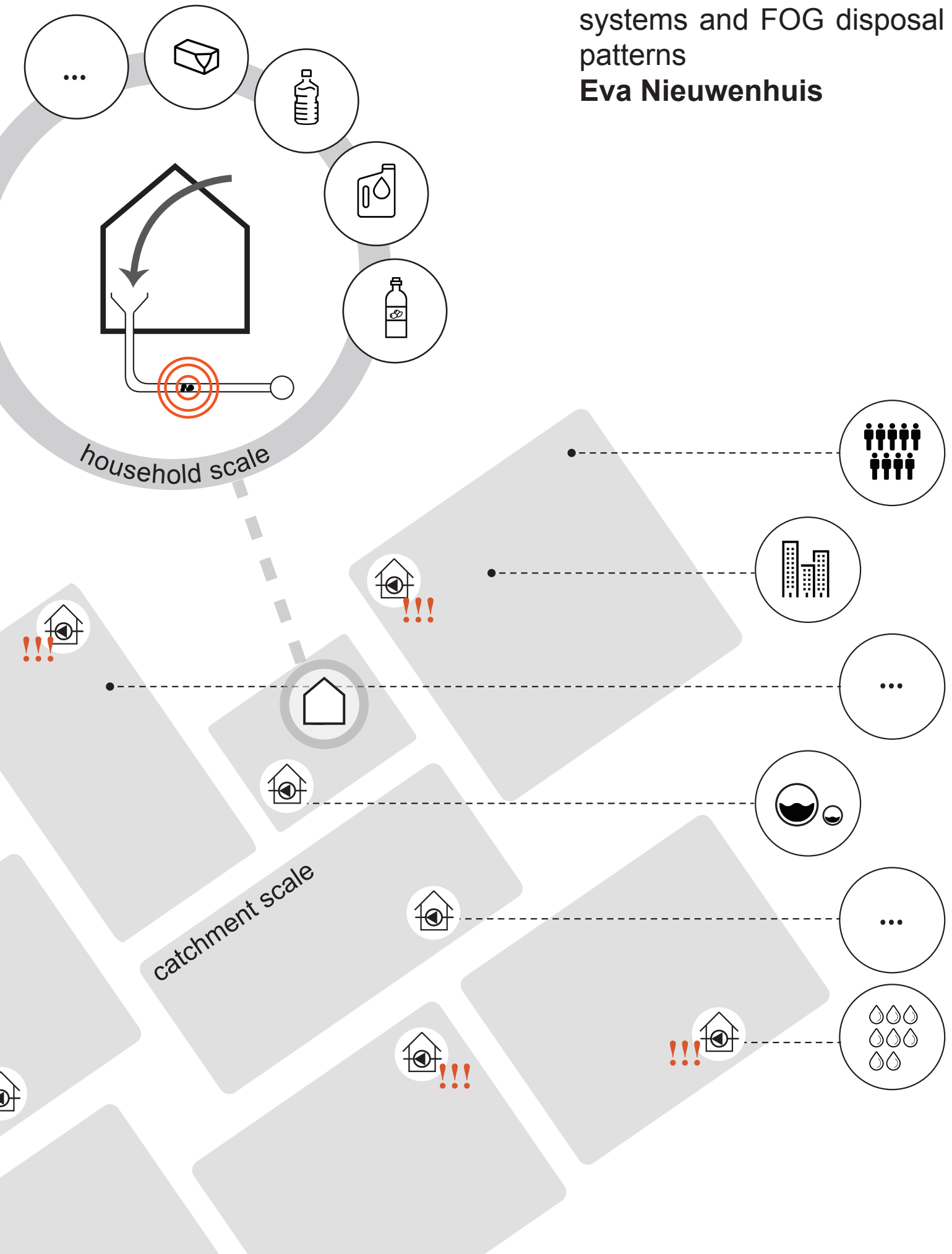


MASTER THESIS | A study on the relationship between fat, oil and grease (FOG) deposits in sewer systems and FOG disposal patterns

Eva Nieuwenhuis



A Study on the Relationship Between Fat, Oil and Grease (FOG) Deposits in Sewer Systems and FOG Disposal Patterns

MSc thesis
of
Eva M. Nieuwenhuis

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Section of Water Management

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Delft

Graduation committee:
prof. dr. ir. F.H.L.R. Clemens
dr. ir. J.G. Langeveld
ir. S.P.A. Duinmeijer
ir. W.M.J. Luxemburg



Summary

Fat, oil and grease (FOG) deposits are one of the leading causes of sewer system blockages, thereby increasing the risks of undesired and polluting flooding and sewer overflows. FOG accumulates throughout the entire sewer network; e.g., in public sewer pipes and lateral house connections it reduces the available discharge capacity, and in pump sumps it increases the risk of pump failures. Previous studies primarily focused on FOG deposits occurring in parts of sewer systems downstream of Food Service Establishments (FSE). It is thought, however, that domestic FOG disposal is also an important contributor to FOG deposits, and therefore warrants further investigation.

