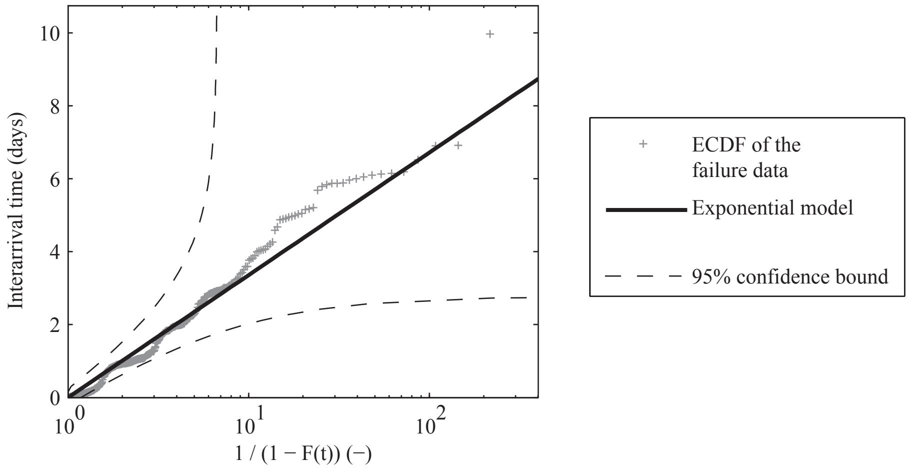

Figure 3.6: Exponential probability plot for the failure mechanism 'incorrect use'.

The superposition of the contributing failure mechanisms in Table 3.2 allows for a comparison between the event rate of lateral house connections and main sewers. As lambda corresponds to the expected number of events per unit of time for a Poisson distribution, it is a suitable indicator for the event rate. For the case study consisting of 53,000 houses, this amounted to 4.88 blockages per 100 houses per year, which is in the same order of magnitude as values reported by the Institution of Sanitary Engineers (1954) for Local Authority owned housing areas in the UK. By normalising the event rate with respect to the mean main sewer length per residential property (5.29 m / property for the Rotterdam area), the results become comparable with similar studies for main sewers.

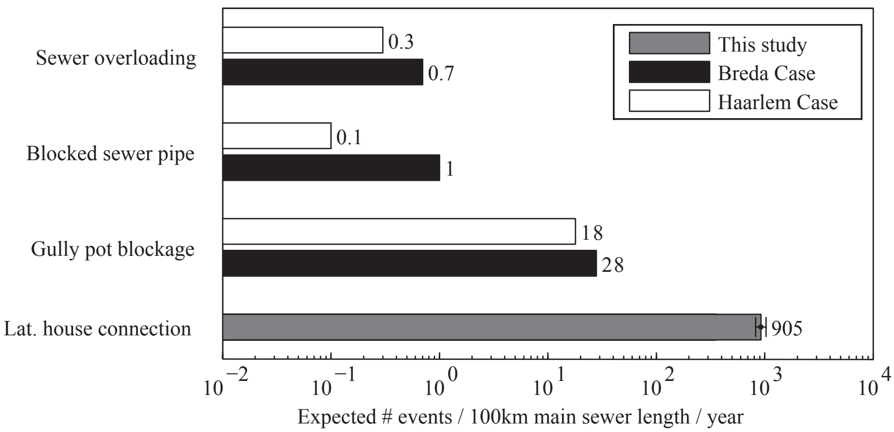

Figure 3.7: Comparison of the number of events for different failure mechanisms of public sewer systems (Ten Veldhuis and Clemens, 2011) and failures of lateral house connections (this chapter).

Figure 3.7 presents the failure rate of lateral house connections determined in this chapter and compares this to the results for other failure mechanisms of main sewers as reported by Ten Veldhuis and Clemens (2011), for two case studies in the Netherlands. The authors adapted a data driven approach for two cases, analysing pluvial flood events reported to the municipality by citizens. Although these data were not from the same municipality in the Netherlands as the data considered in this chapter, they do provide a comparison of the order of magnitude. Event rates of lateral house connections were found to be several orders of magnitude larger than blockage rates of main sewers. These findings verify the conclusion from Chapter 2, that lateral house connections are more susceptible to operational failures than main sewers.

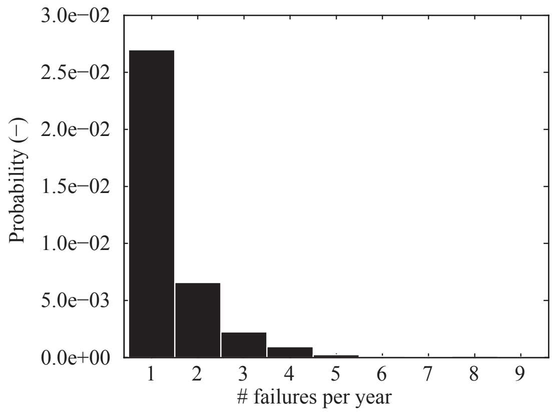

Figure 3.8: Yearly event probability for lateral house connection blockages.

The probability of a property experiencing a specific number of lateral house connection blockages in a year is presented in Figure 3.8. In total, the probability for a property to experience at least one event per year, is approximately 3.5%.

3.3.3 Contribution of failure mechanisms

The results in Table 3.2 provide insight into the contribution of different failure mechanisms. Based on this table, the frequency of occurrence of different failure mechanisms are presented in Figure 3.9, together with a 95% confidence interval. The results in Figure 3.9 show that tree roots was the least common failure mechanism. This may be attributed to generally high groundwater tables in the area, as indicated in Section 2.1.2. As the groundwater influences the moisture gradient, it directly influences the likelihood of root intrusion (Rolf and Stål, 1994). The main failure mechanism was FOG deposits. This result exhibits similarities with Lillywhite and Webster (1979), who reported FOG deposits to be widespread in lateral house connections. Section 2.1.3 stated that the accumulation of FOG deposits do not only depend on the structural condition (e.g. sags) but also on the incorrect use by residents. Therefore, a part of the events attributed to FOG might be due to incorrect use, as spills cause wastewater characteristics to be significantly different from design specifications. The derivation of rates for root causes identified in Chapter 2 is not possible, due to absence of field data.

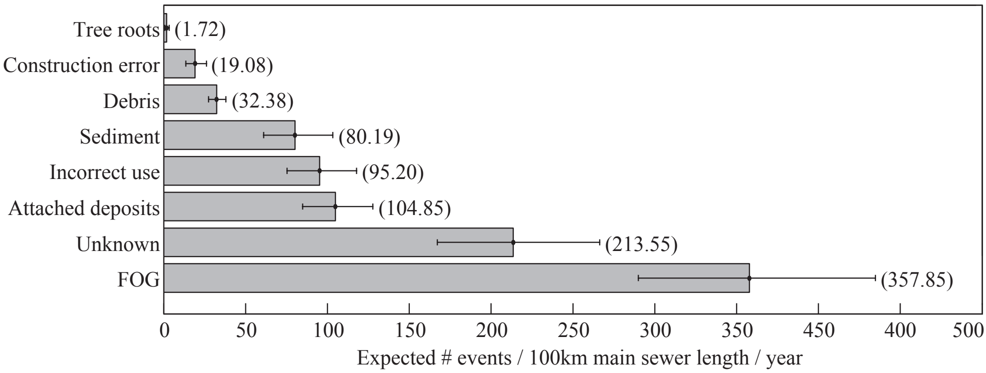

Figure 3.9: Contribution of different failure mechanisms to the failure rate of lateral house connections.

The relative contribution of failure mechanisms for both the housing association studied (subset) and the Netherlands (total dataset) are presented in Figure 3.10. This figure shows that the distribution of failure mechanisms for the case study is comparable to the distribution derived for the Netherlands. Therefore, the results in Figure 3.9 are deemed representative for the Dutch situation. Although errors are inevitable due to a subjective analysis of the situation (Dirksen et al., 2013), both distributions are in agreement. The large number of 'unknown' events indicate that for some events the exact mechanism is difficult to determine. This is in line with Dirksen et al. (2013), who reported that errors related to the identification of defects are inherent to the subjective assessment of visual information.

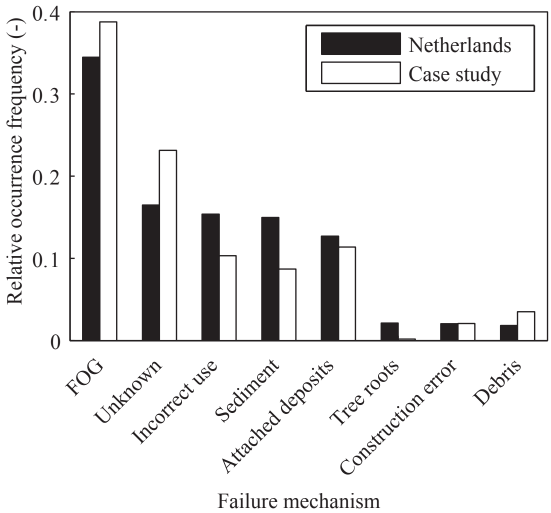

Figure 3.10: The relative occurrence frequency of failure mechanisms for both the total dataset (Netherlands) and the subset (Case study).

3.3.4 Implications for the level of service provision

The possible consequences of a failure are diverse. Commercial sewer maintenance databases and municipal call databases are powerful tools to obtain insight into the impact on sewer serviceability, as it provides a clear view on levels of system performance deemed unacceptable by users. Acceptability by users may also partially explain the difference in the operational failure rate reported for main sewers and lateral house connections in Figure 3.7. It is not uncommon that water can follow alternative flow-routes in case of main sewer or gully pot blockages. Moreover, when water is unable to enter a sewer system it is predominately confined to the public space, limiting undesired consequences. As there is no alternative flow route in case of a blockage in a lateral house connection, residents are more likely to be exposed to undesired consequences. Moreover, lateral connections are the part of the sewer system closest to the user. These properties render residents reluctant to report an event.

Costs as a result of a blockage event consist of two components. The first are the direct costs for repair, needed to restore the object to its original operational state. Table 3.3 shows that although the costs per incident is highest for a main sewer blockage, the costs per 100 km, based on the results in Section 3.3.2 are lowest due to the limited number of recorded events. For lateral house connections, however, the opposite is true. In addition, these higher costs are primarily borne by individual property owners instead of the municipality.

Table 3.3: Estimated costs associated with resolving failure events in various system components (price level 2014, municipality of Amsterdam, the Netherlands).

Event	Costs per event	Costs per 100 km of main sewer per year
Lat. house connection	€90.- to €200.-	€80,000.- to €180,000.-
Gully pot blockage	€150.-	€3,000.- to €4,000.-
Main sewer blockage	€300.-	€30.- to €300.-

The second are the costs related to damage caused by a failure event. Bowen (2006) mentioned that property damage claims against the municipality often follow blockages in main sewers and lateral house connections. Spekkers et al. (2014) interrogated a property-level insurance damage database, for a case study in Rotterdam, the Netherlands. The authors found that 18% of the filed claims relate to blocked household wastewater systems versus 1.5% of the claims that pertain to blocked public wastewater systems. This supports the notion that the operational condition of the public part of the sewer system is not the dominant cause of losses in sewer serviceability and demonstrates the social relevance of this topic.

3.4 Conclusions

This chapter aimed to quantify the contribution of different failure mechanisms to the probability of occurrence of lateral house connection blockages by means of a data driven approach. It is concluded that the lateral sewers connecting building drainage systems to main sewers are more susceptible to blockages than main sewers.

Results show the event rate of lateral house connections is 4.9 blockages per 100 house connections per year or 905 events per 100 km main sewer length per year. This rate is several orders of magnitude larger than rates reported for the main sewer system (0.3 - 0.7 events per 100 km main sewer length per year) and gully pot blockages (18 - 28 events per 100 km main sewer length per year). On a property level, this comes down to a probability of 3.5% that at least one event will occur in a lateral house connection in a given year.

The applicability of reliability theory to describe event rates is demonstrated. On a system level, lateral house connection blockages are modelled as a Homogeneous Poisson Process (HPP). The event rate remained constant in the observation period and individual events were independent. FOG deposits were found to be the dominant failure mechanism, being responsible for more than one third of all events in lateral house connections. The literature discussed in Chapter 2, identified the structural condition of the objects (e.g. presence of sags) and incorrect use by residents to be root causes of this failure mechanism.

The sheer number of events in lateral house connections directly affects the level of service provision. Furthermore, these operational failures pose a high financial burden (€80,000 - €180,000 per 100 km sewer length per year based on the price level in 2014 in the Netherlands), often borne by individual property owners.

4 Analysing spatial patterns in lateral house connection blockages

Chapter 3 revealed the contribution of lateral house connections to losses in sewer serviceability; blockage rates of these sewer components were found to be two orders of magnitude greater than main sewer rates. These results are in line with Cherqui et al. (2015), who reported lateral connection blockages to dominate main sewer blockages for the case study of Bordeaux Urban Community.

In the UK, recent legislation has facilitated the transfer of lateral house connection ownership to water authorities (HMG, 2011). It was believed this transfer would reduce repair burdens for individual households and improve management of the sewer system (Defra, 2011). Adopting a more proactive management strategy can improve the overall level sewer serviceability by focussing maintenance on system components before an actual blockage occurs. Next to being more cost-effective (Fenner, 2000), proactive strategies safeguard citizens from undesired consequences. Nevertheless, moving away from reactive strategies requires information on the condition of lateral house connections, which is typically not available.

Modelling the operational condition of sewers is considered difficult, due to the extensive number of factors influencing the complex processes (e.g. Ashley et al., 2000; Chughtai and Zayed, 2008). Therefore, Rodríguez et al. (2012) opted for a statistical approach to analyse blockage events. Several studies have been devoted to modelling the operational condition of main sewers through empirical equations based on physical properties such as pipe diameter, length, slope, and age (see e.g. Savic et al., 2006; Chughtai and Zayed, 2008). However, data on these properties are generally lacking for lateral house connections, limiting the factors available to explain differences in observed blockage incidences. The effect of missing factors are, however, present in the spatial patterns of observed blockages. By incorporating these spatial patterns in the modelling approach, the effect of missing factors is mitigated. Hence, this chapter describes a statistical approach that takes into account the spatial variation of lateral house connection blockage data to direct inspections and interventions (maintenance

This chapter is based on: Post, J.A.B., Langeveld, J.G., and Clemens, F.H.L.R. (2016). Analysing spatial patterns in lateral house connection blockages to support management strategies. *Structure and Infrastructure Engineering*, doi: `http://dx.doi.org/10.1080/15732479.2016.1245761` or rehabilitation) by identifying parts of the system with a significant higher blockage likelihood. In addition, the identification of external factors discriminating blocked lateral house connections from the stock of non-blocked lateral house connections may help to identify blockage-prone areas in catchments where blockage data have not yet been collected. This chapter includes two examples where the described modelling approach is applied to blockage databases from two cities.

Nomenclature

Symbol	*Description*
ρ	blockage intensity
λ_1	event data
λ_0	non-event data
κ	Gaussian kernel
s	spatial grid points where the intensity is estimated
S	spatial coordinates lateral house connections
c	grid cell size
p	number of grid cells
h	smoothing bandwidth
n_0	number of non-events
n_1	number of events
$\widehat{T}$	Monte Carlo test statistic
f	nonlinear smoothing function
h	expected value of the dependent variable
β	regression weights assigned to factors u
u	factors in the linear predictor

4.1 Methods

Call data from the sewer drainage company introduced in Chapter 3 were analysed by following the procedure described in Figure 4.1. The procedure first removes inconsistencies and errors from the dataset. This step removes duplicate calls for the same event, registration errors, events due to in-house sewer defects and cases where no defect is established. Subsequently, the presence of spatial variation in observed blockage incidences is evaluated to determine whether all areas experience the same blockage likelihood. A non-parametric test for spatial variation is discussed in Section 4.1.1. The occurrence of significant spatial variation confirms that not all lateral house connections experience the same blockage likelihood and motivates the identification of factors that explain this spatial variation. Section 4.1.2 discusses a semiparametric regression model which is able to incorporate relevant explanatory factors that indicate the presence of a blockage. Since data on the physical characteristics of lateral house connections is limited, this model includes an extra term to improve the performance by accounting for the spatial variation caused by missing factors.

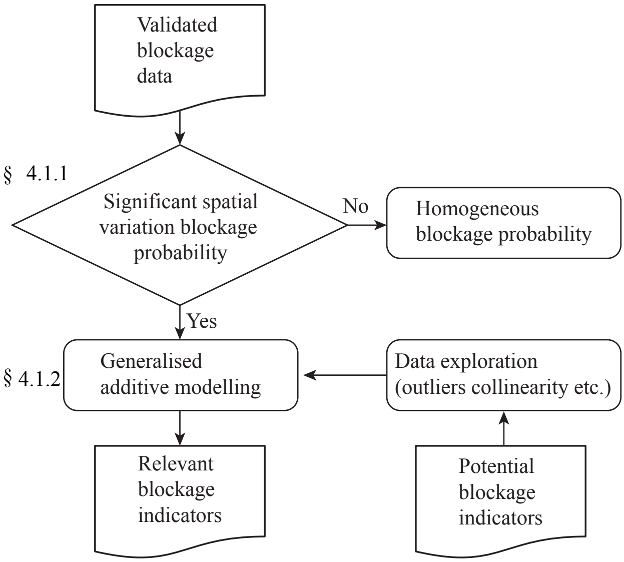

Figure 4.1: Procedure for analysis of spatial blockage data. References to the corresponding Sections where the methods are elaborated have been added.

4.1.1 Non-parametric testing for the presence of spatial variation

Exploring the spatial variability of blockages in a region requires a mixed database with both residential properties that reported one or more blockages λ_1 (event data) and residential properties that did not experience any blockage λ_0 (non-event data). This is necessary to normalise observed blockage rates with the number of residential properties. The blockage intensity is the ratio between events and non-events and is given by:

$$\rho = \frac{\lambda_1}{\lambda_0} \tag{4.1}$$

Direct analysis of the ratio between events and non-events is impracticable, as both data are discrete and do not occur at the same location. Kelsall and Diggle (1995b) computed the bivariate kernel density function to create a continuous two dimensional surface from discrete event data with known spatial coordinates. Figure 4.2 illustrates this principle by showing the cross section of a kernel density function. Kernel density estimation has been applied in the field of urban drainage for the spatial analysis of flood event data (e.g. Caradot et al., 2011; Cherqui et al., 2015).

The bivariate kernel density estimate $\widehat{\lambda}$ for coordinates s on a regular two-dimensional grid, given a sample of n_1 blockages having coordinates $S_1, .., S_\mathrm{i}, .., S_\mathrm{n}$, is given by:

$$\widehat{\lambda}\,(s) = \frac{1}{nh^2} \sum_{i=1}^{n} \kappa \frac{s - S_i}{h} \tag{4.2}$$

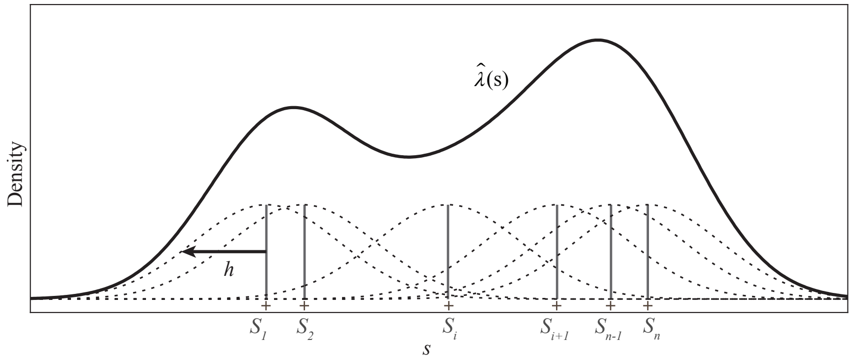

Figure 4.2: Example of the cross section of a bivariate kernel density function at coordinates s, given by the sum of n kernels at coordinates $S_1, .., S_\mathrm{i}, .., S_\mathrm{n}$ and bandwidth h.

where κ is the Gaussian kernel function. The smoothing bandwidth h (i.e. a measure of standard deviation) controls how the density is spread around the point of interest. It is considered a critical parameter, as its value can have a large effect on the accuracy of the estimator (Silverman, 1986; Wand and Jones, 1995). Choosing an inappropriate bandwidth can result in oversmoothed estimates that mask characteristics of the underlying blockage data. The likelihood based cross-validation principle suggested by Habbema et al. (1974); Duin (1976) given by:

$$CV\left(h\right) = -\frac{1}{n}\sum_{i=1}^{n}\left[\log\left(\sum_{\substack{k=1\\k\neq i}}^{n} \kappa\frac{S_k - S_i}{h}\right) - \log\left(\left(n-1\right)h^2\right)\right] \tag{4.3}$$

was used to determine the optimum bandwidth. This equation is implemented in the Spatstat library (Baddeley and Turner, 2005) of R statistical programming software (Core Team, 2014). Testing of the null hypothesis of a constant blockage intensity was performed by means of a Monte Carlo simulation, using the statistic $\widehat{T}$ (Bivand et al., 2008):

$$\widehat{T} = c\sum_{j=1}^{p}\left(\frac{\widehat{\lambda}_{1,j}}{\widehat{\lambda}_{0,j}} - \frac{n_1}{n_0}\right)^2 \tag{4.4}$$

Where n_0 is the number of non-events, c is the grid cell size and p the number of grid cells. This test statistic is computed k times, where each simulation consists of the kernel density estimation of randomly relabelled events and non-events. These simulations form the null-hypothesis of a constant blockage intensity for the region (Kelsall and Diggle, 1995a). The extent to which the observed blockage patterns match these simulations determines whether the null-hypothesis is accepted. This is represented in the p-value, which is estimated by computing the proportion of simulations where the test statistic $\widehat{T}$ exceeds that of the observed blockage data. When the p-value is not consistent with the hypothesis of a constant blockage intensity for the system, there is a significant difference in the lateral house connection blockage likelihood throughout the system under observation.

4.1.2 Generalised additive modelling

This section introduces the regression method used for the identification of factors that distinguish properties with lateral connection blockages from the rest of the property stock. A generalised additive model (GAM) (Hastie and Tibshirani, 1986) is a semiparametric model that extends the generalised linear model (GLM), which itself is a generalisation of the well-known linear model. Generalised linear models extend the linear modelling framework by relaxing the assumption that observations come from a normal distribution. This is essential for the analysis of blockage count data, which are characterised by non-negative integer values. These properties make the Poisson distribution particularly suited as sampling distribution (Fox, 2008).

When data on certain relevant factors are unavailable, the models ability to explain spatial variation in blockage incidences decreases. Next to a reduction in model performance, the remaining unexplained spatial variation may elicit overestimation of the statistical significance of factors in the model (Cressie, 1993). A generalised additive model extents the GLM with an additional nonparametric smoothing term. This nonlinear smoothing function f attempts to capture the excess spatial variation caused by these inadvertently omitted factors by incorporating the spatial structure of the blockage data in terms of x and y coordinates. The general form of this model can be expressed as:

$$\log(\eta_i) = \underbrace{\beta_0 + \beta_1 u_{i,1} + .. + \beta_j u_{i,j}}_{\text{linear predictor}} + \underbrace{f(s_i)}_{\text{smooth function}} \tag{4.5}$$

where the natural logarithm links the sampling distribution of the observations to the linear predictor. Applying the natural logarithm as a link function ensures that the fitted values are positive, regardless of the estimated regression weights.

β refers to the estimated regression weight assigned to each of the j factors u (see Table 4.2), that are expected to be correlated to the occurrence of a blockage. Maximum likelihood estimates for the regression weights were obtained by the method of penalized Iteratively Reweighted Least Squares (Wood, 2000) as implemented in the R library MGCV (Wood, 2006). Penalized regression splines were used as a smoothing function. A spline consists of multiple consecutive fitted polynomials that form a smooth connection at the end of each subdomain. To prevent over-smoothing, the optimum amount of smoothing was determined by means of cross validation.

Bootstrapping

The described generalised additive modelling approach faces two potential challenges:

- Blockage databases are generally imbalanced in the sense that there is an abundance of non-events, i.e. properties with no blockage, which may result in biased regression estimates and standard errors (Zuur et al., 2009).
- Estimated p-values for generalised additive models are known to be less accurate (Keele, 2008).

Bootstrapping is a nonparametric resampling technique that is able to provide a solution to both issues. By resampling the blockage data as input for the generalised additive model, the statistical uncertainty of the estimated regression estimates is quantified without making an assumption about the underlying distribution of each weight β. In addition, bootstrapping can counter the imbalance effect by using a technique from the field of machine learning known as oversampling (see e.g. Radivojac et al., 2004; Osawa et al., 2011). This method assigns different sampling probabilities to events and non-events to obtain a balanced bootstrap ensemble that is not hindered by the effect of non-event abundance.

Model performance

The Receiver Operating Characteristic (ROC) curve summarises model performance by graphically presenting the trade-off between correctly classified blockages and misclassified non-events. The area under the curve (AUC) is a commonly used performance measure for the ROC curve (Bradley, 1997). This measure can be interpreted as the probability that a randomly chosen blocked lateral house connection is rated as more likely to be blocked than a randomly chosen property that did not experience a blockage. A value of 1.0 means that the model is capable of fully discriminating blocked connections from the rest of the property stock, while the baseline of 0.5 represents an accuracy equal to a completely random predictor. This measure of model performance was computed using an independent validation set, obtained from blockage data that was left out of the bootstrap sample.

4.2 Materials

Blockage data from the commercial sewer maintenance company introduced in Chapter 3 served as a practical application of the methods described in Section 4.1. Data pertaining to the cities of Rotterdam and The Hague were selected from the database as case examples. Instead of a two year timespan in Chapter 3, the subset used in this chapter covered a time span of 10 years. Examination of these data provided no apparent evidence of increasing or decreasing blockage rates in this period, indicating the assumption of a constant rate to be appropriate.

As lateral house connections are (partly) located on privately owned ground, authorities in the Netherlands generally require residents to proof that a defect is in the municipal part of the sewer before they cover the costs. Therefore, this type of database has a good coverage of events on both parts. Furthermore, it is not uncommon that the cleaning methods used by commercial sewer companies also resolve blockages located in the municipal part of the lateral connection. As a result, it is likely that municipal call databases underestimate the true number of blockages. For instance, the number of calls received by the commercial sewer company in The Hague is with 1.28 per 100 houses per year a factor 7 greater than the municipality (0.18 calls per 100 houses per year (Gemeente Den Haag, 2011)).

4.2.1 Subsetting data

With a combined population of 1.1 million inhabitants (CBS, 2015) the cities of Rotterdam and The Hague are the 2^{nd} and 3^{rd} largest in the Netherlands. Table 4.1 presents a summary of urban drainage system characteristics for the two cases.

Table 4.1: Factors used as model variables to explain differences in the likelihood of a lateral house blockage.

Characteristics	The Hague		Rotterdam	
Number of residential properties	239,145	(-)	297,740	(-)
Number of inhabitants served	495,085	(-)	610,385	(-)
Ground level variation	1 - 12	m	0 - 8	m
Number of lateral house connections	234,000	(-)	297,000	(-)
Construction year sewer	1890 - 2016	(-)	1920 - 2016	(-)
Total length foul sewers	246	km	152	km
Total length combined sewers	845	km	1779	km

A subset of blockage data from housing associations where the commercial sewer maintenance company was the sole service provider was taken. Selection of housing associations with a service contract offers the following benefits:

- A complete coverage of all blockage events, since the maintenance company is the sole service provider.
- An overview of the property stock that did not experience blockages (non-events) in the period of observation.

The housing associations in the subset represent 26% and 30% of the total property stock in Rotterdam and The Hague respectively. Any high-rise buildings were discarded from the analysis, to ensure that each lateral connection serves one address exclusively. In addition, laterals draining to private sewer systems were also discarded. Figure 4.3 presents the relative contribution of different failure mechanisms for both the full dataset and the analysed set containing data on 27,144 lateral connections. Similarity of the distributions indicate that the subset is representative for the database.

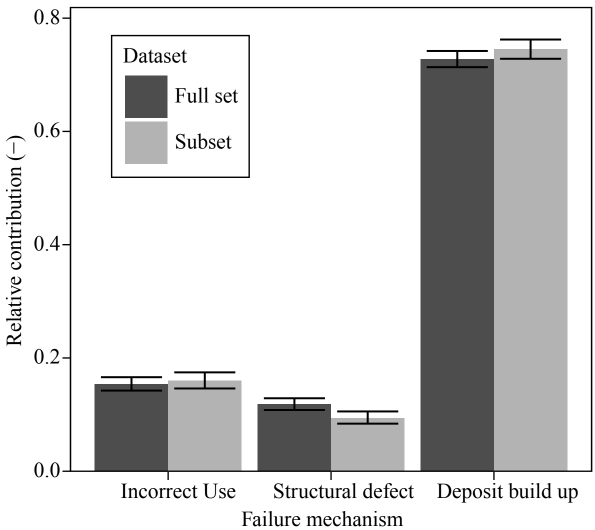

Figure 4.3: Distribution of the observed failure mechanisms: incorrect use (e.g. sanitary towels, kitchen waste etc.), structural defect, deposit build up for both the full dataset and the analysed subset. Error bars represent 95% bootstrap confidence intervals.

4.2.2 Factors that indicate an increase in blockage likelihood

Lateral house connections are characterised by diameters ranging from 117 - 200 mm and gradients varying between 1:50 to 1:200 (Nederlands Normalisatie Instituut, 2011). Factors that may indicate an increased blockage propensity of lateral house connections were identified in Chapter 2 and through interviews with sewer managers. Detailed data on the physical characteristics of these connections are, however, not available. Instead, factors that indicate an increase in the likelihood of a blockage were divided in three groups: physical properties of the main sewer, external factors and socio-economic factors. An overview of the factors included in the modelling approach as model variables is given in Table 4.2.

Table 4.2: Factors used as model variables to explain differences in the likelihood of a lateral house blockage.

Factor	Type	Availability	Unit	Range
Construction year sewer	Property main sewer	Both	(year)	1900 - 2002
Sewer Diameter	Property main sewer	Both	(mm)	150 - 1000
Sewer pipe material	Property main sewer	Rotterdam	-	concrete / plastic / vitrified clay
System type	Property main sewer	Both	-	combined / separate
Construction year building	External	Both	(year)	1900 - 2002
Distance building to main sewer	External	Both	(m)	1.3 - 45
Private front garden	External	The Hague	-	yes / no
Third party work activities	External	The Hague	-	yes / no
Road state	External	Rotterdam	-	acceptable / replacement planned
Settlement rate	External	Rotterdam	(mm/year)	1.0 - 6.5
neighbourhood mean income	Socio-economic	Both	(€$\cdot 10^{-3}$/year)	7.70 - 24.20
neighbourhood proportion non-autochthonous	Socio-economic	Both	-	[0 - 1]

Both cities are being served by predominately combined sewer systems constructed after 1940. They differ with respect to the soil characteristics and management policies concerning lateral house connections. The former refers to the continuous settlement of sewers in Rotterdam due to the presence of peat and clay soil, while The Hague is characterised by mainly sandy soils (Zagwijn et al., 1985). Previous research by Dirksen et al. (2012) has shown that settlement has a substantial impact on sewer system performance. Furthermore, while in Rotterdam the homeowner is responsible for the entire connection, The Hague municipality takes responsibility for lateral connections up to the property boundary. This means that in the absence of a private front garden, the responsibility for a lateral house connection in The Hague lies completely with the authorities. To quantify the effect of these different policies, the presence of a private front garden is included as an external factor. The distance from the property to the main sewer is used as an estimate for the length of the lateral connection.

Data on the state of the road is a potentially valuable indicator for sewer blockages, as both have several common failure mechanisms (e.g. traffic load) (Davies et al., 2001). In addition, these infrastructures may have interaction, as the (partial) collapse of a sewer can affect the stability of the road. Furthermore, underground infrastructure activities by a third party may damage lateral connections, affecting the operational performance of these assets.

Socio-economic factors represent differences in lifestyle, which may affect the composition of domestic wastewater (Ashley et al., 2004). This does not only extent to differences in (sanitary) item disposal habits (Friedler et al., 1996), but may also reflect in food preparation habits that increase the fat, oil and grease (FOG) stock available for accumulation in sewers (Shin et al., 2015). Socio-economic data were available on a neighbourhood level from the online database of Statistics Netherlands (CBS, 2015). 'Neighbourhood mean income' represents the average household income level, while 'neighbourhood proportion non-autochthonous' is an indicator for the magnitude of the allochthonous population in a neighbourhood.

4.3 Results and discussion

This section presents the results of the procedure introduced in Section 4.1 applied to two test examples. First, mapping of the blockage intensity surface and the corresponding results of the Monte Carlo simulation are presented in Section 4.3.1. Subsequently, Section 4.3.2 identifies factors that may indicate an increase in the blockage likelihood by means of the bootstrapped generalised additive model. The remainder of this section discusses the performance of this model and the implications for management strategies.

4.3.1 Significance of the spatial variation

Bandwidth of the kernel function

Both the properties that reported at least one blockage and properties that reported no blockage were used to estimate a joint smoothing bandwidth for the kernel density function. Figure 4.4 shows the cross validated likelihood function and the values for the bandwidth that minimise these function. Bandwidth values for both test examples are of a similar order of magnitude. These values represent the standard deviation of the Gaussian kernel and are a measure of the distance at which individual blockages still contribute to the kernel density estimate at a given point in space. The extent to which the derived bandwidth values are transferable to other cases depends on the characteristic spatial scale of the blockage patterns.

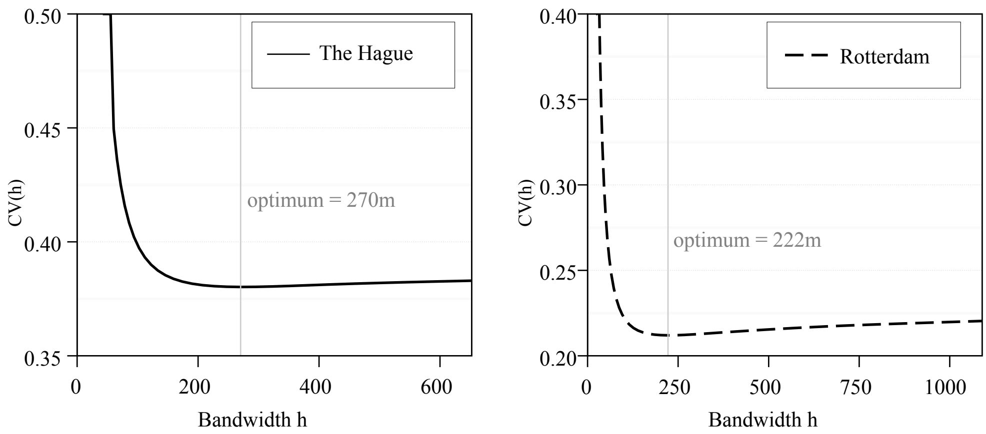

Figure 4.4: Shape of the likelihood based Cross-Validation (CV) function from Equation 4.3 for the bandwidth h of the kernel density function from Equation 4.2. Vertical grey lines show the derived optimum values.

In both cases, the likelihood function is less sensitive to larger values for the bandwidth. Arguably, adopting the relative small estimated bandwidth in this flat region is supported by the fact that larger values for the bandwidth may cause over-smoothing that hides features in the underlying data.

Estimated p-value

Results for the significance test of a spatially constant blockage intensity for the entire system yield significant p-values for both Rotterdam ($p = 0.001$) and The Hague ($p = 0.004$), based on 999 simulations. These results provide evidence of substantial spatial variation in the intensity of lateral house connection blockages. Statistical significance of local peaks are visualised in Figure 4.5 by means of contours of the 0.975 and 0.025 p-values derived from the simulations. This figure shows several hotspots experiencing significantly high blockage intensities.

Interestingly, some areas with high estimated blockage intensities were found to be outside the p-value surfaces, indicating non-significance. Detailed inspection of the underlying blockage data revealed those areas to have a low building density, resulting in an estimate of the local blockage intensity that is inflated when the denominator of Equation 4.1 approaches zero. This demonstrates the added value of the Monte Carlo test approach, as this method is insensitive to regions with a low data density where the occurrence of a single blockage event has a profound impact on the estimated intensity.

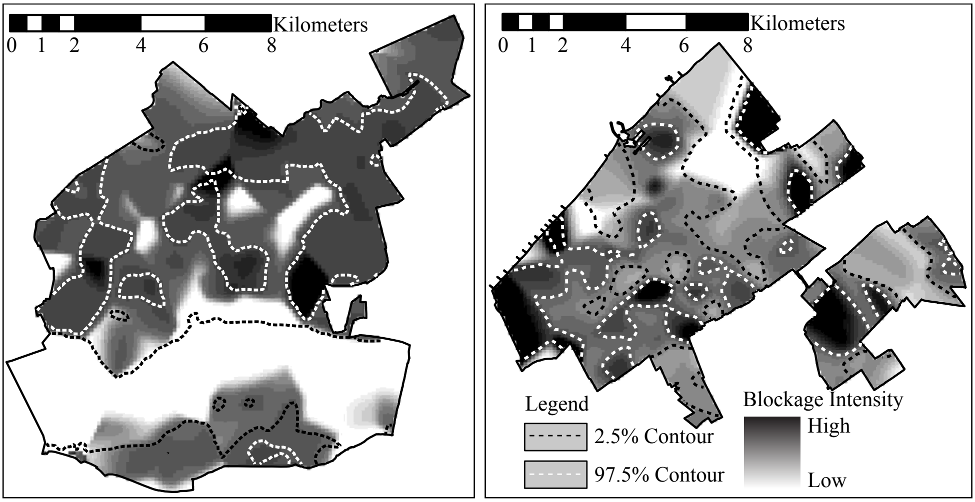

Figure 4.5: Kernel ratio of the intensity of blockages for Rotterdam (left panel) and The Hague (right panel). Dark colours denote regions with a high blockage intensity. White dashed lines and black dashed lines indicate the 97.5% and 2.5% Monte Carlo simulation contours respectively. P-values for both Rotterdam (0.001) and The Hague (0.004) provided evidence to reject the hypothesis of a constant blockage intensity for the city.

4.3.2 Factors explaining the spatial variation in observed blockage incidences

Rejection of the hypothesis of a constant blockage intensity for both cities motivated application of the bootstrapped Generalised Additive Modelling (GAM) approach discussed in Section 4.1.2. This regression model quantified the ability of the factors specified in Section 4.2.2 to explain observed blockage incidences. The extra nonparametric smoothing term was added to improve model performance by accounting for missing spatially varying factors. All continuous factors were standardised to obtain the same unit for every regression estimate β.

Data exploration
Exploration of the data revealed a high Pearson correlation between model factors 'neighbourhood mean income' and 'neighbourhood proportion non-autochthonous' for the cities of The Hague (-0.88) and Rotterdam (-0.67). This correlation can likely be attributed to differences in the level of education (Lautenbach and Otten, 2007). High correlations between factors may inflate model parameter standard errors (Zuur et al., 2010), making valid inferences on relevant model factors more difficult. Also taking into account the moderate correlation with other variables, it was decided to drop the latter variable ('neighbourhood proportion non-autochthonous') from the set.

Structure of the linear predictor

A distribution of weights β for each factor based on 50,000 bootstrap samples were derived from the GAM. Subsequently, confidence intervals containing the true value of the regression weights β with probability 0.95 were computed. The sample size showed to be sufficient for the distributions of regression weights to converge to stable values for the 95% confidence intervals. These intervals were adjusted for bias and skewness (Efron, 1987) to obtain accurate estimates. When the computed 95% interval contains zero for a given factor, it is concluded that the factor is not significantly different from 0 at the 5% level. The final structure of the linear predictor in Equation 4.5 consists of all the significant factors in the model.

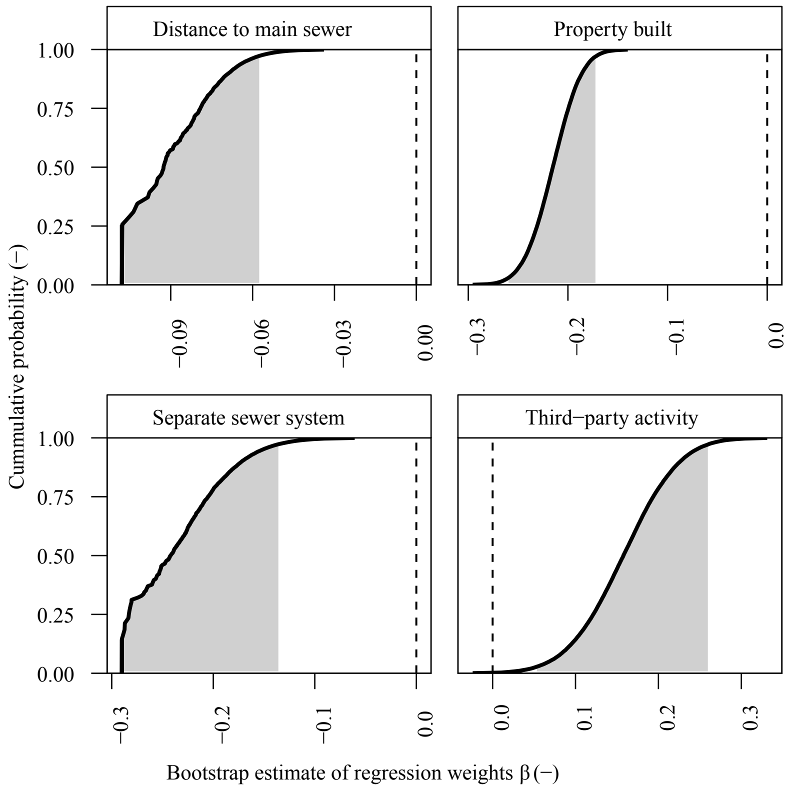

Figure 4.6: Empirical cumulative distribution function of the standardised regression weights β for each factor for The Hague that is significantly different from 0, based on 50,000 bootstrap samples. The 95% confidence interval is depicted by the grey area. Factors are considered significantly different from zero, when the dashed vertical line at $\beta = 0$ is not contained within the 95% confidence interval.

Figure 4.6 depicts the empirical cumulative distribution of all the regression weights β for The Hague that were found to be significant. A cumulative probability of 0.50 is equivalent to the median. From the median values of the weights β it can be concluded that the year of building construction was the dominant continuous factor discriminating lateral house connections that experience blockages from the rest of the stock. Age is a known indicator for structural deterioration (see e.g. Davies et al., 2001; Ariaratnam et al., 2001; Baur and Herz, 2002), which may also affect the susceptibility to other failure mechanisms such as tree roots (see Chapter 2.1.2). Distributions of the weights β for both categorical factors are in the same order of magnitude.

Although 'construction year of the main sewer' was found to be significant, this factor was dropped from the linear predictor since analysis of the bootstrap estimates revealed collinearity with 'construction year of the property' and to some extent with the factor 'system type' and to some extent with the factor 'system type' (see Figure 4.7).