Consequently, the objective of this research was to investigate the relationship between domestic FOG disposal patterns and the occurrence of FOG deposits in sewer systems. By considering both the household scale and the scale of catchments, it was possible to study the influence of individual and population disposal patterns. The influence of general system characteristics, such as pump sump dimensions and sewer system type, were also taken into account.

The first part of this study focused on the influence of individual disposal patterns; samples of FOG deposits were collected from clogged building drainage systems (kitchen drains and lateral house connections), and questionnaires were conducted to reveal information about the household's cooking and disposal habits. Only three out of the eleven households showed a link between the cooking fats and oils used and the FOG deposits collected, as their fatty acid profiles displayed similarities. The FOG deposits collected from the lateral house connections mainly contained saturated fats, while cooking oils and fats predominantly consist of unsaturated fat. It is therefore thought that in-sewer transformations from unsaturated to saturated acid had already taken place in building drainage systems.

The outcomes of the physical and chemical tests, together with the Fourier transform infrared FTIR spectroscopy analysis performed for this study, demonstrated that the FOG deposits collected from building drainage systems were, similar to FOG deposits from main sewers, metallic salts of fatty acids. Despite this similarity, the deposits collected from different locations within the sewer network displayed a great variation, suggesting that they resulted from different formation mechanisms.

The deposits from kitchen drains tended to be grainy, and had a low fat content (9 - 15%) and high calcium levels (2.74 - 14.9%), suggesting the accumulation of debris. The FOG deposits collected from lateral house connections were softer and had a more waxy consistency. Their fat content was higher (one third, up to their full weight), predominantly consisting of palmitic acid (C16:0). In comparison with previously analyzed FOG deposits from main sewers, the lateral house connection deposits also had high levels of calcium (0.15 - 3.70%). As building drainage systems are not made of concrete, these results show that concrete is not essential for the FOG deposit formation process in sewer systems; background levels of calcium in drinking water and calcium present in food are thought to account for the calcium in the FOG deposits. In addition, the samples obtained from FOG deposits in lateral house connections contained glycerol, suggesting that

saponification was ongoing. It is thought that oil hydrolysis had taken place close to or within the FOG deposit matrix.

For future research it is recommended to increase the sample size and conduct a questionnaire with both people with and without frequent FOG blockages. This could provide more profound insights into the relationship between individual FOG disposal patterns and FOG deposits.

The second part of this study focused on the influence of population disposal patterns on the occurrence of FOG deposits, by studying the severe accumulation of FOG at pumping stations in relation to catchment demographics and sewer system characteristics. Generalized linear mixed model (GLMM) procedures were used to model the probability of the presence or absence of FOG in pump sumps for a dataset consisting of 126 observations from five different cities. The random component of the GLMM resolved the violation of independence that resulted from the correlation between pumping stations in the same city.

The model revealed that severe accumulation of FOG in pump sumps was negatively correlated to the average income of inhabitants attached to the catchment. This suggests that individuals within an income-group shared FOG disposal patterns. Such patterns might be culture-bound, as the dropped variable 'percentage of non-western immigrants' was highly correlated with income.

Furthermore, FSE density and kinetic energy of wastewater per unit of volume per day were found to be important factors correlated with the occurrence of FOG deposits. The importance of the first variable follows logically from the extensive use of cooking oils and fats by FSEs. The latter variable was negatively correlated with the probability of FOG accumulation; a higher kinetic energy pump sump may keep the FOG particles in suspension, thereby preventing the accumulation of FOG. Since the dropped variable 'daily operation time' was highly correlated with the variable 'total kinetic energy', the average pump operation time per day could also be a factor influencing FOG accumulation.

While higher values for kinetic energy may prevent the accumulation of FOG, they could also increase the risk of air entrainment; thus, the most appropriate balance between the prevention of FOG accumulation and the prevention of air entrainment has to be found. In addition, as FOG is known to accumulate at various locations within the sewer network, further investigation is warranted to identify the location within the sewer network where the associated costs for the removal of FOG are lowest.

It must be noted that the assumptions of independence and homogeneity, which are inherent to GLMMs, were not fully met by the data, possibly as a consequence of the sampling method used. Despite this violation, the reported results provide important insights into factors influencing the accumulation of FOG. For future research it is recommended to systematically record the accumulation of FOG and use a more balanced dataset. This could also increase the predictive performance of the model, thereby providing information for preventing the accumulation of FOG or making municipal maintenance strategies more effective.