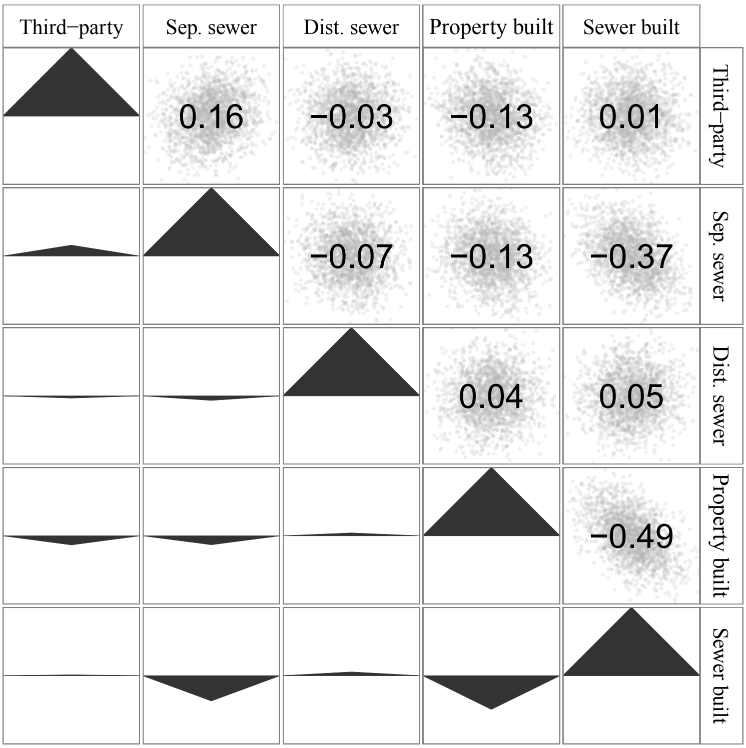

Figure 4.7: Correlation matrix of the regression weights β for each significant factor for The Hague, based on 50,000 bootstrap samples. Triangles indicate the strength and direction of the correlation.

It seems that the presence of a garden has no effect on the blockage likelihood. This implies that the privately owned part of a lateral connection is not more susceptible to blockages than the municipal part, even though municipal policy stipulates that the municipal part should be replaced when the main sewer rehabilitation projects are initiated. On the other hand, Figure 4.8 shows this private part to be rather small (e.g. 30% of all gardens has a length ≤ 2 meters), potentially obscuring any effect.

Figure 4.8: Boxplot of the garden lengths, used to approximate the length of the lateral house connection on private ground.

The empirical cumulative distribution of the weights derived for Rotterdam are depicted in Figure 4.9. In comparison to example of The Hague, more factors were found to be significant. Both examples show evidence of a positive relation between age and the blockage likelihood. This might be attributed to the material use and joining methods in different time periods (Lillywhite and Webster, 1979). In addition, the time since construction can be an indicator of deterioration (e.g. Marlow et al., 2010; Davies et al., 2001). The negative weights β associated with separate sewer systems demonstrate that combined lateral connections are more prone to blockages. Arthur et al. (2009) arrived at similar findings for a sewer system in the UK.

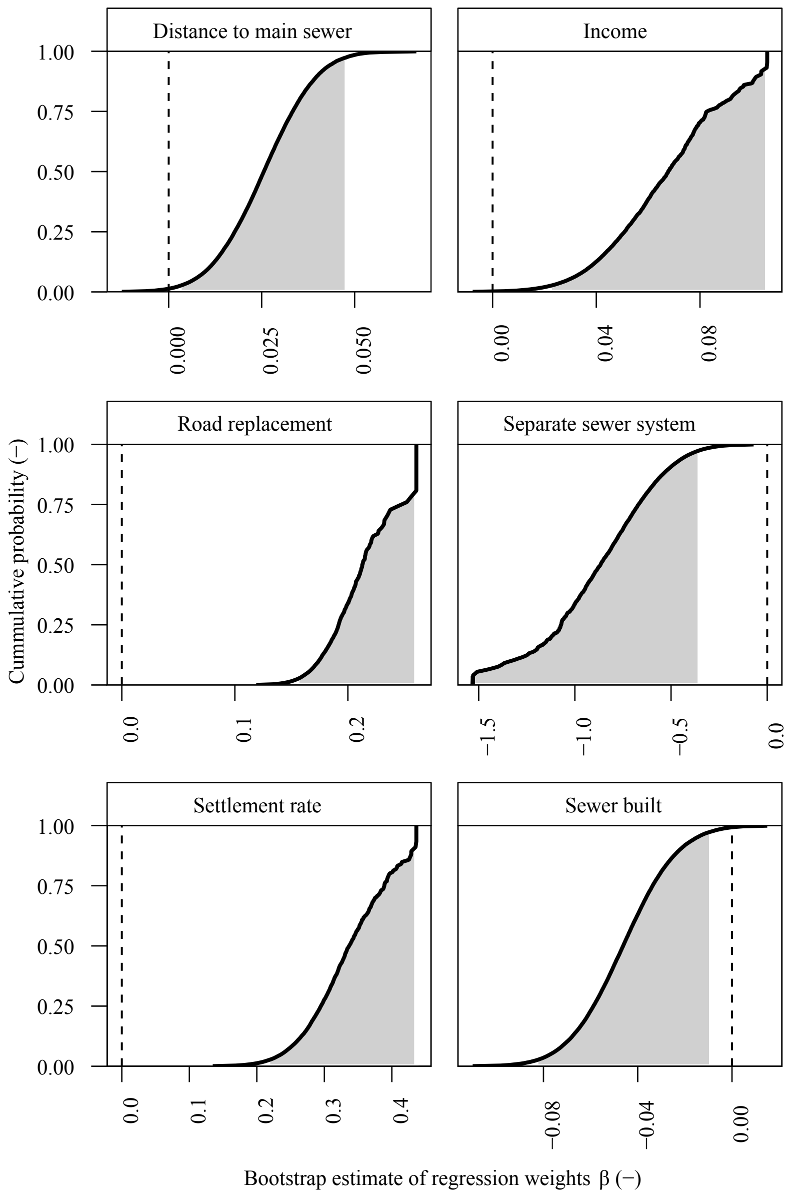

Figure 4.9: Empirical cumulative distribution function of the standardised regression weights β for each factor for Rotterdam that is significantly different from 0, based on 50,000 bootstrap samples. The 95% confidence interval is depicted by the grey area. Factors are considered significantly different from zero, when the dashed vertical line at $\beta = 0$ is not contained within the 95% confidence interval.

From median values for the regression weights β in Figure 4.9, it can be concluded that ground settlement is the dominant continuous factor for Rotterdam. Sewer settlement is a common phenomenon in delta build cities. It can lead to differential settlement in combination with pile-founded buildings. These relative movements may result in deterioration such as disconnecting joints or fractures (DeSilva et al., 2005; Dirksen, 2013). Furthermore, the formation of sags due to ground settlement is conducive to the accumulation of fat, oil and grease (FOG) deposits (Lillywhite and Webster, 1979).

The model provides evidence of a relation between the observed condition of the road and the lateral house connection blockage propensity. This leads to the hypothesis that either the condition of the road is influenced by the structural state of the underlying house connections, or both infrastructures are affected by similar latent factors.

4.3.3 Improving model performance by adding a spatial smoothing function

The modelling approach adopted in this chapter extends a sewer blockage model, based on explanatory factors, with an extra term that captures any remaining spatial variation in blockage incidences. A likelihood ratio test was performed to determine whether the addition of the smoothing function f in Equation 4.5 resulted in a significant performance improvement. For both examples p-values < 0.001 were found, clearly favouring the models with an added smoothing function. This demonstrates that the model is capable of accounting for some of the spatial variation caused by factors (e.g. material, slope, structural defects) for which no data was available.

4.3.4 Classification accuracy of the models

The Receiver Operating Characteristic (ROC) curves presented in Figure 4.10 show the trade-off between the proportion of correctly classified blockage events (true positive rate) and the proportion of incorrectly classified non-events (false positive rate). Clearly the modelling approach performs better for the Rotterdam example (AUC = 0.80), with classification accuracies for The Hague (AUC = 0.62) being only slightly better than a random predictor (AUC = 0.50). This may be partly attributed to the difference in data availability. For instance, 'ground settlement rate' is an important factor for Rotterdam, that is absent for The Hague.

In terms of asset management, Figure 4.10 illustrates the amount of required investments on (in)correctly classified lateral house connections versus system performance gain by interventions on blockage prone laterals. For instance, Figure 4.10 shows that when the objective is to plan an intervention for 75% of all lateral house connections in Rotterdam that experienced a blockage, an intervention will also be planned for the 30% incorrectly classified lateral house connections that did not experience a blockage. It should be noted that although this model can enhance the decision-making process

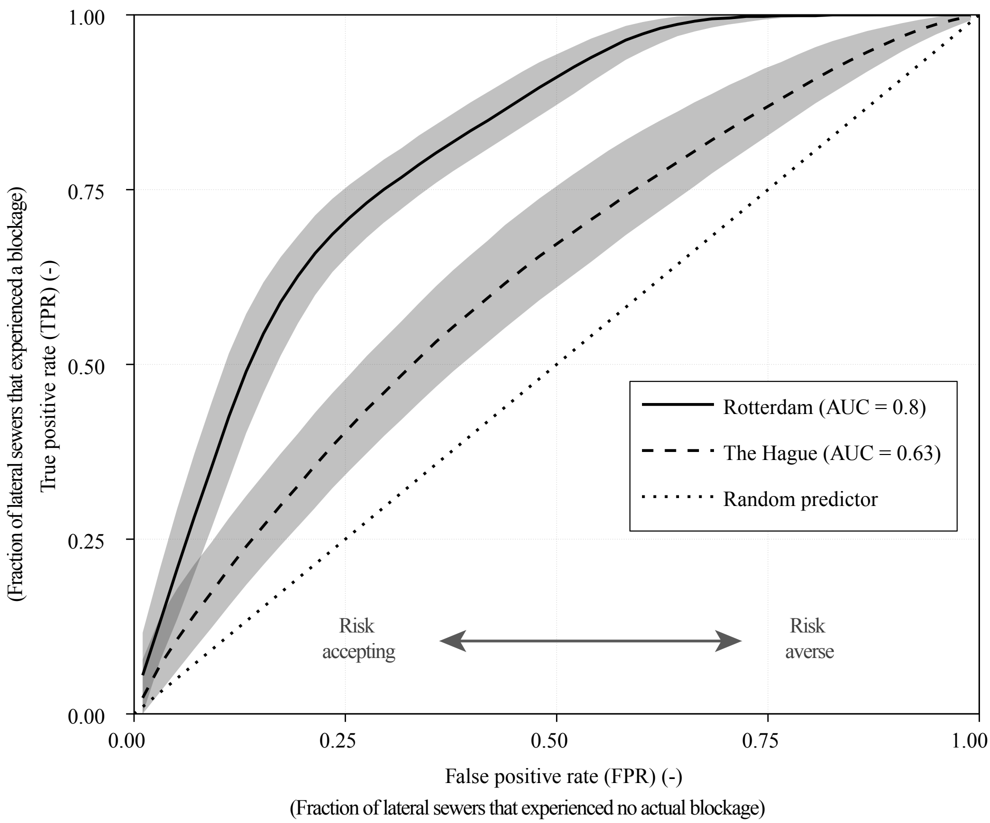

Figure 4.10: Receiver Operating Characteristic (ROC) curves for both The Hague and Rotterdam, illustrating the trade-off between the true positive rate and the false positive rate. Grey areas correspond to the 95% confidence interval. The Area Under the Curve (AUC) is a measure of the overall model performance.

involved in prioritising intervention decisions, it offers no guarantee that the planned intervention will be effective. This depends on the type of intervention (maintenance or rehabilitation) and the underlying failure mechanism (see Chapter 2.1). However, due to the poor model performance for The Hague, investments are per definition less cost-effective. Considerably more investments in incorrectly classified laterals (60%) are needed to cover 75% of all lateral house connections that experienced a blockage. The left quadrant of Figure 4.10 is more risk-accepting, corresponding to less proactive interventions, while requiring more reactive interventions. The right quadrant is more risk-averse and is aimed at reducing reactive interventions by proactively improving the condition of lateral house connections. Consequently, the modelling approach presented in this chapter can guide the prioritisation of interventions. For example, the prioritisation of inspections when the ownership of lateral house connections is taken over by the water authorities or the rehabilitation of lateral house connections in conjunction with main sewer projects.

4.4 Conclusions

This chapter describes a procedure to analyse the spatial variation of lateral house connection blockages to identify factors that differentiate blocked components from the rest of the stock. For two cities, Monte Carlo simulations on blockage data revealed a significant spatial variation in the blockage likelihood.

Subsequently, the bootstrapped generalised additive model was able to identify factors that distinguish blocked laterals from the remaining stock. Age seems to be a relevant deterioration indicator for the two examples discussed, suggesting an increasing trend in the number of blockages. In addition, lateral house connections draining to separate systems experience lower blockage incidence compared to combined systems. The relationship between the blockage propensity and third party (planned) activities indicates the presence of shared failure mechanisms or the interaction between different types of infrastructures. Furthermore, addition of a spatial smoother function significantly improved model predictions. This demonstrates the added value of the applied modelling approach, as it is able to mitigate the effect of unknown, but relevant, factors that are missing in the linear predictor of the model.

Identification of blockage prone lateral house connections can enhance the prioritisation of maintenance and rehabilitation decisions. As such, it is a prerequisite for effective proactive strategies. Analysis of the ROC curves provide key information for decision-making, by taking into account the generalised additive model performance in assessing the trade-off between costs and benefits in terms of interventions on correctly classified blocked lateral house connections. In the total absence of data on relevant factors that may indicate an increased blockage likelihood, investigation of the Monte Carlo simulation results provides an overview of areas with a significant higher blockage incidence where inspections and interventions are most promising.

5 Monitoring and modelling of sediment accumulation in gully pots

The two functions assigned to gully pots are conflicting, as the continuous trapping of solids eventually impairs the hydraulic performance. The literature reviewed in Chapter 2 identified two distinct different findings from data-driven studies: (1) stabilising sediment bed levels without hydraulic restrictions after a period of time (Butler and Clark, 1995; Conradin, 1989) and (2) gully pot blockages as main contributor to flooding in public areas (Caradot et al., 2011; Ten Veldhuis et al., 2011). Both findings have implications concerning the functions assigned to gully pots. The former implies that solids and attached pollutants suspended in runoff are no longer retained, but transported to the downstream system. The latter entails that the hydraulic capacity is impaired as the capacity of the sand trap is exceeded.

The performance of gully pots is safeguarded by preventive cleaning activities that are undertaken after a specified period. Currently, the maintained cleaning interval is independent of catchment and physical properties of gully pots that affect the accumulation of solids. Next to providing information to optimise maintenance interval on a catchment scale, knowledge on the factors that influence sedimentation processes can aid to further improve gully pot design. To this end, this chapter provides a procedure to model the long term accumulation of solids in gully pots.

Prediction models for solids transport in gully pots are described by e.g. Fulcher (1994); Butler and Karunaratne (1995); Deletic et al. (2000). These models are based on dense time series with a duration varying from one to several storm events or artificial events for a limited (1 - 60) number of gully pots. Although this duration is adequate to simulate transport processes during individual events, the characteristic time scale of the solids induced blockage process in gully pots calls for time series covering a period of at least one year. Considering the complex transport processes discussed in Chapter 2 and the corresponding parameter uncertainty, Rodríguez et al. (2012); Pratt et al. (1987) opted for a probabilistic approach. Section 5.2 discusses a

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This chapter is based on: Post, J.A.B., Pothof, I.W.M., Langeveld, J.G., and Clemens, F.H.L.R. (2016). Monitoring and statistical modelling of sedimentation in gully pots. *Water Research*, 88:245-256, doi: `http://dx.doi.org/10.1016/j.watres.2015.10.021` generalised linear mixed modelling (GLMM) approach to time series of multiple gully pots. Sufficient monitoring locations are essential for probabilistic modelling, as the potential correlation between successive measurements over time results in less unique information. To this end, Section 5.1 introduces a monitoring campaign comprising monthly measured sediment bed levels of 300 gully pots for a duration of more than a year.

Nomenclature

Symbol	*Description*
t	observation number
i	gully pot identity
p	the probability of a success
ϵ	random part of the generalised linear model
η	linear predictor containing the deterministic part of the generalised linear model
d	available sump depth
y	measured sediment bed level
v	normalised sediment bed level with respect to the sump depth
x	quantitative explanatory variable
β	model weight assigned to explanatory variable x
ϕ	autocorrelation strength
ω	noise term
a	shape parameter for the beta distribution
b	shape parameter for the beta distribution
θ	over-dispersion parameter
$\mathbf{z}$	row incidence vector for the random effects

5.1 Materials

Sediment bed levels of gully pots in a residential urban area in Amsterdam, the Netherlands were monitored. The catchment area has 10.5 ha of surfaces that contribute to the runoff into the separate sewer system. A sample size of 300 gully pots was selected from the catchment with 801 gully pots to allow for valid inferences given the spatial variation of the process measured.

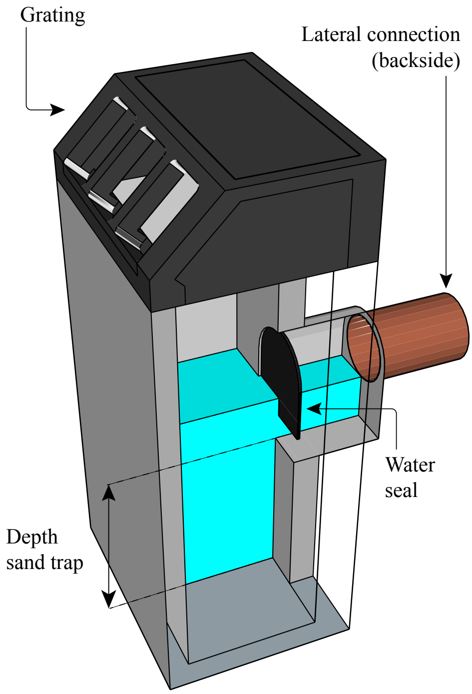

Figure 5.1: Schematisation of a roadside gully pot, with the lateral connection positioned at the back.

Data on the properties of gully pots in the study area was inventoried prior to the measurements. This includes geometrical data describing the physical properties of each gully pot (depth of the sand trap, surface area, manufacturer, presence of a water seal, position of the lateral connection with respect to the grating) and catchment properties (contributing area, slope, road type). Based on the spatial distribution of the physical properties of the gully pots (see Figure 5.1), a stratified sampling design was applied. This sampling technique improves estimates of both the population and the sub-groups by taking a proportional sample from each sub-group. Stratification distinguished between the presence of a water seal, the position of the lateral connection and the depth of the sand trap. Table 5.1 shows the frequency distribution over the different strata.

Table 5.1: Frequency distribution of the different strata.

Water seal	Depth sand trap	Position lateral connection		
		Back	Front	Side
No	[0 - 20]	11	23	14
	(20 - 40]	5	5	12
Yes	[0 - 20]	13	41	75
	(20 - 40]	11	21	79

The associated costs and spatial spread render continuous monitoring for this sample size impractical. Instead, an apparatus able to rapidly measure the height of the bed has been constructed. The principle is illustrated in Figure 5.2. It consists of a punctured disk attached to a shaft, with a retractable rod in the middle. The disk rests on the sediment bed, while the rod is driven through until the bottom of the gully pot is reached. The rod is equipped with a sequence of marks at $5 \cdot 10^{-3}$m intervals enabling the operator to determine the height of the bed. Tests with repeated measurements from the same gully pot indicate the error to be smaller than the increment of the instrument scale.

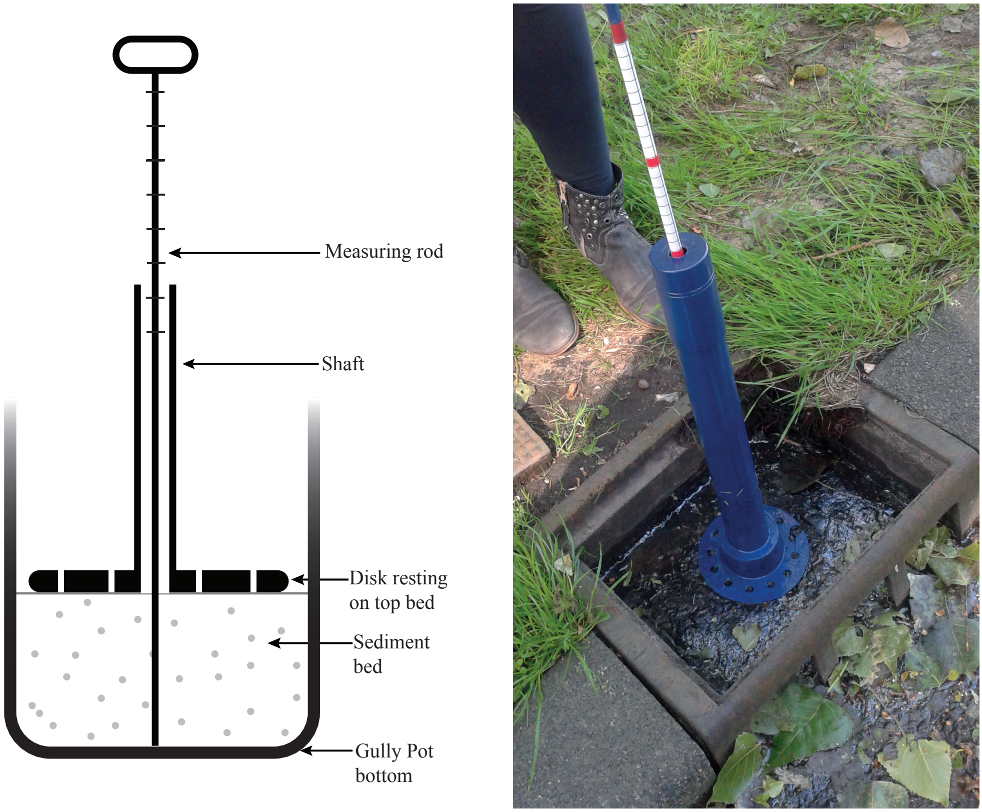

Figure 5.2: Illustration of the device used to measure sediment bed levels in gully pots.

Three weeks prior to the first measurement, all gully pots were emptied and lateral connections cleaned. In addition, the hydraulic capacity of the lateral connections was tested by means of a vehicle mounted sewer jetting installation capable of providing a flow of 100 l/min, equivalent to 60 mm/h on 100 m^2, assuming the design standard applied in the Netherlands (Ganzevles and Oomens, 2008). In case of a defect, the gully pot was removed from the dataset. This excluded the influence of external failure mechanisms not related to the sedimentation mechanism, such as collapse or deformation of the geometry. Gully pots were removed from the monitoring set when more than one measurement was missing, e.g. due to accessibility, or in case of signs of tampering. In addition, gully pots presumed blocked due to the accumulation of sediment during the monitoring period were tested by means of a vehicle mounted sewer jetting installation to validate this observation. The duration of the campaign was chosen to be longer than the standard preventive cleaning interval of once or twice per year and to include all four seasons.

5.1.1 Data collection

The contributing area and average slope for each gully pot was determined by means of the eight-direction flow approach described in Jenson and Domingue (1988). The digital elevation model (DEM) used to deduct these flow patterns is based on high-resolution altimetry data obtained by airborne laser scanning (Van der Zon, 2011) and has a spatial resolution of $0.5 \cdot 0.5$ m. The vertical stochastic error for the grid is $2.5 \cdot 10^{-3}$ m. Confounding objects (e.g. cars and trees) were filtered from the DEM and were interpolated from the surrounding data. Both Kriging with an external drift (KED) based on land use and Ordinary Kriging (OK) were considered as interpolation methods. However, analysis of the variogram of the regression residuals showed no substantial improvement (1.5%) of the semivariance. Hence, Ordinary Kriging was applied to interpolate the DEM.

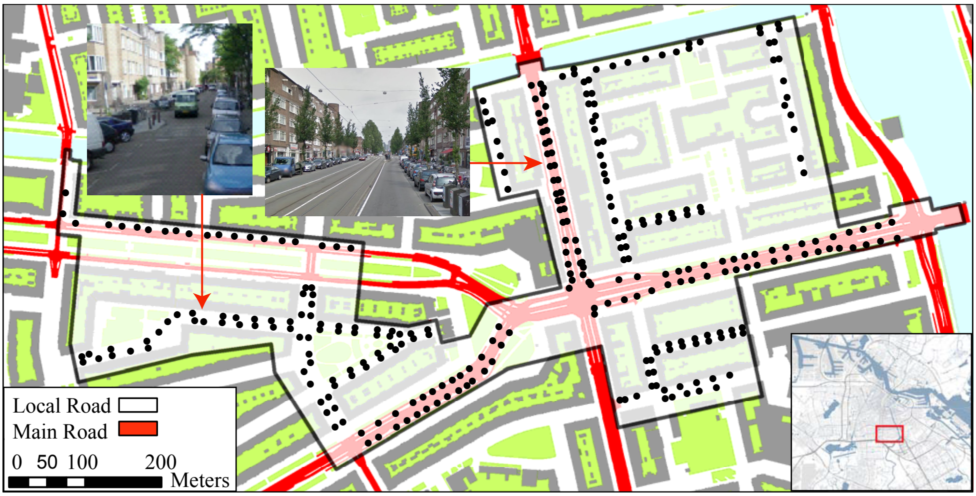

Figure 5.3: Measurement area in Amsterdam, the Netherlands. Gully pots are marked by circles.

The area has two road types, being main roads and local roads (see preview photos in Figure 5.3). The former has a continuous traffic flow (2000 - 6000 vehicles/day) and a road surface consisting of asphalt pavement. The latter is characterized by brick paving (<2000 vehicles/day) and parking lots. The area is considered to be a dense urban environment, developed as a residential area with some commercial properties concentrated around the main roads. An overview of the monitoring area is given in Figure 5.3.

5.2 Methods for data analysis

As the processes associated with the transport and subsequent sedimentation of solids are complex and not fully understood, deterministic storm water quality modelling is associated with various difficulties (Deletic et al., 2000; Freni et al., 2009). Moreover, a deterministic approach requires the estimation of various site specific parameters, which are subject to uncertainty (David and Matos, 2002). Based on these considerations, this chapter applies a probabilistic approach. Sediment bed level data were analysed by applying a Generalised Linear Mixed Model (GLMM) from a Bayesian perspective. The four components that compose this model are discussed in Section 5.2.1 - 5.2.4. Selection of the structure of these components follows the protocol suggested by Zuur et al. (2009), which is summarised in Figure 5.4. First, the data exploration procedure outlined in Section 5.2.5 was applied. Subsequently, the random part and the distribution of the response variable were determined with the complete deterministic part including interactions between the physical properties and the elapsed time since cleaning. After validation, model selection was applied to identify relevant explanatory variables in the deterministic part.

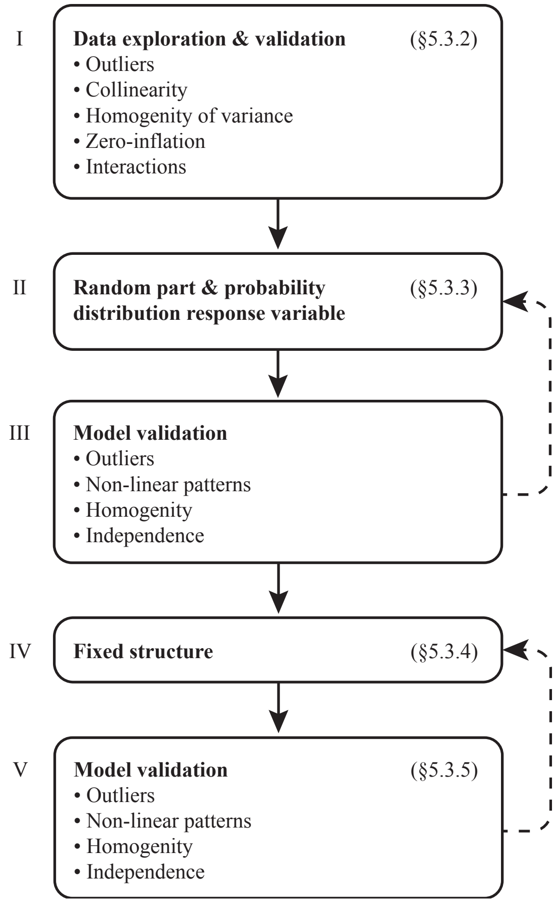

Figure 5.4: procedure for the selection of the components of a GLMM. References to the corresponding sections where the results are presented have been added.

5.2.1 Structure of the deterministic part

The linear predictor η contains the deterministic part of the model, which is a linear function of k explanatory variables and is given by

$$\eta_{t,i} = \beta_0 + \beta_1 x_{t,i,1} + ... + \beta_k x_{t,i,k} \tag{5.1}$$

where t represents the observation number and i the gully pot. β refers to the weights assigned to the respective explanatory variables x, summarised in Table 5.2. β_0 is the intercept.

Table 5.2: Explanatory variables and their characteristics.

Variable	Index	Type	Unit	Range
Depth sand trap	x_1	continuous	(cm)	[9 - 44]
Catchment slope	x_2	continuous	(%)	[1.3 - 4.3]
Time since cleaning	x_3	continuous	(days)	[21 - 420]
Contributing area	x_4	continuous	(m)	[5 - 1380]
Cum. Rainfall depth	x_5	continuous	(mm)	[115 - 1160]
Water seal	x_6	categorical	-	yes / no
Position lateral connection	x_7	categorical	-	front / back
Position lateral connection	x_8	categorical	-	side / back
Road type	x_9	categorical	-	main / local

5.2.2 Structure of the random part

The model assumption of independence is not guaranteed, as successive observations from the same gully pot can be expected to be more similar compared to observations from other gully pots. This violation of independence was resolved by extending the deterministic part η with a correlation structure to model inter-gully pot variation and the correlation caused by this variation. Two extensions were considered. The first candidate was a random intercept, which implies that all pairs of observations from the same subject gully pot are equally correlated (i.e. compound symmetry correlation) and defines the random part as

$$\varepsilon_{t,i} = N\left(0, \sigma_i^2\right) \tag{5.2}$$

Alternatively, an auto-regressive process of order 1 (AR-1) model was considered. It is a special case of the autoregressivemoving-average model family. This structure has correlations, between observations from the same gully pot, that decline exponentially with time and is given by

$$\begin{aligned} \varepsilon_{t,i} &= \phi\varepsilon_{t-1,i} + \omega_{t,i} \\ \omega_{t,i} &= N\left(0, \sigma^2\right) \end{aligned} \tag{5.3}$$

where the estimated parameter ϕ is the strength of the autocorrelation and ω the noise term.

5.2.3 Distribution of the response variable

Each outcome of the response variable is assumed to be generated from a particular distribution. This chapter analyses the normalised sediment bed level v, which is defined as the sediment bed level y normalised with respect to the available sump depth d. Two distributions were considered, the first being the binomial distribution, with probability p, specified by

$$\begin{aligned} &y_{t,i} \sim Binomial\left(p_{t,i}, d_{t,i}\right) \\ &E\left(y_{t,i}\right) = p_{t,i} \cdot d_{t,i} \text{ and } \operatorname{var}\left(y_{t,i}\right) = p_{t,i} \cdot d_{t,i} \cdot (1 - p_{t,i}) \end{aligned} \tag{5.4}$$

However, when the variation of the data is inflated compared to the theoretical expected variance according to the binomial model (i.e. over-dispersion), a more general model is required. Alternatively the response variable can be described by a beta-binomial distribution. This mixed distribution permits heterogeneity by modelling the probability of success as a beta distribution. Parameters a and b describe the beta distribution. The expected value of the beta-binomial is similar to the expected value of the binomial distribution in Equation 5.4. Yet, the variance is given by

$$\mathrm{var}\left(y_{t,i}\right) = p_{t,i} \cdot d_{t,i} \cdot \left(1 - p_{t,i}\right) \cdot \left(1 + \frac{d_{t,i}}{\theta + 1}\right) \tag{5.5}$$

Where the parameter $\theta = a + b$ accounts for over-dispersion. For large values of θ, the variance converges to that of the binomial distribution.

5.2.4 Link function

Subsequently, the link function describes the relationship between the expectation of the response variable and the extended deterministic part. The logistic link is such a function and is given by

$$p_{t,i} = \frac{e^{\eta_{t,i} + \varepsilon_{t,i}}}{1 + e^{\eta_{t,i} + \varepsilon_{t,i}}} \tag{5.6}$$

Introduced by Berkson (1944), it approximates the inverse cumulative distribution function of the Gaussian distribution and is able to model binomial data effectively (Hardin and Hilbe, 2007).

5.2.5 Data exploration and model validation

The process of exploration and validation provides information about eligible model structures and explanatory variables. Outliers may influence the statistical analysis and cause over-dispersion (Hilbe, 2007). In addition, an abundance of zero measurements may result in biased parameter estimates and incorrect standard errors (Zuur et al., 2010). Graphical exploration of the explanatory variables and the response variable allowed for the identification of both zero abundances and outliers.

Strong collinearity between explanatory variables may result in unreliable parameter estimates, as the estimates may respond erratically to small changes in the data (Zuur et al., 2013). Collinearity was assessed by inspecting pair-plots and computing Variance Inflation Factors (VIF) for high-dimension relations.

Following the model specification, the influence of individual observations was analysed by computing Cooks distance (Cook, 1977). This statistic represents the normalised change in fitted values when one observation is removed. Pearson residuals were extracted from the model to verify the assumptions inherent to GLMMs. Homogeneity of variance was verified by graphical techniques, as statistical tests are sensitive to non-normality (Sokal and Rohlf, 1995). Non-linear patterns in the residuals may indicate that the model needs to be extended with quadratic terms (Zuur et al., 2013). Mantel correlograms of the residuals were analysed to determine whether there is any inherent spatial or temporal dependency.

5.2.6 Bayesian inference

In recent years, Bayesian inference has gained an increasing amount of attention in the field of environmental engineering (see e.g. Kanso et al., 2006; Liu et al., 2008; Korving et al., 2006; Egger et al., 2013). The Bayesian framework considers unknown parameters as random variables. The uncertainty about these parameters is expressed by the posterior density function. This approach is not hindered by the potential inaccurate penalized quasi-likelihood generally applied to GLMMs in a frequentist framework (Zhao et al., 2006). Bayes' theorem evaluates the posterior density by updating prior information when new observations are available and is given by,

$$P\left(\boldsymbol{\beta}|\mathbf{y}\right) = \frac{P\left(\mathbf{y}|\boldsymbol{\beta}\right)P\left(\boldsymbol{\beta}\right)}{P\left(\mathbf{y}\right)} = \frac{P\left(\mathbf{y}|\boldsymbol{\beta}\right)P\left(\boldsymbol{\beta}\right)}{\int P\left(\mathbf{y}|\boldsymbol{\beta}\right)P\left(\boldsymbol{\beta}\right)d\boldsymbol{\beta}} \tag{5.7}$$

where $P\left(\boldsymbol{\beta}|\mathbf{y}\right)$ is the joint posterior density of parameter vector $\boldsymbol{\beta}$ based on prior information and observations $\mathbf{y}\left(y_{1,1}, y_{1,2}, ..y_{n,t}\right)$ from n different gully pots on t occasions. The prior probability density $P\left(\boldsymbol{\beta}\right)$ represents expert information or historical observations before new data are involved. The marginal likelihood is denoted by $P\left(\mathbf{y}\right)$ and is a fixed normalising factor, scaling the sum of the posterior likelihood to one. $P\left(\mathbf{y}|\boldsymbol{\beta}\right)$ is referred to as the likelihood function, which for a binomial generalised linear mixed model can be expressed as,

$$P\left(\mathbf{y}|\boldsymbol{\beta},\varepsilon\right) = \prod_{n=1}^{N}\prod_{t=1}^{T}\begin{pmatrix} d_{n,t} \\ y_{n,t} \end{pmatrix}\left[p_{n,t}\left(\boldsymbol{\beta}_{n,t},\varepsilon_n\right)\right]^{y_{n,t}}\left[1-p_{n,t}\left(\boldsymbol{\beta}_{n,t},\varepsilon_n\right)\right]^{d_{n,t}-y_{n,t}} \tag{5.8}$$

where,

$$p_{n,t}\left(\boldsymbol{\beta}_{n,t},\varepsilon\right) = \left[1+e^{\mathbf{x}_{n,t}^{\mathrm{T}}\boldsymbol{\beta}_{n,t}+\mathbf{z}_{n}^{\mathrm{T}}\varepsilon}\right]^{-1} \tag{5.9}$$

includes both the deterministic and random part. $\mathbf{z}$ is a row incidence vector for the random part. Non-informative priors were used for the regression parameters, representing the lack of knowledge about the parameters. These distributions have a negligible influence on the posterior distribution. A half-Cauchy(25) prior was used for the standard deviation parameter, as recommended by Gelman (2006) and Marley and Wand (2010). This prior expresses the belief that the random intercepts are concentrated close to the common intercept.

Integration over the denominator of Equation 5.7 is considered to be infeasible for most practical applications due to high-dimensionality of $\boldsymbol{\beta}$ (Qian et al., 2003). Markov Chain Monte Carlo (MCMC) algorithms do not require evaluation of the marginal likelihood, since the posterior distribution is sampled directly. This chapter considered the Gibbs sampler (Geman and Geman, 1984) as MCMC algorithm. It is referred to as an alternating conditional sampler, as it samples from the conditional distribution of each parameter with respect to the remaining parameters. The Gibbs sampler has been found to be particular suited for multidimensional problems (Gelman et al., 2003) and is implemented in the open source software JAGS (Plummer, 2003), which was called from the R software environment (Core Team, 2014).

Convergence of the MCMC algorithm is essential for a correct estimation of the posterior distribution for the parameters of interest. To this end, the Gelman-Rubin diagnostic (Gelman and Rubin, 1992) was used. This diagnostic compares the variance of the independent Markov chains to the variance between the chains.

5.3 Results and discussion

4500 sediment bed level measurements spanning 15 months (Sept. 2013 - Nov. 2014) were available at the end of the monitoring campaign introduced in Section 5.1. 2% of the locations were removed from the set due to missing measurements or suspected tampering. A total rainfall depth of 1160 mm was recorded. Section 5.3.1 presents the results of this campaign. The remainder of this chapter is dedicated to applying the procedures introduced in Section 5.2. This involves applying a generalised linear mixed modelling (GLMM) approach to the field data in order determine how the properties of gully pots affect their operational condition over time.

5.3.1 Field measurements

The distribution of measured sediment bed levels for each measurement day are presented in the respective violin plots in Figure 5.5. This figure shows a main cluster, consisting of a majority of the gully pots, which experienced stable bed levels several months after cleaning. In contrast, a fraction of all measured gully pots experienced progressive accumulation, eventually resulting in a blockage. The latter group covers approximately 5% of all gully pots at the end of the campaign. Based on the measured sediment levels, gully pots in this group were distinctly separated from the main cluster. The presence of these two distinct groups verifies both literature on gully pot blockages and equilibrium sediment bed levels discussed in Chapter 2. As stable bed levels imply that solids and attached pollutants are no longer trapped, the measurements in Figure 5.5 show that compared to the cleaning frequency needed to prevent blockages, a relatively high frequency is required for gully pots to have an impact on water quality aspects.

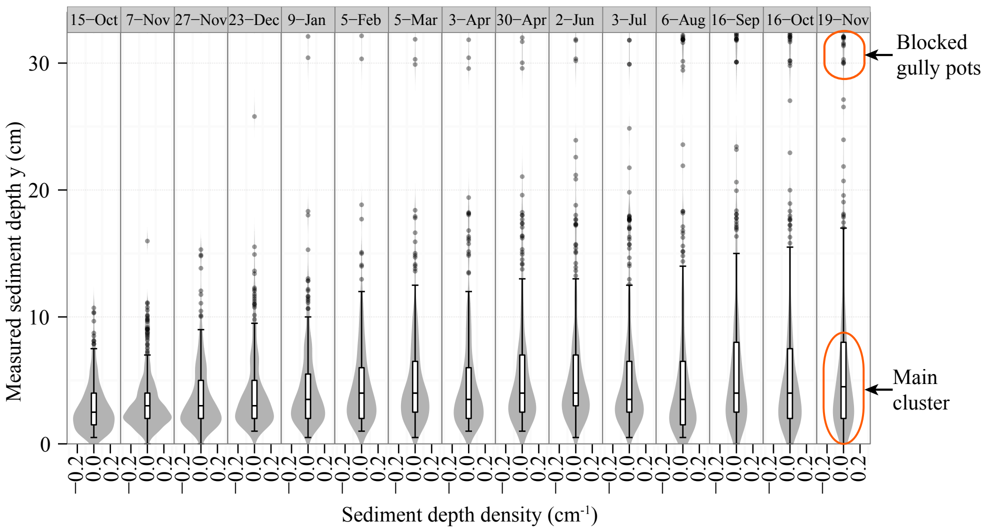

Figure 5.5: Box-violin plot of the measured sediment bed levels over time. The symmetrical density plot shows the distribution of sediment bed levels for each day of measurement. The box plot presents quartiles and individual points representing outliers. Vertical jitter was added to the outliers to aid visual interpretation.

5.3.2 Data exploration

Graphical exploration of the data revealed no clear signs of outliers or zero-inflation. Analysis of the Cook's distance statistic discussed in Section 5.2.5 showed no particular influential observation. A pair-plot of the normalised sediment bed levels v, and all explanatory variables is depicted in Figure 5.6. All explanatory variables were standardised to improving mixing of the MCMC chains. This pair-plot shows that the elapsed time since cleaning x_3 and the cumulative rainfall depth x_5 are strongly correlated, demonstrating that these variables cannot be identified separately. This is confirmed by the corresponding variance inflation factor of 64.16, which is larger than the cut-off range of 5 - 10 suggested by Montgomery and Peck (1992). Therefore it was decided to exclude the cumulative rainfall x_5 as explanatory variable.

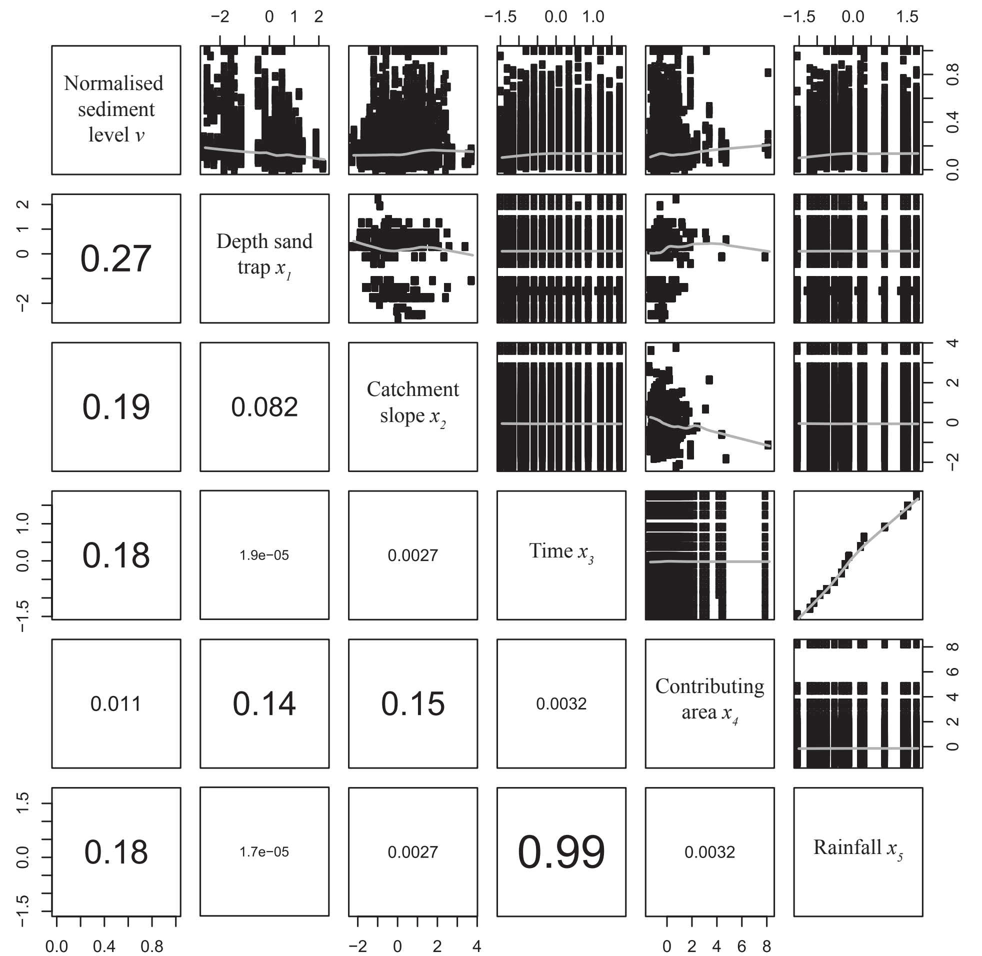

Figure 5.6: Pair-plot of the response variable and all continuous standardised (dimensionless) explanatory variables x. The lower left part contains pair-wise correlations, whereas the upper right part contains scatterplots with a locally weighted polynomial (LOESS) added to reveal patterns in the scatter.