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After a little over seven years, I have come to the moment of graduation, and at this moment I want to thank all people that have helped, guided and supported me to come to this point. The past years have flown by, and although I did not take the easiest route to become a civil engineer, I have enjoyed (almost) every moment of it. This master thesis is the final piece of the puzzle of my student life, and has been carried out in the department of Water Management at the Section Sanitary Engineering. It was performed within the Dutch 'Kennisprogramma Urban Drainage'.

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List of Abbreviations

Abbreviation	Meaning
AIC	Akaike information criterion
C14:0	Myristic acid
C16:0	Palmitic acid
C18:0	Stearic acid
C18:1	Oleic acid
C18:2	Linoleic acid
DLVO	Derjaguin, Landau, Verwey, and Overbeek
DW	Dry weight
DWF	Dry weather flow
FFA	Free fatty acid
FOG	Fat, oil and grease
FWD	Food waste disposer
FSE	Food service establishment
FTIR	Fourier transform infrared
GI	Grease interceptor
GLM	Generalized linear model
GLMM	Generalized linear mixed model
IO	Inspection opening
LCFA	Long chain fatty acid
RRS	Riool Reinigings Service
SES	Socioeconomic status
TG	Triglyceride
US	United States
VFD	Variable frequency drive
VIF	Variance inflation factor

1 Introduction

Sewer systems are vital for public health and city life. They provide underground sewage collection and transport from houses, commercial buildings and industrial plants to wastewater treatment facilities. Due to the accumulation of solid material in wastewater, sewer pipes get clogged. This decreases the available discharge capacity, thereby increasing the risks of flooding and the occurrence of sewer overflows that discharge (diluted) wastewater into open water bodies. Flooding and overflows potentially release high loadings of pathogens, nutrients and solids, which bring along undesirable health risks and potential environmental damage (EPA, 2004).

Sewer blockages are found to be the dominant failure mechanism in sewer systems (Arthur et al., 2009). In the United States, such blockages cause 48% of all sanitary sewer overflows, of which fat, oil and grease (FOG) deposits are reported to be the leading cause: almost half of all sewer blockages in the US are related to FOG deposits (EPA, 2004). A recent statistical analysis of failure mechanisms in lateral house connections in the Netherlands showed that more than one third of all failure events were related to FOG deposits (Post et al., 2016b).



Figure 1 - Severe accumulation of FOG in London's sewer system (Glanfield, 2014)

FOG deposits are accumulated suspended solids in sewer systems and have an adhesive character. Figure 1 shows FOG deposits that are firmly attached to interior sewer pipe walls. They can significantly reduce and sometimes even completely block the wastewater flow (He et al., 2015). FOG deposits have a grainy, sandstone-like texture with high yield strengths (Keener et al., 2008), that require intensive cleaning activities such as hydraulic jetting (Dirksen et al., 2012; Mattsson et al., 2014b). Waternet, the water company of Amsterdam and its surrounding area, estimated that it removed 520,000 kg of FOG from pumping stations and sewer pipes in their service area of around 23,000 ha in 2007.

Annually, it spends an estimated one million euros on the removal of FOG (Waternet, 2009).

The formation of FOG deposits in public sewer pipes is often described as the solidification of cooking oils when they are poured down the drain and then cool down in sewer pipes. The formation mechanisms, however, have appeared to be much more complex. Recent studies have shown that most FOG deposits in sewer pipes result from a saponification process, driven by, *inter alia*, fast alkali-driven hydrolysis due to cleaning processes, that lead to the formation of calcium-based fatty acid salts (He et al., 2011, 2013; Keener et al., 2008; Williams et al., 2012).

1.1 Problem statement

Previous studies mainly focused on the chemical aspects of FOG deposit formation. Although these studies have revealed general information on locations in public sewer systems that are prone to FOG accumulation, they have hardly taken into account the particular sewer contexts of FOG accumulations. A study focusing on the relationship between sewer structural configuration and FOG build-up, suggested that low flow velocities enhance FOG accumulation (Dominic et al., 2013). Since the results, however, were based on pilot experiments, they provided only limited information on FOG accumulation in full-scale sewer systems. The study did not explain the differences in severity of FOG deposits in different catchment areas, nor did it provide information on the contextual factors influencing the accumulation of FOG.

In addition, previous studies hardly elaborated on the probable impact of domestic disposal patterns on FOG deposits, and focused mainly on food service establishments (FSEs) (Dominic et al., 2013; He et al., 2011; Williams et al., 2012), and the fishing and meat industries (Cammarota and Freire, 2006; Mattsson et al., 2014b) as the main contributors to FOG problems. Consequently, FOG deposits have primarily been collected from public sewers, often close to food processing industries. As far as known to the author, no deposits have yet been collected from building drainage systems.