Subsequently, the Bayesian approach presented in section 5.2.6 was applied to the collected sediment bed data in order to determine which physical and catchment properties distinguish progressive accumulation from stabilizing sediment bed levels.

5.3.3 Random part and probability distribution of the response variable

Estimations of the relative quality of the proposed probability distributions and random parts in section 5.2.2 - 5.2.3 was obtained by means of the Akaike information criterion (AIC) (Akaike, 1973), which is a penalized likelihood method. Each model included the complete set of explanatory variables and interactions for the physical properties. The AIC values given in Table 5.3 demonstrate that the models with an autoregressive component outperform their counterparts. The binomial GLMM with AR-1 correlation structure has the best relative performance. The Akaike weights (wi) in this table represents the probability that this model has the best performance, given the data and the other proposed models.

Table 5.3: AIC analysis for four competing model structures

Model	AIC	wi AIC
Binomial GLMM with AR-1	19,416.24	$1.00 \cdot 10^{0}$
Binomial GLMM	30,597.16	$0.00 \cdot 10^{0}$
Beta-binomial GLMM with AR-1	19,474.30	$2.47 \cdot 10^{-13}$
Beta-binomial GLMM	20,566.96	$1.33 \cdot 10^{-250}$

Analysis of the Pearson residuals revealed that the binomial GLMM is subject to an over-dispersion of 2.92. The beta-binomial GLMM allows for this extra dispersion through θ in Equation 5.5. A comparison of the mean values for θ derived from the beta-binomial GLMM with and without an AR-1 correlation structure, $4.32 \cdot 10^4$ versus 20.03 respectively, demonstrates the effectiveness of this component to capture the over-dispersion. Since $4.32 \cdot 10^4 \gg d_{t,i}$ (available sump depth), the variance of the beta-binomial distribution in Equation 5.4 converges to the variance of the binomial distribution.

5.3.4 Deterministic structure

The optimal deterministic structure was obtained by applying backwards selection based on the 95% highest probability density interval (HPDI). None of the interaction terms for the physical properties were significant. In addition, the explanatory variables: x_6 'presence of a water seal' and x_2 'catchment slope' are not significant from 0 at a 5% level and were excluded from the model. Exclusion of the interaction terms implies that the effect of the physical properties on the retaining efficiency does not change as the sand trap progressively silts. Figure 5.7 presents the marginal posterior distributions of the weights β_k for each explanatory variable x_k of the optimal model.

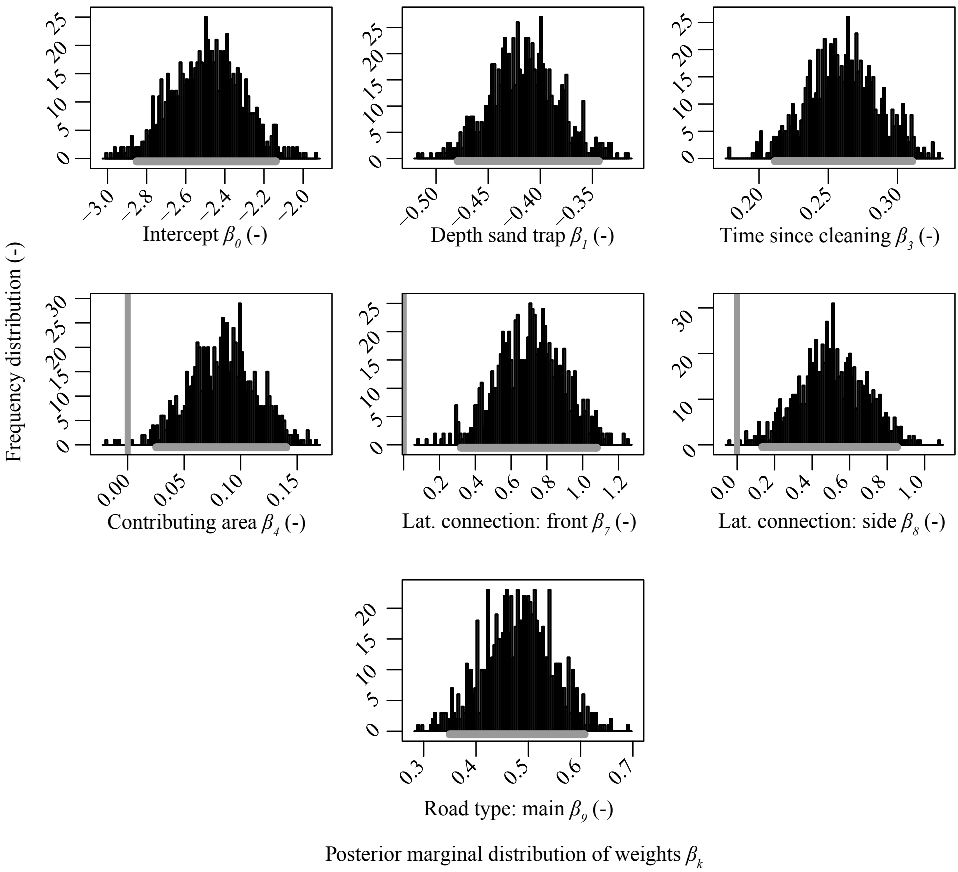

Figure 5.7: Marginal posterior distributions of the weights β_k for each explanatory variable x_k. The horizontal line shows the 95% credible interval for 800 MCMC samples. The vertical line depicts the intersection with the y-axis, indicating whether the credible interval contains zero.

The variables x_8 'position of the outflow pipe (side)' and x_4 'contributing area' have the largest p-values, 0.001 and 0.005 respectively. The deterministic component of the estimated GLMM with standardised (dimensionless) covariates and mean weight values from Figure 5.7 can be written as:

$$\begin{aligned}\eta_{t,i} = & -2.490 - 0.415 \cdot Depth_{t,i} + 0.261 \cdot Time_{t,i} \\ & + 0.084 \cdot Area_{t,i} + 0.710 \cdot PipeOut_{t,i}(front) \\ & + 0.503 \cdot PipeOut_{t,i}(side) + 0.481 \cdot Road_{t,i}(main)\end{aligned} \tag{5.10}$$

The predicted mean values for the normalised sediment bed level v, without the random component, for the different levels of the categorical explanatory variables are visualised in Figure 5.8. Credible intervals provide a region that contains the mean fitted values with a 95% probability, based on the marginal posterior distribution of the explanatory variables. The positive weight for β_9 'road type (Main Road)' compared to the baseline, corresponds to a higher sediment bed level for the gully pots located in main roads. Similar inferences hold for the weights β_7 and β_8 corresponding to the side of the lateral connection. The higher sediment bed levels for main roads are in accordance with the statements in Chapter 2, which ascribe the difference to the increased solids supply associated with the traffic intensity. It is possible that the position of the lateral connection influences the rolling motion of flows in the sump reported by Faram and Harwood (2003), which results in high velocities near the sediment-water interface.

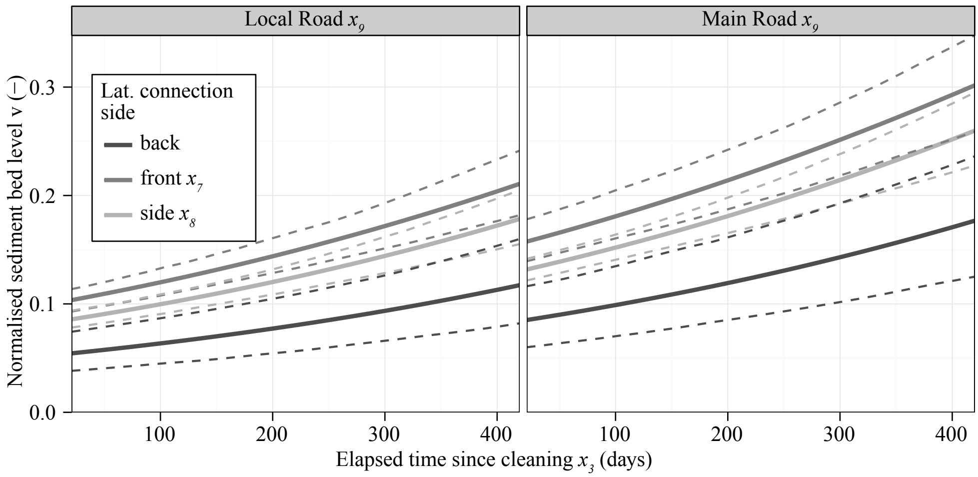

Figure 5.8: Fitted normalised sediment bed levels v for the entire population (without the random component) based on the marginal posterior distribution of categorical explanatory variables x_g 'road type' and x_7-x_8 'position of the lateral connection', with 95% credible intervals.

Memon and Butler (2002) found that the depth of the sand trap is an important parameter, having a considerable impact on the reduction of the suspended solids load to downstream sewer components. The negative weight β_9 in Equation 5.10 corresponding to the depth of the sand trap demonstrates that in addition to improving the water quality, increasing the depth of the sand trap also reduces the probability of a blockage. Evidently, a reduction in the ability to retain sediment does not compensate for the smaller volume of the sand trap under similar solids loading conditions.

The contributing area to each gully pot x_4 is positively correlated with the normalised sediment bed level. Therefore it seems that, for the range of values for the contributing area in this chapter (5 - 1380m^2), the impact of a higher solids supply associated with a larger contributing area predominates the scouring effect of an increased flow rate.

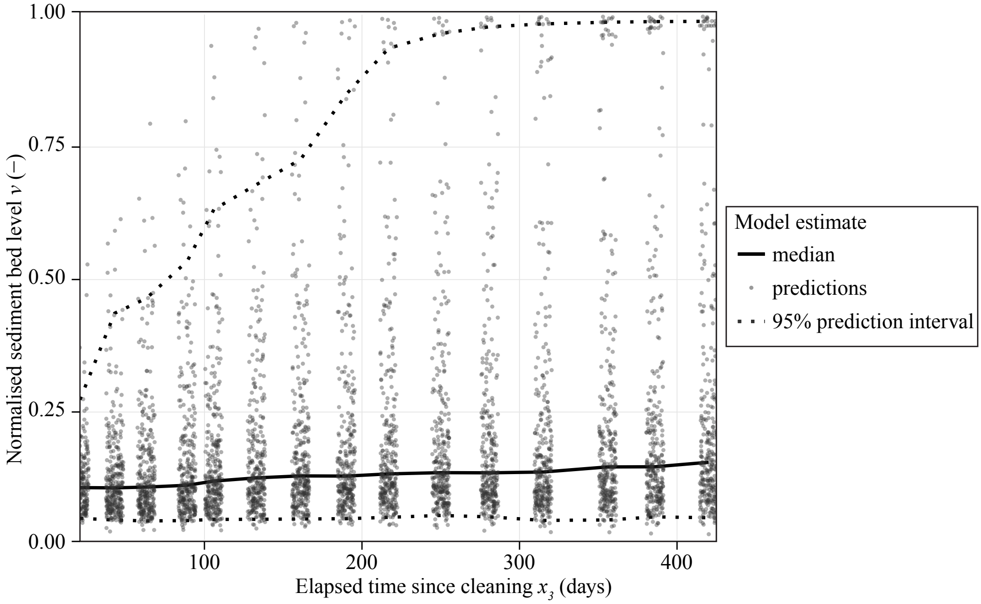

Figure 5.9: Model results of the Binomial GLMM with AR-1 correlation for the normalised sediment bed level v over time, including a prediction interval containing 95% of the observed data. Horizontal jitter was added to visualise overlaying points.

Estimated normalised sediment bed levels including the random part are presented in Figure 5.9. This figure illustrates that the proposed modelling approach is able to reproduce the dense cluster of gully pots in a near equilibrium state observed in Figure 5.5, as well as the blocked gully pots. Figure 5.10 shows the propagation of the estimated blockage rate for the area, given the parameter uncertainty. The threshold where the monitored gully pots become susceptible to blockages was found to be 100 days.

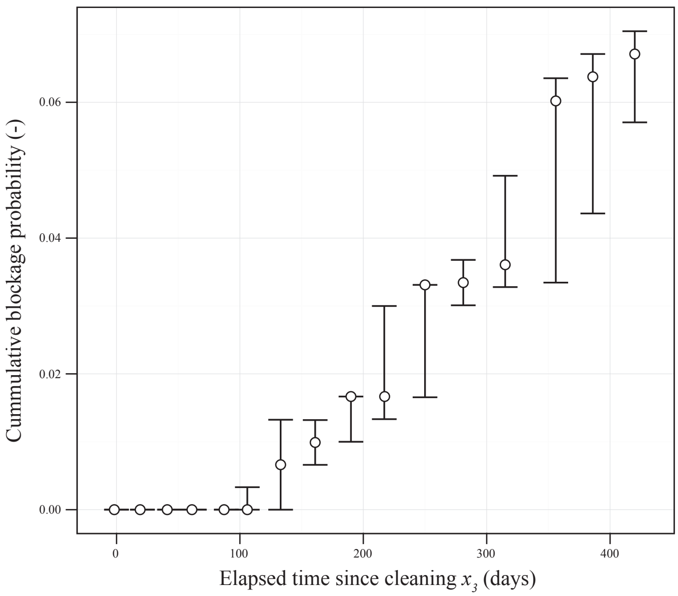

Figure 5.10: The mean estimated cumulative blockage probability over time, including 95% credible intervals.

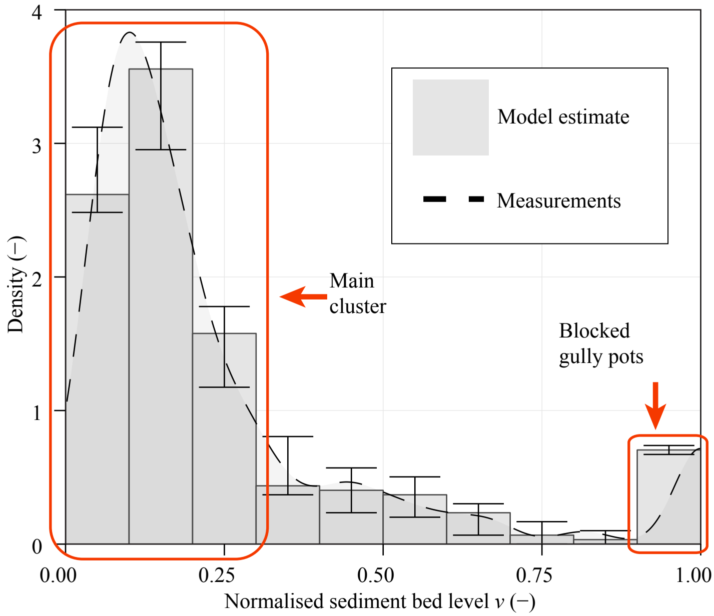

Figure 5.11: Kernel density plot of the distribution of the measured sediment bed levels for the final day of measurement, expressing the variability of the sediment bed levels over a gully pot population of 298 individuals. In addition, a histogram of the corresponding model estimate including 95% credible intervals is added.

Further analysis of the model estimates for the last day of measurement is presented in Figure 5.11. The measured normalised sediment bed levels are within the 95% credible intervals for each bin, suggesting agreement between model estimates and field observations over the entire range. This confirms that the model is able to discriminate progressive accumulation from stabilizing sediment bed levels, given the estimated model parameters.

5.3.5 Model validation

Analysis of the model residuals suggested no serious violation of homogeneity. The Mantel correlogram in Figure 5.12 shows that there is no significant spatial correlation present in the model residuals at distances of more than 5 meters. The corresponding density graph presents the distribution of the Euclidean distances between each gully pot. This graph reveals that although there was some spatial dependence present at small distances, this concerns only a small fraction $(2 \cdot 10^{-4})$ of the total sample of gully pots. As such, this figure demonstrates that there are no spatially correlated variables (e.g. trees, local construction activities) missing in the model. The absence of a residual spatial dependence demonstrates that there are no clusters of gully pots with higher normalised sediment bed levels. This implies that maintenance strategies can be optimised when taking into account the explanatory variables x_k of the deterministic structure. Moreover, in the presence of a gully pot blockage there is no evidence of an increased blockage probability for adjacent gully pots. Therefore, the vulnerability to an event is reduced, as alternative flow routes may compensate for the occurrence of a blockage. With respect to the design of the public space, this entails that increasing the gully pot density directly adds to redundancy.

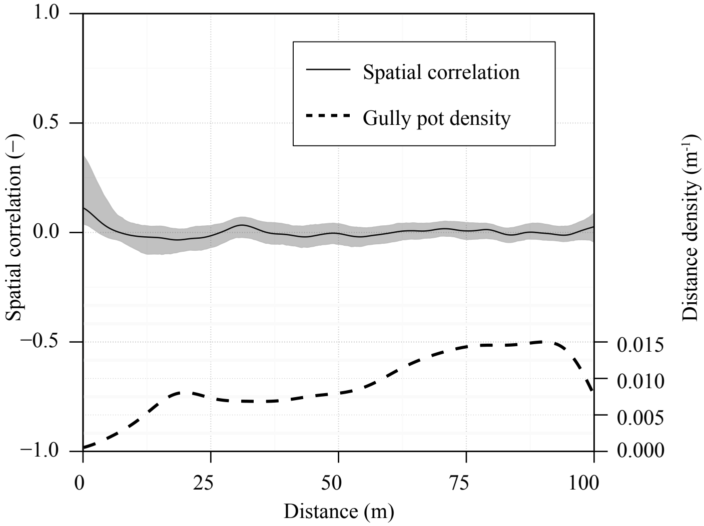

Figure 5.12: Spatial correlation of the model residuals, including 95% confidence bounds, plotted together with the empirical density function of gully pots interdistances.

The effectiveness of the AR-1 model to catch the temporal dependence in the residuals was illustrated in Figure 5.13. This figure shows the difference between the rejected binomial GLMM with a compound correlation structure and the selected binomial GLMM with AR-1 correlation structure. The former model structure was positively autocorrelated for several orders, as successive residual values tend to persist on one side of the mean. It exhibits a slow meandering pattern, in which residuals were consistently overestimated at the start of the time series and underestimated at the end. A clear seasonal pattern was, however, not present. Furthermore, the low-lag positive autocorrelation confirms that the sampling density of the monitoring campaign was sufficient to reconstruct the long term sedimentation process in gully pots.

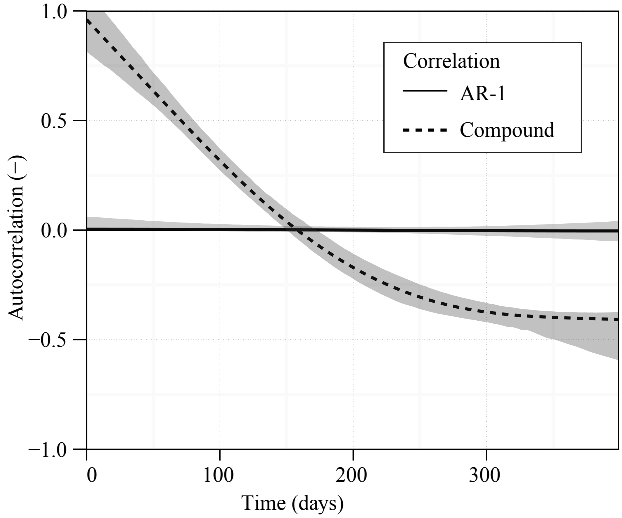

Figure 5.13: Autocorrelation of the rejected binomial GLMM with compound correlation and the chosen binomial GLMM with AR-1 correlation structure. 95% confidence bounds were added.

5.3.6 Generalisation

The results presented in Figures 5.8 - 5.10 are case specific due to the set of properties for gully pots in the study area. Under the assumption of sample representativeness, the marginal posterior distributions of the model parameters in Figure 5.7 can be generalised and applied to similar designed gully pots beyond the frame of the study area, e.g. to improve gully pot design. The healthy data-paramter ratio and the absence of any highly influential outliers or underdispersion indicate that there are no apparent signs of overfitting. Results found in this chapter are generally consistent with the literature in Chapter 2. In addition, the proposed method for modelling sedimentation in gully pots can be applied to measurements from other study areas.

5.4 Conclusions

This chapter provides a procedure to model the long term accumulation of solids that leads to blockages. To this end, field measurements from 300 gully pots were analysed by means of a generalised linear mixed model (GLMM). Analysis of the measurements revealed the presence of two distinct regimes. A majority of the gully pots reached equilibrium sediment bed levels after several months. The inability of these gully pots to effectively trap solids and associated pollutants can affect the quality of receiving water bodies and performance of downstream drainage and treatment facilities. A fraction of all gully pots (5%) experienced a blockage due to the progressive accumulation of sediment. These blockages may cause flooding problems during storm events.

From the model results it can be concluded that the depth of the sand trap and the position of the lateral connection are physical properties that distinguish progressive accumulation from stabilising sediment levels. The latter was believed to influence the velocity profile at the sediment-water interface. The former demonstrates that requirements concerning hydraulic efficiency and pollutant retention for water quality purposes are not necessarily conflicting; both benefit from deeper sand traps. No interaction between the physical properties and the elapsed time since cleaning was found to be significant. This entails that the effect of these physical properties do not change as the sediment bed level increases. The road type and the area contributing to runoff were found to be relevant catchment properties. As the parameter estimate for the latter is positive, this indicates that the higher solids supply predominates the scouring effect associated with an increased flowrate.

The absence of residual spatial correlation indicates that there are no clusters of gully pots with higher normalised sediment bed levels. Since the blockage probability is spatially independent, there is no evidence that alternative drainage paths through adjacent gully pots will be unavailable in case of a blockage. As this limits the exposure to flooding events, the vulnerability of the public space to blockages reduces.

Findings from this chapter may aid to support maintenance strategies on a system scale and to improve gully pot design. Knowledge of properties that contribute to progressive accumulation and eventually blockages, may justify investments during the design phase in order to minimise future maintenance and blockages. That is, decision makers should consider the physical and catchment properties that prevent progressive accumulation of solids, when aiming to prevent gully pot blockages. In addition, the absence of a residual spatial dependence allows for directing preventive maintenance, taking these properties into account. Compared to the cleaning frequency needed to prevent blockages, a relatively high frequency is required for gully pots to have an impact on water quality aspects.

6 The effectiveness of proactive strategies for gully pots and lateral connections

Results from the monitoring campaign in Chapter 5 shows that the continuous trapping of solids over time can cause blockages that affect the hydraulic performance of gully pots. In addition, main sewers are subject to continuous deterioration processes (Hahn et al., 2002; Wirahadikusumah et al., 2001), which are also typical for the anterior part of the system. Silting of gully pots is managed by vacuum excavation cleaning, while blockages and collapses of lateral connections call for hydraulic cleaning or rehabilitation.

Although asset management of main sewers has evolved to proactively allocating resources to deliver the required service level in a cost-effective way (Le Gauffre et al., 2007), the anterior part of the sewer system is primarily maintained by reactive strategies. Cyclic cleaning of gully pot sand traps is an exception, as this involves preventive cleaning activities at regular scheduled intervals. The effectiveness of these preventive activities depends on the flood risk within the cleaning interval (Swanson, 2001). Instead of quantitative data, this interval is based on the available budget (Fenner, 2000), vulnerability of the draining area or expert judgement. Still Caradot et al. (2011) reported gully pot blockages due to sediment accumulation to remain the dominant cause of urban floodings. Alternatively, several studies modelled the accumulation of sediment in gully pots (e.g. Butler and Karunaratne, 1995; Deletic et al., 2000). However, these models rely on the calibration of site specific parameters that limit the feasibility on a catchment scale. The model structure proposed Chapter 5 also relies on additional measurements for reliable predictions in other catchment areas. In addition, the availability of adjacent gully pots may also avert the occurrence of a flooding event in case of a blockage.

This chapter is based on: Post, J.A.B., Langeveld, J.G., and Clemens, F.H.L.R. (2016). Quantifying the effect of proactive management strategies on the serviceability of gully pots and lateral sewer connections. *Structure and Infrastructure Engineering*, in press.

Closed Circuit Television Inspections (CCTV) of main sewers are common (Dirksen et al., 2013), whereas lateral connection condition data necessary to prioritise proactive work are generally unavailable. In addition, decision support models rely on the formation of groups with similar characteristics (Ana et al., 2009; Duchesne et al., 2013) such as age and materials, which are mostly unknown for the anterior part of the sewer system.

Despite the lack of data, the direct impact of the anterior part of the sewer infrastructure on the overall level of sewer service provision calls for the optimisation of management strategies. Evaluating the effectiveness of proactive work is pivotal, as it provides explicit motivation for the deployment of resources. Therefore, this chapter describes a statistical approach to quantify the effectiveness of proactive work to reduce citizen calls. Calls concerning events are a measure of serviceability, a performance indicator that has received wide acceptance in sewerage provision (Arthur et al., 2009; Ashley and Hopkinson, 2002). By evaluating the relationship between proactive management strategies and their contribution to system performance, the proposed techniques support sound decision-making where the merits of proactive and reactive management strategies are balanced to optimise costs and sewer serviceability.

The structure of this chapter is as follows. First a procedure to analyse gully pot blockages and lateral connection blockages is described. The analysis of gully pot blockages is based on a database comprising call data collected in two municipalities covering over 150,000 gully pots and 3478 reported flooding events. For the analysis of lateral connection blockages, call data were collected for two areas in two periods: *period A*, the reference period, prior to the proactive maintenance of all lateral connections and *period B*, the period after the proactive maintenance. Results from the application of the proposed procedure to these data and the implications are discussed in Section 6.3.

6.1 Methods

This Section presents statistical methods to analyse call data with the aim to quantify the effect of proactive management strategies. The first part is dedicated to analysing the effect of cyclic gully pot cleaning. The second part describes a Bayesian method to quantify the ability of lateral connection rehabilitation activities to decrease call rates.

Nomenclature

Symbol	*Description*
T	random variable denoting the time to a reported blockage event
τ	elapsed time since cleaning
n	population size of gully pots
Y	number of registered calls
$\widehat{F}(\tau)$	Kaplan-Meier estimate of the cumulative call distribution function
$h(\tau)$	hazard function
$H(\tau)$	cumulative hazard function
κ	kernel function
b	kernel bandwidth
λ	constant call rate Exponential distribution
α	scale parameter Weibull distribution
β	shape parameter Weibull distribution
E	expected number of calls
SCR	standardised call ratio
θ	scale parameter Gamma distribution
v	shape parameter Gamma distribution

6.1.1 Analysing the effect of cyclic gully pot cleaning

The effectiveness of gully pot cleaning is determined by the evolution of the number of registered calls on flood events over time. When the probability of a call is unaffected by preventive cleaning activities, the strategy is considered to be ineffective in maintaining the hydraulic performance of the system. This study analyses trends in the operational performance of gully pots by describing the distribution of times to a registered call on a blockage event. The time to a blockage event is defined as the random variable T, which represents the time between cleaning and a registered call.

Analysis of the data is complicated by the fact that not all gully pots in a given population experience a blockage before scheduled cleaning activities are initiated. All that is known about these gully pots is that their time to blockage is beyond the cleaning interval. This is commonly referred to as right censored data. Further complexity is added by the initiation of a cleaning cycle, during which the size of the remaining population eligible for blockage changes continually. Both issues are schematised in Figure 6.1, for 6 arbitrary gully pots.

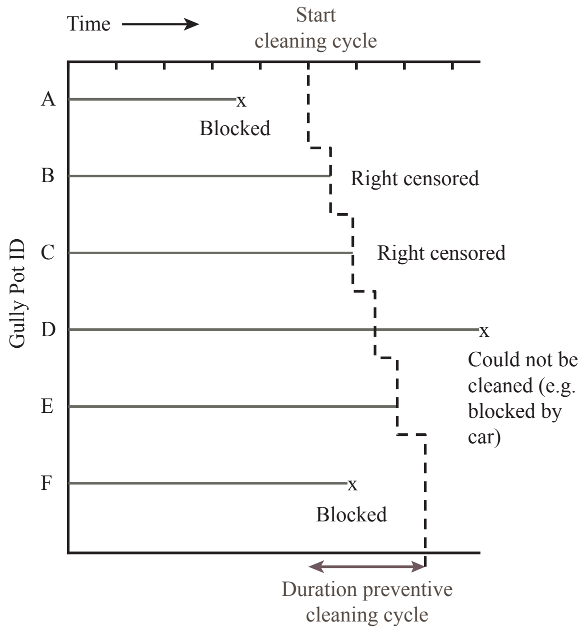

Figure 6.1: Example of the timelines of 6 gully pots. A timeline ends when either a gully pot is preventively cleaned (censored) or is reported blocked by citizens. Consequently, the remaining population at risk of a blockage varies over time.

The Kaplan-Meier estimate (Kaplan and Meier, 1958) is a non-parametric method that does not suffer from the aforementioned issues, as it considers the varying number of gully pots at risk of a blockage at a given time. The estimate of the cumulative distribution function (CDF), giving the probability of a call before time τ, is given by

$$P\left(T \leq \tau_k\right) = \hat{F}\left(\tau_k\right) = 1 - \prod_{i=1}^{k} \frac{n_i - Y_i}{n_i} \tag{6.1}$$

where n_i are all the gully pots at risk at time step i, Y_i all the calls on blocked gully pots and the elapsed time since cleaning. For comparison, two other common parametric failure models are evaluated: the Exponential distribution and the Weibull distribution. The versatile Weibull distribution (Weibull, 1951) is able to approximate several continuous failure distributions and is generally capable of modelling both increasing and decreasing trends in call rates (Tobias and Trindade, 2011). The CDF of this distribution is given by

$$F\left(\tau\right) = 1 - \exp\left(-\left(\frac{\tau}{\alpha}\right)^{\beta}\right) \tag{6.2}$$

with scale parameter α and shape parameter β. Estimates of the parameter β that exceed 1 indicate increasing call rates, corresponding to deteriorating gully pot performance over time. Confidence intervals for the parameters of the Weibull distribution are obtained by bootstrapping (Efron, 1979). This involves randomly resampling, with replacement, observed call data and deriving the Weibull parameters for each sample.

The Exponential distribution is characterised by a constant call rate λ. This implies that blockages occur randomly in time and are unaffected by preventive cleaning. This distribution is a special case of the Weibull distribution where $\beta = 1$ and $\alpha = \lambda^{-1}$.

A more formal way to illustrate trends in registered calls rates is the hazard function. It represents the conditional probability of a call in the interval $[\tau, \tau + d\tau)$, given that no call was registered prior to τ. In mathematical form this is denoted as

$$h(\tau) = \lim_{d\tau \to 0} \frac{\Pr(\tau \leq T < \tau + d\tau | T \geq \tau)}{d\tau} \tag{6.3}$$

The hazard function is undefined at time steps with no calls. Therefore, Tanner and Wong (1983) proposed the application of kernel smoothers (i.e. local weighted averaging) to construct a continuous function from a set of point estimates at each time step. Considering that the cumulative hazard function is related to Equation 6.1 by $H(\tau) = -\ln(1 - F(\tau))$, the kernel estimate of the hazard function is given by

$$\hat{h}(\tau) = \frac{1}{b} \sum_{i=1}^{k-1} \kappa\left(\frac{\tau - \tau_i}{b}\right) \ln\left(\frac{1 - F(\tau_i)}{1 - F(\tau_{i+1})}\right) \tag{6.4}$$

Where κ is the kernel function and b is the bandwidth. It is generally accepted that the choice of the kernel function is not crucial (Silverman, 1986). This study employed the Epanechnikov kernel. The bandwidth was optimised by minimising the integrated mean squared error, since the effect of the value on the hazard estimate is considered pivotal. When the derived hazard function $\hat{h}(\tau)$ is horizontal, it corresponds to the constant call rate λ assumed by the Exponential distribution.

6.1.2 Modelling the spatial structure of lateral connection calls

Quantifying the effect of lateral connection rehabilitation activities requires the collection of data both before and after the rehabilitation intervention. Standard hypothesis testing relies on a direct comparison of these data to detect an intervention effect. For lateral connections, this effect can be obscured by the inherent variation in hydraulic and solids loadings over time (Ellis and Harrop, 1984; Pratt et al., 1987). For example, an observed effect in the number of calls can be the result of a severe storm event or seasonal leaf-fall instead of an improved operational condition.

In the field of spatial epidemiology it is common to analyse the relative risk (e.g. Bernadinelli et al., 1997; Clayton and Kaldor, 1987). Relative risk represents the degree to which the probability of an event in an area is higher or lower than the standardised city mean. This can be expressed as the ratio between the observed number of reported calls in a rehabilitated area and the expected number of events, which is derived from the underlying city mean call rate. As the city is assumed to be subject to similar hydraulic loads, this approach is considered to be more appropriate than standard hypothesis testing. Serviceability improvements can be quantified by comparing differences in the standardised call ratio (SCR) before and after rehabilitation activities. In addition, analysis of the spatial distribution of standardised call ratios allows for the identification of areas with a significant increased call incidence, where proactive strategies are most promising.

Assuming mutual independence between observed calls concerning lateral connection blockages, the Poisson distribution is a typical candidate to model observed calls Y_j in neighbourhood j of the p neighbourhoods in a city and is given by

$$Y_j \sim Poisson\left(SCR_j E_j\right) \tag{6.5}$$

where the SCR (Standardised Call Ratio) represents the true, but unknown, neighbourhood specific relative call ratio. In the case where SCR_j equals unity, the neighbourhood in question shows no deviation from the overall call probability in the city. The expected number of calls E_j is estimated by

$$E_j = n_j \frac{\sum\limits_{j=1}^{p} Y_j}{\sum\limits_{j=1}^{p} n_j} \tag{6.6}$$

which is simply the mean number of calls per gully pot in the city multiplied by the number of gully pots in area j.

A limitation of the Poisson distribution, is its inability to capture the extent of variation generally present in count data compared to the expected variance (i.e. overdispersion) (Lawson, 2013). This is due to the fixed relation between the mean and the variance assumed by this distribution. Consequently, the model may improperly indicate the presence of a significant effect as credible intervals are too narrow. Alternatively, the excess variation in the data can be accommodated by a second model layer, describing the prior distribution of the SCR_j as a Gamma distribution with shape parameter ν_j and scale parameter θ_j. The linkage between the different elements of the model is depicted in Figure 6.2. The left part of this figure contains all registered calls before inspection and rehabilitation activities, while the right part contains all registered calls following these activities. ΔSCR is the difference distribution that yields information on whether the intervention resulted in a statistically significant difference in the call ratio.

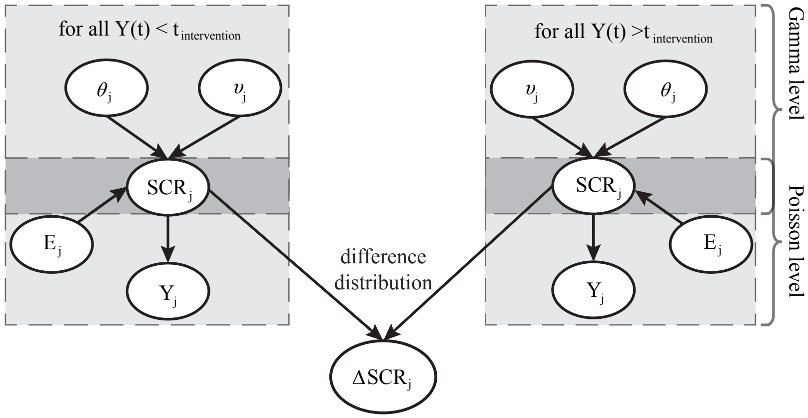

Figure 6.2: Directed Acyclic Graph (DAG) illustrating the linkage between the different elements in the Poisson-Gamma model used to quantify developments of the *SCR* (Standardised Call Ratio).

The *SCR* was estimated by applying a Bayesian approach, which considers unknown parameters as random variables. Bayesian inference takes into account parameter uncertainty and is therefore particularly suited for interpreting the significance of any change in the *SCR* owing to rehabilitation activities. Given Bayes theorem, the joint posterior density can be expressed as

$$P\left(\mathbf{SCR}|\mathbf{Y}\right) \propto P\left(\mathbf{Y}|\mathbf{SCR}\right) P\left(\mathbf{SCR}\right) \tag{6.7}$$

where $P(\boldsymbol{SCR})$ represents the second level of the model, described by a gamma distribution. $P(\boldsymbol{SCR}|\boldsymbol{Y})$ is referred to as the likelihood function, which for the first level is given by

$$L\left(\mathbf{Y}|\mathbf{SCR},\mathbf{E}\right) = \prod_{j=1}^{p} \frac{\left(E_j SCR_j\right)^{-Y_j} \exp\left(-E_j SCR_j\right)}{Y_j!} \tag{6.8}$$

and for the second level

$$L\left(\mathbf{SCR}|\theta,\upsilon\right) = \prod_{j=1}^{p} \frac{{\theta_j}^{\upsilon_j}}{\Gamma\left(\upsilon_j\right)} {SCR_j}^{\upsilon_j-1} \exp\left(-\theta_j \upsilon_j\right) \tag{6.9}$$

The posterior distribution was evaluated by means of the Markov Chain Monte Carlo (MCMC) method. This study applied the Gibbs sampler (Geman and Geman, 1984) as MCMC algorithm, which was implemented in the open source software JAGS (Plummer, 2003) and was called from the R software environment (Core Team, 2014). Non-informative flat gamma (0.01, 0.01) priors for $\boldsymbol{\nu}$ and $\boldsymbol{\theta}$, represented the lack of knowledge about the gamma parameters.

6.2 Call data

The methods described in Section 6.1 were applied to a dataset of linked proactive (Sections 6.2.1- 6.2.2) and reactive maintenance data. Reactive maintenance data from the citizen call registers of two municipalities in the Netherlands were interrogated. The different failure mechanisms responsible for flooding events are depicted in Figure 6.3. In total, 92% of all registered calls were attributed to the performance of gully pots and lateral connections. Since both sediment deposits and non-particulate matter (cans, packaging material, etc.) are both removed by cyclic cleaning, potentially 72% of all gully pot blockages can be prevented. Rehabilitation of lateral connections can reduce the number of structural defects and the susceptibility to tree root intrusion, which form 55% of all calls pertaining to lateral connections. Consequently, intensifying proactive strategies for these components can potentially reduce the total number of calls by up to 63%.

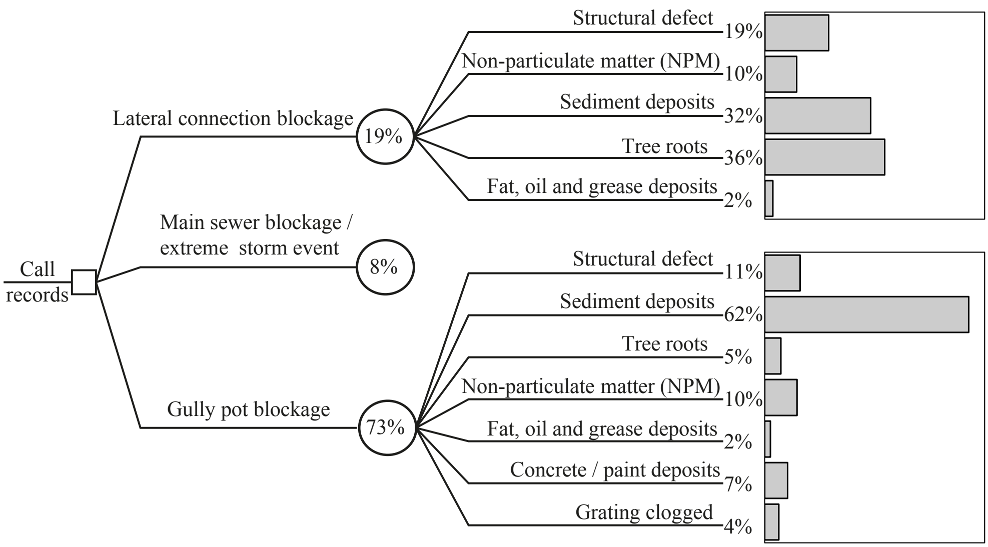

Figure 6.3: Tree diagram of the contribution of different failure mechanisms to flooding events registered in the call database.

A subset of call data that were attributed to the operational condition of gully pots and lateral connections by municipal workers were selected for this study. With a combined population of 524,000 inhabitants (CBS, 2014), these subsets contained 3096 calls (period 03-2012 – 08-2015) for the city of Utrecht and 382 calls (period 10-2014 – 10-2015) for the city of Almere. The latter is a relatively new city with most of the sewer infrastructure developed after 1970, while most of the sewer infrastructure in Utrecht has been developed after 1950. Characteristics of these two cities are presented in Table 6.1.

Table 6.1: Characteristics of the cities of Utrecht and Almere.

Characteristics	Utrecht		Almere	
Number of inhabitants served	328,164	(-)	196,013	(-)
Ground level variation	1 - 6	m	-4.5 - -2.5	m
Number of gully pots	79,000	(-)	73,000	(-)
Construction year sewer	1950 - 2016	(-)	1970 - 2016	(-)
Total length storm sewers	167	km	640	km
Total length combined sewers	611	km	0	km

6.2.1 Preventive cyclic cleaning of gully pots

Data on the location of gully pots eligible for blocking were collected during cyclic preventive cleaning of the gully pot sand traps. This included the time of cleaning. Although the normal cleaning frequency was once a year, cleaning frequencies for individual gully pots varied due to local circumstances (e.g. inability to clean due to parked vehicles). In some cases, this resulted in the exclusion from a cleaning cycle. As a consequence, data were available for well beyond the standard cleaning interval of one year.

6.2.2 Proactive inspection and rehabilitation of lateral connections

Two neighbourhoods in the city of Utrecht with close to 1250 gully pots were selected to investigate the effect of extensive proactive maintenance. Call data from the period prior to the proactive activities served as a reference to quantify the evolution of calls with respect to the period after these activities.

Next to the normal cyclic cleaning activities of the gully pot, lateral connections were hydraulically jetted and inspected by means of CCTV. The resulting dataset contained detailed information on the condition of these assets. If the condition of an asset was rated unacceptable, an intervention was planned and the asset was proactively rehabilitated. Characteristics of the two neighbourhoods are presented in Table 6.2. The majority of pipes that were rated unacceptable experienced tree root intrusion or a (partial) collapse.

Table 6.2: Characteristics of the two neighbourhoods where lateral connections were subject to proactive maintenance.

		Neighbourhood	
		Taagdreef	Queeckhovenplein
Inhabitants		4000	1135
Total nr. Gully pots		951	278
Condition unacceptable		26%	50%
Main sewer age (mode)		55 years	60 years
Pipe material	PVC	38%	34%
	vitrified clay	62%	66%

6.3 Results and discussion

The results presented in this section consist of two parts. First, the impact of preventive gully pot cleaning on the reactive maintenance workload is determined. To this end, the Kaplan-Meier estimate and the hazard function was computed to determine how the number of calls concerning gully pot blockages developed as a function of time. Second, the influence of lateral connection inspection and rehabilitation was investigated by comparing standardised call ratios ($SCR's$) before and after an intervention.

6.3.1 Evolution of sediment induced blockages in gully pots

The probability of a call due to excessive sediment deposits in a gully pot in Utrecht are depicted in Figure 6.4. Increasing confidence interval widths are the result of right censoring, as the remaining population of gully pots eligible for blocking decreased over time. In addition to the Kaplan-Meier estimate, the parametric exponential distribution with a constant instantaneous call rate λ is depicted in this figure. The empirical blockage data exhibit an increasing departure from this distribution, as the elapsed time since cleaning increases. This implies an increasing call rate and the invalidity of the constant call rate assumption.

The shape parameter β of the Weibull distribution in Table 6.3 provides further evidence for an increasing call rate over time, as both the estimate and the 95% confidence interval exceeds 1. The scale parameter α has wide confidence interval corresponding to substantial parameter uncertainty. Since this parameter is an indicator of the characteristic time until a blockage, more precisely the 63.2^{th} percentile, this uncertainty can be attributed to the maximum bound of the data (550 days).

The hazard function presented in Figure 6.5 illustrates the increasing trend in the call rate more clearly. These results suggest that progressive silting of the sand trap eventually takes its toll on the hydraulic performance of gully pots. The sudden increase in the call rate suggests that for this case, the interval between successive cleaning cycles should not exceed 400 days.

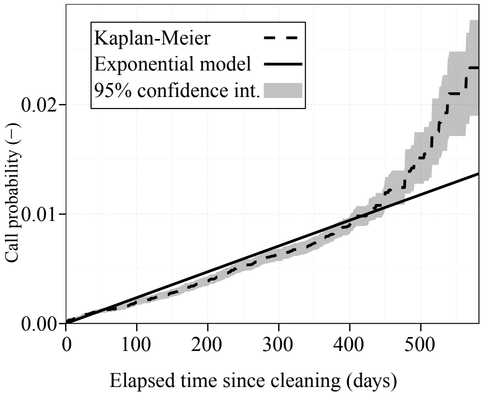

Figure 6.4: Kaplan-Meier estimate of the probability that a gully pot is reported blocked for Utrecht as a function of the elapsed time since cleaning. An Exponential model assuming a constant call rate λ is added.

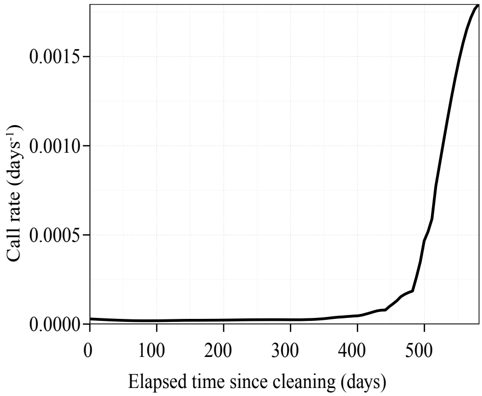

Figure 6.5: Kernel estimate of the hazard function for Utrecht as a function of the elapsed time since cleaning.

Table 6.3: Parameter estimates for the Weibull distribution parameters α and β, for the city of Utrecht and Almere. Bootstrap resampling was used to obtain 95% confidence intervals.

		City			
	Weibull parameter	Utrecht		Almere	
β	estimate	1.43	(-)	1.99	(-)
	95% confidence interval	[1.33, 1.55]	(-)	[1.54, 2.61]	(-)
α	estimate	7995	(days)	5724	(days)
	95% confidence interval	[10429, 13513]	(days)	[2740, 14961]	(days)

Figure 6.6 shows a similar trend for call data in Almere. Blockages due to excessive sediment deposits in gully pots appear to be non-random in time and subject to increasing call rates as the time since cleaning progresses. Table 6.3 shows that confidence intervals for the scale parameter α and the shape parameter β of the Weibull distribution are of the same order of magnitude as for Utrecht.

On the whole, the hazard function shows an increasing call rate for both cities, indicating that progressive silting may eventually impair the gully pots ability to transport runoff to the sewer system. These findings provide evidence that cyclic cleaning is effective to reduce citizen calls caused by this failure mechanism. Generalisation of the characteristic time scales of derived blockage rates may be limited, as different parameters influence the trapping efficiency of gully pots (Memon and Butler, 2002). However, these methods can be applied to any catchment where sufficient call data are available.

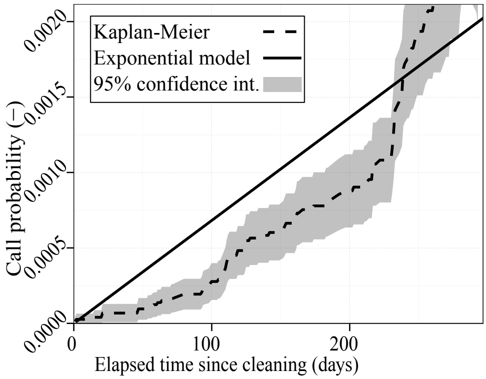

Figure 6.6: Kaplan-Meier estimate of the probability that a gully pot is reported blocked for Almere as a function of the elapsed time since cleaning. An Exponential model assuming a constant call rate λ is added.

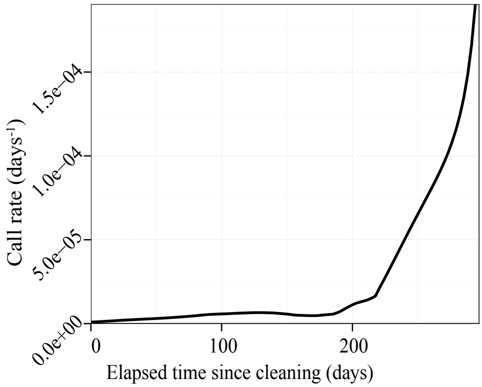

Figure 6.7: Kernel estimate of the hazard function for Almere as a function of the elapsed time since cleaning.

Results for the presented cases are in line with the experimental findings of Butler and Karunaratne (1995), who reported an overall positive particle retention efficiency. A monitoring study by Conradin (1989) resulted in somewhat different conclusions, as sediment beds were observed to reach an equilibrium state below the level of the outflow pipe after approximately 6 months. However, the results are in line with the progressive silting regime identified in Chapter 5.

Kaplan-Meier estimates can aid to balance preventive and reactive actions to determine an optimum level of service, given the available budget. Compared to the sediment measurement data needed for the modelling approach discussed in Chapter 5, the local call data required for the Kaplan-Meier estimates are generally available. It should be noted that the number of recorded calls is likely an underestimation of the true number of gully pot blockages as some events may not be observed (events at remote locations or during the night), alternative flow paths might be available or single flooding events may involve multiple blocked gully pots. For example, 5% of the monitored gully pots in Chapter 5 were found to be blocked after 14 months. Yet, no citizen calls in the area were received by the municipal call centre in that period. Although the derived call probabilities are low, gully pots are still responsible for a majority of all calls (see Figure 6.3) due to their sheer numbers. With cyclic gully pot cleaning costs varying between €3 to €6, proactive costs are low compared to €100 to €200 for reactive actions (Ten Veldhuis, 2010). Figure 6.8 shows the financial trade-off between proactive and reactive maintenance, given this cost range and the Kaplan-Meier estimates. This figure shows that cyclic gully pot cleaning is cost effective. The total costs are minimised when a cleaning frequency between 12 and 16 months is maintained. However, these costs do not include damage costs and societal consequences and should therefore only serve as an absolute upper limit for the cleaning interval.

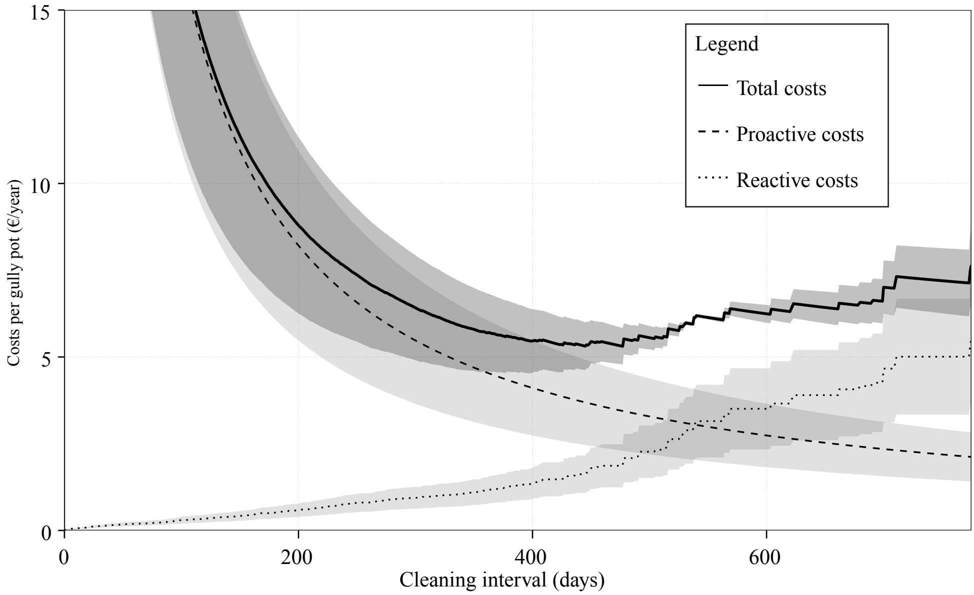

Figure 6.8: Estimated proactive and reactive maintenance costs for Utrecht as a function of the cleaning interval. Reactive maintenance needs are based on the Kaplan-Meier estimates. Uncertainty bands represent the maintenance cost range given by Ten Veldhuis (2010).

6.3.2 The effectiveness of preventive maintenance on lateral connections

The Standardised Call Ratio (*SCR*) discussed in Section 6.1.2, reflects the degree to which the call rate in a neighbourhood is different from the overall city mean rate. Analysis of the Poisson model used to estimate the *SCR* revealed substantial overdispersion ($15.56 \gg 1$), as the data exhibited extra variation which could not be captured by the model. Therefore, results were analysed using the two-level Poisson-Gamma model. The Gelman-Rubin diagnostic (Gelman and Rubin, 1992) revealed no convergence problems of the MCMC chains. Figure 6.9 shows the estimated *SCR*'s for neighbourhoods in Utrecht. In total 14 neighbourhoods were found to have significantly higher call rates, indicating areas where proactive inspection and rehabilitation is most promising.

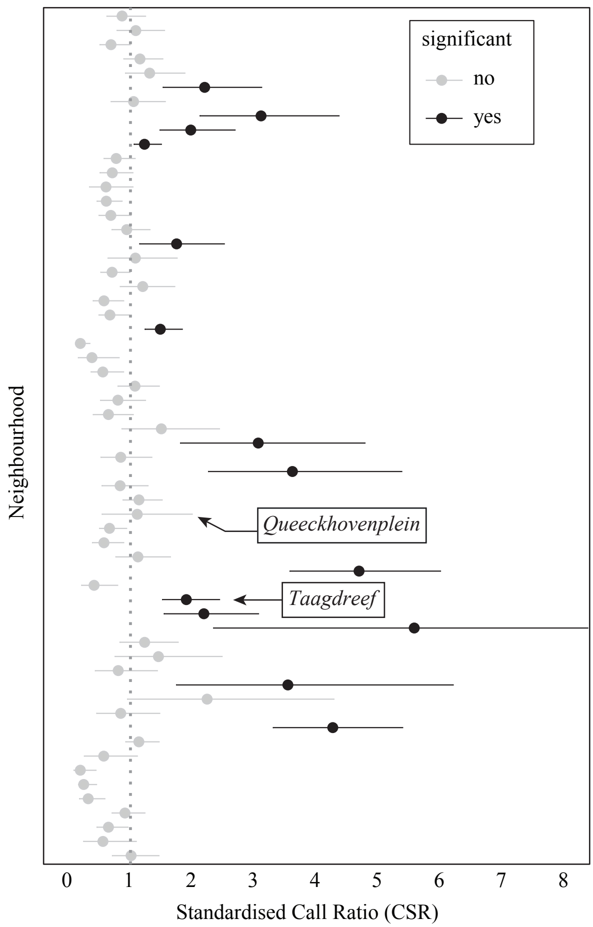

Figure 6.9: 95% credible intervals of the Standardised Call Ratio (*SCR*) for neighbourhoods in Utrecht, the Netherlands before the intervention. The dotted line indicates the standardised mean city call rate and significant increased rates are indicated by black credible intervals.

The neighbourhoods Taagdreef and Queeckhovenplein introduced in Section 6.2.2 were inspected and lateral connections were rehabilitated when deemed necessary. From these two neighbourhoods, only Taagdreef has a significantly increased call ratio according to Figure 6.9. Table 6.4 shows both the observed and expected number of calls before and after rehabilitation activities. The expected number of calls was based on the overall mean city call rate, according to Equation 6.6. For Queeckhovenplein the number of observed calls was lower than expected, while for Taagdreef the number of observed calls exceeded the expectation prior to intervention.

Table 6.4: Observed and expected calls for two Neighbourhoods in Utrecht before and after maintenance activities.

		Neighbourhood	
Rehabilitation	Type	Taagdreef	Queeckhovenplein
Before	Observed	13	2
	Expected	8.51	6.69
After	Observed	11	0
	Expected	21.77	2.1

The effectiveness of these proactive activities to reduce the number of calls was quantified by computing the change in *SCR* after the intervention. Figure 6.10 shows differences of posterior samples for the *SCR* before and *SCR* after rehabilitation activities. For the Taagdreef case there is evidence of a significant improvement in the number of calls, as the 95% credible interval does not contain zero. There is insufficient evidence to make similar statements for Queeckhovenplein. This could be the result of the size of the area, which limits the amount of registered calls (see Table 6.4). Alternatively, the relatively low *SCR* before the intervention (see Figure 6.9) implies that the overall potential to improve the operational condition in this neighbourhood was limited.

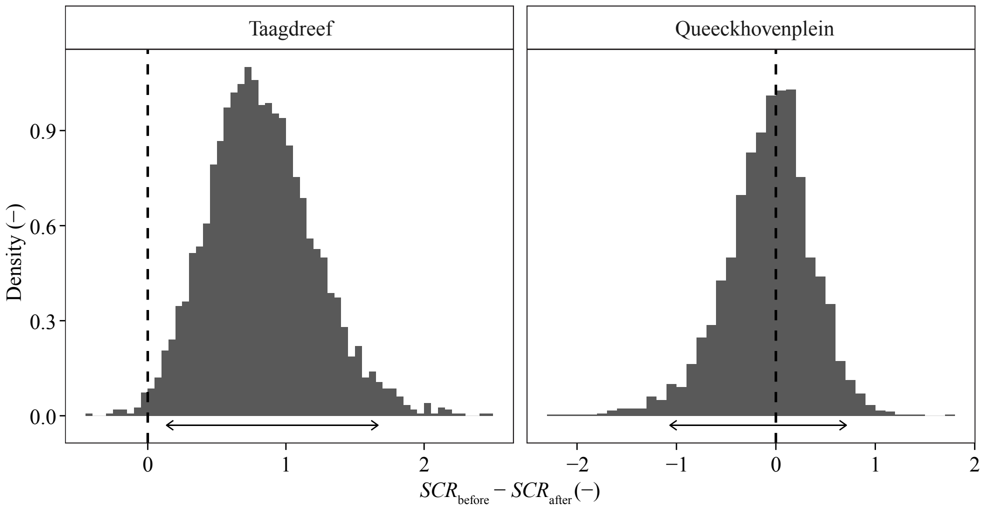

Figure 6.10: Difference posterior distribution of the Standardised Call Ratio (*SCR*) before and after maintenance activities for two neighbourhoods in Utrecht. Arrows indicate the 95% credible interval, which provide evidence of a significant difference if zero is not included.

It should be noted that lateral connection rehabilitation does not only safeguard these components from collapse, but may also reduce susceptibility to more recurring failure mechanisms such as the intrusion of tree roots (Ridgers et al., 2006).

6.4 Conclusions

This chapter describes an approach to quantify the effectiveness of proactive work on gully pots and lateral connections to improve sewer system performance. To this end, a procedure has been presented which can support decision-makers to optimise management strategies by evaluating the effect on the level of service provision. From the application of this procedure to examples concerning registered calls on flood incidents due to failures of the anterior part of the sewer system, the following conclusions are drawn.

Increasing call rates as a function of the time since cleaning provide evidence that gully pot blockages are non-random and that preventive cyclic cleaning is effective to reduce the number of registered citizen calls. These results suggest that the continuous trapping of solids eventually impairs a gully pots hydraulic performance. This is also reflected in the estimated parameters for the Weibull distribution that show an increasing blockage propensity as the time since cleaning passes. The magnitude of the derived call rates compared to blockage rates from Chapter 5 suggests that either calls underestimate the true number of flooding events, or that blockage related flooding events are averted due to presence of adjacent gully pots.

Analysis of the non-parametric Kaplan-Meier estimate can aid sewer managers to optimise management strategies, as it allows for a quantitative assessment of the balance between proactive and reactive actions. For instance, results show that a cleaning interval between 12 and 16 months minimises the total maintenance costs for Utrecht. It should be noted, that generalisation of the obtained results may be limited due to the local characteristics of the urban environment. However, the Kaplan-Meier estimator can be applied to other cases without making any assumptions about the distribution of the underlying data.

The proposed two-level Bayesian hierarchical model is able to provide valuable information on the effectiveness of lateral connection rehabilitation to improve sewer serviceability. Analysing the Standardised Call Ratio (SCR) is considered to be appropriate, as it compares changes in local call rates relative to the mean call rates for the city. Application of this model revealed a significant improvement in the level of sewer serviceability in an area that was experiencing above mean call rates. This provides evidence that inspection and rehabilitation of lateral connections was effective. Given the disproportional contribution of lateral connections to the risk of flood incidents, the findings from this study justify the allocation of resources to the proactive rehabilitation of these components. In addition, analysing the SCR allows for the identification of areas with significant increased call rates, where preventive inspection and rehabilitation actions are likely most effective.

7 Conclusions and recommendations

Maintaining the delivery of services such as the collection and transport of wastewater and excess stormwater by sewer infrastructure is essential to prevent urban flooding and safeguarding hygienic standards. The operational condition of the anterior part of the sewer system, which is the part closest to the user, directly affects the performance of the system. Nevertheless, the performance of this part of the sewer system is seldom addressed in research. Appropriate sewer asset management considers the impact of components on system serviceability for the allocation of available resources. Currently the anterior part of the sewer system is primarily managed reactively. Moving away from these reactive strategies requires knowledge on the effectiveness of proactive strategies and information on blockage prone components to prioritise management decisions. The objective of this thesis is to provide a methodology that supports the development of management strategies for the anterior part of the sewer system.

7.1 General conclusions

In contrast to main sewers, literature on the mechanisms that affect the operational condition of lateral (house) connections is limited. This knowledge gap is hindering the understanding of lateral (house) connection blockage formations and the formulation of effective management strategies. Interrogation of literature on main sewers that are strongly related to these components indicated lateral (house) connections to be more susceptible to shared failure mechanisms. The identification of root causes of these mechanisms will improve the decision-making process involved in specifying the type of intervention. Incorrect user behaviour and standard of workmanship were repeatedly identified as a root cause of blockages. Next to being responsible for pipe collapses, the structural condition seems to determine the extent to which lateral connections are able to cope with incorrect use, before a blockage occurs. Modern pipe materials appear to be less susceptible to blockages, although it is not clear whether this can be attributed to the properties of the material or the effects of the time in service.

7.1.1 Lateral house connections

Analysis of blockage data shows that the number of lateral house connection blockages is several orders of magnitudes greater than blockage rates for main sewers and gully pots. In combination with the potential consequences and associated financial burdens, it is concluded that these pipes have a significant impact on the overall level of service provision. As such, lateral house connections represent a part of the sewer system in need of attention. FOG deposits were the dominant failure mechanism in the case studied, being responsible for more than one third of all registered blockage events. The different failure mechanisms of lateral house connections exhibited no increasing or decreasing trends in event rates. The absence of an increasing trend demonstrates that for this case there is no apparent progressive deterioration on a system scale within the observation period of two years. Statistical evidence to dismiss the hypothesis of a Homogeneous Poisson Process (HPP) for this data was weak, suggesting a repairable system with independent blockage events.

Not every area experiences the same probability of a lateral house connection blockage. Evidence of spatially varying blockage rates demonstrates the presence of differences in the factors that influence the complex blockage mechanisms. Modelling the spatial variability allows for the identification of factors that explain differences in observed blockage rates and can be used to estimate rates for other areas. Identification of blockage prone lateral house connections can enhance the prioritisation of maintenance and rehabilitation decisions. As such, it is a prerequisite for effective proactive strategies. Taking into account the model performance in decision-making is imperative, as it determines the amount of collateral investments on blockage-free lateral house connections. The performance of the proposed Generalised Additive Model (GAM) varied, depending on the availability of data on factors that explained observed blockages. However, adding a spatial smoother did improve model performance, as it mitigated the effect of unknown, but relevant factors that were missing in the model. The significance of factors such as age and settlement rate indicate that blockage rates exhibit an increasing trend on the long term. More time invariant factors, such as mean household income, suggest that blockages also occur randomly throughout the service life of a pipe.

7.1.2 Gully pots and lateral connections

Successive gully pot measurements revealed two distinct silting regimes in gully pot sand traps. A majority of all gully pots reached equilibrium sediment bed levels after several months, while the remainder (5%) experienced progressive accumulation of sediments that eventually resulted in a blockage. Hydraulic restriction due to the continuous accumulation of sediments first occurred after 100 days. The vulnerability of the public space to a gully pot blockage may be limited, as the lack of residual spatial correlation provides no evidence that alternative drainage paths through adjacent gully pots will be unavailable. Under the assumption of a stable sediment concentration in the inflow, the equilibrium bed levels found in the majority of all gully pots suggest that particles and attached pollutants are no longer retained and are transported to the downstream drainage system. A Generalised Linear Mixed Model (GLMM) revealed that, besides physical properties such as the sand trap depth and the position of the lateral connection, contributing area and road type are factors that distinguish gully pots with stable sediment bed levels from blocked gully pots. Knowledge on these properties may justify investments in the design phase to reduce maintenance efforts after construction. For instance, deeper sand traps benefit both the retention of pollutants and the hydraulic performance. The impact of gully pots on water quality aspects and the performance of treatment facilities and downstream system components depends on the interval between preventive cleaning cycles. This interval is much shorter than necessary to prevent blockages.

In the absence of gully pot measurements, call data on flood problems in public areas reported by citizens are a valuable data source. Excessive sediment deposits in gully pots was the dominant mechanism resulting in reported events (45% of all calls) for a case study, demonstrating the need for a proper motivation of the cleaning frequency. An increasing call probability in the period after gully pot cleaning provides evidence that preventive cleaning activities are effective in reducing the number of flooding events. Analysis of these data allows for a quantitative assessment of the balance between proactive and reactive interventions, which can be used to improve current maintenance strategies.

Bayesian hierarchical modelling revealed significant spatial variation in the blockage propensity of lateral connections for a case city. Analysis of local changes in spatial call data following rehabilitation provides valuable information on the merits of proactive work on lateral connections. The Taagdreef neighbourhood area was experiencing above city mean call rates before rehabilitation and received significantly less calls after the intervention. The inability to detect an effect for the Queeckhovenplein neighbourhood area demonstrates the need for sufficient data. In addition, the absence of above city mean call rates before rehabilitation may suggest that the overall potential to improve the serviceability of lateral connections in that area was limited. The overall contribution of structurally related defects to lateral connection calls in the city (55%) implies that proactive rehabilitation is more effective than cleaning. The hierarchical modelling approach adopted can be used to identify areas with increased call rates, where these interventions are likely most effective.

7.2 Recommendations for research and applications

Municipal and commercial sewer databases are the main data source used in this chapter. Despite the growing consensus that data collection during reactive work can serve more than justifying repairs, these data still limit the extent to which the processes that affect the performance of the anterior part of the sewer system are understood. Current data collection facilitates daily operations, but is insufficient to provide data on all failure mechanisms and root causes. The basis for proper data collection should ensure that observations cannot fit multiple categories (mutual exclusivity), but always corresponds to one category (exhaustive). However, given the non-informative methods commonly used to resolve blockages, the level of detail required by researchers and decision makers may not be realistic in practice. Therefore, data collection on blockage mechanisms is a trade-off between data uncertainty and data requirements. Moreover, lateral (house) connections are generally not regarded as objects with attributes in databases. As a consequence, specific data on the properties of these objects (e.g. age, material etc.) is unknown. An additional gain of specifying lateral (house) connections as objects in databases, is that data on proactive and reactive work are automatically joined.

There is no standard for the uniform collection of data on blockage events that allows for a valid comparison between the findings in this chapter and findings from regions with different characteristics (e.g. topography, urban fabric, local policy). Application of the methods presented in these thesis to data from other regions will demonstrate to which extent results from this can be generalised.

Call databases represent events that have been reported by citizens or municipal workers. Therefore, it is likely that these databases systematically underestimate the true number of events. The willingness to report can be influenced by factors such as ignorance, acceptance and the level of accessibility of call centres. An incomplete coverage of gully pot blockages has already been indicated in Chapter 6. Yet, no formal analysis of the impact of this uncertainty on the results has been conducted. In addition, there are multiple commercial sewer companies that resolve blockages in lateral house connections. This means that the coverage of these databases depends on their market share. This thesis compensated for this data uncertainty by selecting data from housing associations with a service contract. Despite the sheer number of houses in this subset, selection of these data may have introduced an unknown bias. Therefore, further research with data stemming from other sources is recommended.

This chapter evaluates the consequences of lateral house connection blockages as the inability to sufficiently discharge wastewater and excess storm water. More research is needed to explore and quantify the full extent of the consequences of a lateral house connection blockage. This can vary from the inability to use household appliances to tangible damage and health risks due to in-house flooding.

More research should be dedicated to the individual mechanisms that result in a blockage. Failure mechanisms may differ both in temporal evolution and spatial variation. For instance, the prevalence of an illegal spill is likely independent of time, while the probability of a collapse is expected to increase over time. Knowledge on these processes may improve component design and support the development of maintenance strategies that are tailored to address these failure mechanisms.

The review of relevant transport processes in Chapter 2 describes the physical mechanisms that influence the trapping efficiency of gully pots. Current understanding of these mechanisms does not yet fully explain the prevalence of one of the two distinct silting regimes in a gully pot. As this determines the extent to which gully pots are effective solids trapping devices and blockage sensitive, it is a relevant topic for further research.

7.2.1 Remarks for future application

Currently, lateral house connections are omitted in sewer system assessments. The significant impact on the level of service provided by sewer systems provides ground for the transfer of lateral house connection ownership to local water authorities. This transfer would facilitate appropriate sewer asset management, as work can be prioritised to components depending on their impact on sewer serviceability. In addition, individual households are provided with some relief from the instantaneous financial burden associated with the rehabilitation of deteriorated components. Combining the rehabilitation of lateral house connections with other sewer works provides opportunities to reduce costs. A modelling approach such as suggested in Chapter 4 can support rehabilitation and maintenance strategies by identifying areas that will likely benefit the most from proactive activities.

By quantifying the effectiveness of gully pot cleaning with respect to the number of reported events, the procedure suggested in this thesis provides an appropriate basis for the optimisation of gully pot cleaning frequencies. Physical properties and catchment characteristics that influence the blockage probability can be taken into account when determining the cleaning frequency for a given area. In addition, knowledge on the relation with physical properties can be used to improve gully pot design.

The procedure proposed in Chapter 6 can identify areas that are prone to an increased probability of a lateral connection defect. This procedure is also capable of monitoring serviceability improvements following the allocation of resources. Monitoring improvements is relevant to evaluate the effectiveness of work and to justify investments.

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Summary

The anterior part of the sewer system consists of a system of gully pots and lateral (house) connections that drain to main sewers. The total length of lateral house connections can be similar to the total length of the sewers they drain to. In addition, there are 7 million gully pots with corresponding lateral connections in the Netherlands alone. Considering the potential consequences of a lateral house connection blockage, proper functioning of these system components is essential. Analysis of literature on main sewer infrastructure strongly related to lateral (house) connections indicate these components to be more susceptible to shared failure mechanisms. Both incorrect use by citizens and the structural condition seem to influence the blockage propensity. Furthermore, recent research has revealed gully pot blockages to make larger contributions to flooding in public spaces than intense storm events and main sewer blockages. Gully pots are equipped with a sand trap to prevent solids from being transported to the downstream water infrastructure. The continuous trapping of solids may eventually impair the hydraulic performance. Lack of knowledge on the condition of the anterior part of a sewer system has led to the prevalence of reactive strategies, where activities are undertaken after the consequences of an operational failure becomes apparent. Next to being more costly, these strategies expose citizens to the consequences of a failure such as tangible damages and health risks. Alternatively, proactive strategies are characterised by activities that are undertaken before a failure occurs. Preserving the functionality of lateral (house) connections and gully pots, given the available resources, calls for knowledge on the effectiveness of proactive strategies and information on blockage prone components to balance proactive and reactive activities. To this end, the general objective of this thesis is to provide a methodology that supports the optimisation of management strategies for the anterior part of the sewer system.

Part I: Lateral house connections

Data on the different failure mechanisms that result in a lateral house connection blockage are obtained from a commercial sewer maintenance database. These data exhibit no signs of system aging within a two year period, as increasing or decreasing trends in event rates are not significant. Therefore, the times between successive events can be described by a common distribution. Statistical evidence to reject the hypothesis of a Homogenous Poisson Process (HPP) is weak, suggesting a repairable system, where the times between successive events are independent and exponentially distributed. In comparison with event rates for other sewer system components such as main sewers and gully pots, lateral house connection blockage rates are several orders of magnitude greater. Fat, oil and grease (FOG) deposits are the dominant failure mechanism recorded by maintenance workers, being responsible for more than one third of all blockages. Due to the sheer number of blockages and the financial burden associated with repair, the impact on sewer serviceability is considerable.

Modelling these blockage events to identify areas where proactive work is most promising is non-trivial, as data on lateral house connection properties (e.g. age, material etc.) are generally missing. These data are necessary to explain local differences (i.e. spatial variations) in observed blockage incidences. Given the complex processes that influence blockage formations, a statistical analysis is opted. The first step of the statistical procedure evaluates whether there is any significant spatial variation present in the blockage data. A Monte Carlo simulation based on randomly relabelling blockage data in two-dimensional x and y space provides information on the likelihood of observing certain spatial blockage patterns. The presence of significant spatial differences in blockage incidences for both the Rotterdam and The Hague case justifies the identification of factors that explain this variation. The second step of the procedure involves a Generalised Additive Model (GAM) which can account for factors that can explain differences in the probability of a blockage. A spatial smoother that captures the spatial structure in terms of x and y coordinates is added. Therefore, this model is able to mitigate the effect of unknown, but relevant, factors that are missing in the model. Next to main sewer properties such as age and system type, ground settlement and interactions with other underground infrastructure are factors that influence the probability of a lateral house connection blockage. Receiver Operating Characteristic (ROC) curves provide key information for decision-making, by taking into account model performance in assessing the trade-off between costs and benefits. This may contribute to defining a balance between proactive and reactive strategies where the level of service provision is optimised, given the available resources.

Part II: Gully pots and lateral connections

Sediment bed level data from 300 gully pots measured monthly for a duration of 15 months show two distinct silting regimes. A majority of all gully pots reach equilibrium sediment bed levels after several months, while the remainder (5%) experience progressive accumulation of sediments that eventually result in a blockage. Stable sediment bed levels imply that solids and attached pollutants suspended in runoff are no longer retained. This suggests that gully pots from this group do not contribute to improving the water quality. The second regime indicates an increased flood risk as the hydraulic performance may be compromised. A Generalised Linear Mixed Model (GLMM) is able to identify which gully pot properties and catchment characteristics distinguish gully pots that experience progressive silting from gully pots with stabilising sediment bed levels. Depth of the sand trap and the position of the lateral connection are relevant physical properties. The road type and the area contributing to runoff are catchment properties that distinguish silting regimes. Knowledge on these parameters can aid to improve gully pot design and the identification of groups which benefit from similar preventive cleaning intervals. Besides the properties that promote gully pot blockages, the absence of gully pot clusters with a higher blockage probability provides no evidence that alternative drainage paths through adjacent gully pots are unavailable in case of a blockage. As this limits the exposure to flooding events, the vulnerability of the public space to gully pot blockages reduces.

Quantitative analysis of call data on flooding events from two municipalities in the Netherlands provides information on the effectiveness of proactive gully pot cleaning to reduce reactive maintenance. A monotonically increasing hazard function indicates that the probability of a gully pot blockage increases as a function of the time since cleaning. Provided that the data collected during gully pot cleaning is of sufficient quality, The Kaplan-Meier estimate is able to make valid inferences beyond the cleaning interval.

To investigate the impact of lateral connection inspection and rehabilitation, a database of call data has been built for two areas in two periods. Reference period A, prior to the proactive lateral connection activities and period B, the period following the proactive activities. A two-level Bayesian hierarchical model is used to quantify serviceability improvements, by investigating whether the intervention has a significant impact on the number of calls in the case areas, relative to the entire city. One area has insufficient data to detect an effect, while the other case area shows a significant reduction in the number of calls following proactive activities. Alternatively, the Bayesian hierarchical model can be used to identify areas with increased call rates, where inspection and rehabilitation activities are likely most effective. The presented methods quantify the effectiveness of proactive work, which is a prerequisite for the appropriate management of gully pots and lateral connections.

Samenvatting

Het geheel aan kolken, kolkleidingen en huisaansluitingen vormen samen het voorliggende deel van een rioolstelsel. Alleen in Nederland zijn er naar schatting al 7 miljoen kolken met bijbehorende kolkleidingen. Daarnaast is de totale lengte aan huisaansluitingen vergelijkbaar met de lengte van het rioolstelsel waar naar afgevoerd wordt. Gezien de mogelijke gevolgen van een verstopte huisaansluiting, is een goede werking van deze stelselonderdelen essentieel. Literatuur over riolen sterk gerelateerd aan kolkleidingen en huisaansluitingen geven al een indicatie dat deze onderdelen waarschijnlijk gevoeliger zijn voor gedeelde faalmechanismen. Onjuist gebruik en de structurele toestand van de leiding worden genoemd als mechanismen die de kans op een verstopping beïnvloeden. Recent onderzoek heeft aangetoond dat kolkverstoppingen een grotere bijdrage leveren aan de frequentie van wateroverlast dan rioolverstoppingen en hevige neerslag. Kolken zijn normaliter uitgerust met een zandvang, welke ontworpen is om het transport van slibdeeltjes naar de benedenstroomse waterinfrastructuur te reduceren. Het continue afvangen van deeltjes kan op den duur echter een negatief effect hebben op het hydraulisch functioneren van een kolk.

Door een gebrek aan kennis over de operationele staat van het voorliggende deel van een rioolstelsel worden deze onderdelen vooral reactief beheerd. Reactief beheer omvat alle werkzaamheden die ondernomen worden nadat een operationele storing bekend is. Naast dat deze vorm van beheer duurder is, worden burgers ook nog eens blootgesteld aan de mogelijke gevolgen van defecten zoals schade en gezondheidsrisicos. Proactief beheer wordt gekenmerkt door werkzaamheden die ondernomen worden voordat een defect zich voordoet. Om het huidige niveau van dienstverlening in stand te houden met de beschikbare financiële middelen, is kennis over de effectiviteit van proactief beheer en informatie over verstopping gevoelige componenten noodzakelijk om een juiste balans tussen proactief en reactief beheer te vinden. Het doel van dit proefschrift is om een methodiek te presenteren die het optimaliseren van beheer strategieën voor het voorliggende deel van de riolering ondersteund.

Deel I: Huisaansluitingen

Gegevens over de verschillende faalmechanismen die resulteren in een verstopte huisaansluiting zijn afkomstig uit de database van een commercieel ontstoppingsbedrijf. Binnen het tijdsbestek van 2 jaar zijn er geen tekenen van systematische veroudering, aangezien er geen significante toe- of afname is in het aantal gemelde verstoppingen per tijdseenheid. Dit betekent dat de intervallen tussen opeenvolgende verstoppingen beschreven kunnen worden met een gezamenlijke verdeling. Het statistisch bewijs om de hypothese van een Homogeen Poisson Proces (HPP) te verwerpen is zwak. Dit wijst op een systeem dat herstelbaar is na een verstopping, aangezien opeenvolgende verstoppingen onafhankelijk zijn en exponentieel verdeeld. In vergelijking met andere systeemonderdelen zoals riolen en kolken, is het aantal verstoppingen in huisaansluitingen een aantal ordes van grootte hoger. Vet- en olieafzettingen zijn de dominante faalmechanismen, welke verantwoordelijk zijn voor meer dan een derde van alle geregistreerde verstoppingen. Op basis van het aantal verstoppingen en de financiële lasten als gevolg van reparaties, kan gesteld worden dat de invloed op het niveau van dienstverlening aanzienlijk is.

Het modelleren van verstopte huisaansluitingen om zo gebieden te identificeren waar proactieve werkzaamheden het meest belovend zijn is niet triviaal, aangezien gegevens over de eigenschappen van huisaansluitingen (leeftijd, materiaal, etc.) doorgaans ontbreken. Deze gegevens zijn nodig om lokale verschillen (oftewel ruimtelijke variatie) in het aantal geregistreerde verstoppingen te verklaren. Gezien de complexiteit van de processen die leiden tot een verstopping, is er gekozen voor een statistische aanpak. De eerste stap van de statistische procedure beoordeelt of er sprake is van significante variatie in de ruimtelijke spreiding van verstoppingen. Een Monte Carlo simulatie, gebaseerd op het willekeurig toewijzen van verstoppingen in tweedimensionale x en y ruimte, geeft inzicht in de kans op het waarnemen van bepaalde ruimtelijke verstoppingstructuren. Significante verschillen in de spreiding van verstoppingen voor zowel de Rotterdam als Den Haag case-studie, rechtvaardigen de identificatie van factoren die deze spreiding kunnen verklaren. De tweede stap van de procedure betreft een Generalised Additive Model (GAM) waarin factoren die ruimtelijke verschillen in de kans op een verstopping verklaren, meegenomen worden. In dit model is een term toegevoegd die de ruimtelijke structuur van verstoppingen in x en y coördinaten vertegenwoordigt. Daardoor kan het effect van onbekende, maar relevante, factoren die ontbreken in het model gecompenseerd worden. Naast eigenschappen van het riool zoals aanlegjaar en stelseltype, zijn bodemdaling en interactie met andere ondergrondse infrastructuur factoren die de kans op een verstopte huisaansluiting beïnvloeden. Receiver Operating Characteristic (ROC) curves bieden waardevolle informatie voor besluitvorming binnen rioleringsbeheer door modelprestaties mee te nemen in de afweging tussen kosten en baten. Dit kan een bijdrage leveren aan het definiëren van een balans tussen proactief en reactief beheer waar het niveau van dienstverlening geoptimaliseerd is met de middelen die beschikbaar zijn.

Deel II: Kolken en kolkleidingen

Maandelijkse metingen van de slibniveaus van 300 kolken voor een periode van 15 maanden tonen twee verschillende regimes voor de opbouw van slib. Een meerderheid van alle slibniveaus bereikt een evenwichtsdiepte na enkele maanden, terwijl slibmetingen in de overige zandvangen (5%) een gestage groei laten zien. Het laatstgenoemde regime kan uiteindelijk leiden tot een verstopping. Een evenwichtssituatie suggereert dat deeltjes en daaraan gehechte verontreinigingen niet meer bezinken in de zandvang en dat de kolk geen bijdrage meer levert aan het verbeteren van de waterkwaliteit. Een Generalised Linear Mixed Model (GLMM) is in staat om kolk en afstroomgebied eigenschappen te identificeren die van invloed zijn op het slibregime van een kolk. Diepte van de zandvang en de oriëntatie van de kolkleiding zijn relevante kolkeigenschappen. Het wegtype en het afstromend oppervlak zijn eigenschappen van het afstroomgebied die van invloed zijn op het slibregime. Inzicht in het effect van deze eigenschappen kan bijdragen aan het verbeteren van het ontwerp van een kolk. Bovendien kunnen deze resultaten gebruikt worden om een gemeenschappelijk reinigingsinterval te bepalen voor kolken met dezelfde eigenschappen. Doordat clusters van kolken met een grotere verstoppingskans afwezig zijn, is het aannemelijk dat alternatieve stromingspaden naar naastgelegen kolken nog beschikbaar zijn in het geval van een verstopping. Dit beperkt de kwetsbaarheid van de openbare ruimte, aangezien de omvang van wateroverlast gering blijft.

Een kwantitatieve analyse van wateroverlast meldingen voor twee gemeenten in Nederland geven inzicht in de effectiviteit van preventief kolken reinigen om reactieve werkzaamheden te reduceren. Er is sprake van een constant toenemende verstoppingskans naarmate de tijd sinds reiniging verstrijkt. Mits de gegevens die verzameld zijn tijdens kolkreiniging van voldoende kwaliteit zijn, is aan de hand van de Kaplan-Meier schatter informatie te verkrijgen over de verstoppingskans die verder gaat dan het gehandhaafde reinigingsinterval.

Om de effecten van kolkleiding inspectie en vervanging te onderzoeken, is een database met meldingen voor twee gebieden opgezet. Elke gebied kent twee perioden: referentieperiode A, welke alle meldingen bevat voor er proactieve werkzaamheden uitgevoerd zijn en periode B, die alle meldingen bevat na deze werkzaamheden. Een twee-laags Bayesiaans hiërarchisch model is gebruikt om verbeteringen in het niveau van dienstverlening te kwantificeren. Dit model schat in welke mate de interventie een significante impact heeft op het relatieve aantal meldingen in de casegebieden, ten opzichte van de stad als referentie. Één van de gebieden had onvoldoende data om een effect te detecteren. Het tweede gebied heeft een significante afname in het aantal meldingen na de werkzaamheden. Bovendien is het mogelijk om een Bayesiaans hiërarchisch model te gebruiken om gebieden te identificeren met een verhoogde kans op een melding, waar proactieve inspectie en vervangings werkzaamheden het meest belovend zijn. De voorgestelde methoden kwantificeren de effectiviteit van proactieve werkzaamheden, wat een voorwaarde is voor het doelmatig beheer van kolken en kolkleidingen.

List of publications

Peer-reviewed journals

Post, J.A.B., Langeveld, J.G., and Clemens, F.H.L.R. (2016). Quantifying the effect of proactive management strategies on the serviceability of gully pots and lateral sewer connections. *Structure and Infrastructure Engineering*, in press.

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About the author

Johan Post was born in Amsterdam, the Netherlands on July 12th 1987. He followed his lower general secondary education at Vechtstede College in Weesp, where he received his VMBO-T diploma in 2003. Following a short stay at the school for intermediate vocational training, he received his Havo diploma for completing the school for higher general secondary education in 2005. Subsequently, he started his study Civil Engineering at the University of Applied Sciences Amsterdam. His interest for wastewater developed during his first internship at Witteveen+Bos consultants. During his second internship at Waternet this focus shifted toward the collection and transport of wastewater. He stayed involved with Waternet after completing this internship as part of the team responsible for modelling the hydraulic performance of sewer systems. In 2009 he finished his bachelor thesis on the role of the urban environment in dealing with heavy rainfall. Next, Johan started his master at Delft University of Technology. He graduated cum laude in 2012 on the design of a monitoring network for the application of data assimilation. This master thesis was awarded with the Gijs Oskam award for best young researcher in the field of urban water. In November 2012, he started as a PhD Candidate at Delft University Technology in the Sanitary Engineering section. This research focussed on the anterior part of the sewer system. Next to this research, he was involved in tutoring several master students, further development of the Fundamentals of Urban Drainage course and assisting the organisation of the 8^{th} International Conference on Sewer Processes & Networks. His work from the last four years resulted in this thesis.