A recent case study in The Netherlands showed, however, that lateral house connections are more susceptible to blockages than main sewers, and that FOG is the dominant failure mechanism in lateral house connections (Post et al., 2016b). In addition, analysis of two FOG deposit samples from an apartment area suggested that private users also contribute to the severity of FOG deposit problems (He et al., 2011). Furthermore, a survey done among 127 Norwegian and Swedish sewer operators reported that respectively 48 and 22% of the operators experienced FOG-related problems in residential areas (Mattsson et al., 2014b). They explicitly mentioned the severity of FOG accumulation in areas with high-rise apartment buildings and a relatively high number of immigrants. Despite these findings related to domestic disposal patterns, no research has yet been carried out on FOG deposits in building drainage systems; whether the deposits are comparable to FOG deposits in main sewers and to what extent domestic wastewater disposal affects the FOG deposits.

Since FOG deposits can lead to flooding and sewer overflows, which bring along undesirable health, environmental and financial costs, there is a clear need for an improved understanding of the conditions that make areas more prone to the accumulation of FOG. In addition, it is expected that the consequences of blockages will become more severe in the near future because of projected increases in precipitation and city growth (Semadeni-Davies et al., 2008). Identifying either user-based or system-based factors that are related to FOG accumulation will enable authorities to prevent severe FOG accumulation and to investigate how FOG maintenance strategies can be improved.

1.2 Research aim

The purpose of this study is to investigate how user-based and system-based factors influence the severity of FOG accumulation in sewer systems. To study the relationship between domestic disposal patterns and the occurrence of FOG deposits, this thesis uses the scale of both households and catchments, areas that are confined and controlled by pumping stations at downstream locations in these areas. The accumulation of FOG are studied both at the entrance points of catchments (kitchen drains and lateral house connections) and in the most downstream points of catchments (pumping stations).

By considering FOG deposits on a household scale, the influence of individual FOG disposal patterns can be investigated, while by considering FOG deposits on the scale of catchment areas, the influence of population disposal patterns can be studied. As pumping stations collect wastewater from the entire catchment, the influence of disposal patterns that are shared by a catchment's population can be investigated based on catchment demographics. The influence of general system characteristics, such as pump sump dimensions and sewer system type, are also taken into account.

The use of both units of analysis (households and catchments) might enable the identification of relationships between individual FOG disposal patterns and demographic data.

1.3 Scope of this study

As the objective of this thesis is to identify the relationship between the FOG disposal patterns of individual users and FOG deposits in sewer systems, the scope of this study is limited to domestic disposal patterns. The study therefore focuses solely on building drainage systems and pumping stations located in residential catchments.

1.4 Research questions

Based on the purpose of this study, the following research question is derived:

“What is the relationship between fat, oil and grease (FOG) deposits in sewer systems and FOG disposal patterns?”

To answer this question, five sub questions are formulated:

1. What is the relationship between the occurrence of FOG deposits in building drainage systems (kitchen drains and lateral house connections) and FOG disposal patterns?
2. What are the chemical and physical characteristics of FOG deposits in building drainage systems?
3. What are the differences between FOG deposits collected from building drainage systems and FOG deposits collected from main sewers?
4. How does the accumulation of FOG in pumping stations relate to demographics and general sewer system characteristics of corresponding catchments?
5. What are important factors representing FOG disposal patterns and general sewer system characteristics that influence the accumulation of FOG in pumping stations?

1.5 Hypothesis

Based on the research questions, the following hypothesis is formulated. If a situation comparable to the situation in previous studies were to occur in Dutch sewer systems, it can be expected that individual disposal patterns would contribute to FOG problems in sewer systems downstream. Extensive disposal of cooking oils, disposal of cooking oils with particular fatty acid profiles and the disposal outside daily peak flows are expected to enhance the FOG deposit formation in building drainage systems and further downstream in sewer systems. Since some aspects of lifestyle are strongly represented by certain demographic groups, it is hypothesized that FOG problems are related to demographics and will thus vary considerably in severity among catchments and in corresponding pumping stations. In addition, it is expected that pumping stations with structural configurations that enable high flow velocities in the pump sump are less prone to FOG build-up, as they keep the FOG particles in suspension. It is thought that such pumping stations could prevent the build-up of FOG in areas where the disposal of FOG is extensive.

1.6 Thesis outline

Figure 2 visualises the outline of this thesis and indicates how the different parts are related. Since this study uses the scale of both households and catchments, most chapters consist of two separate parts.

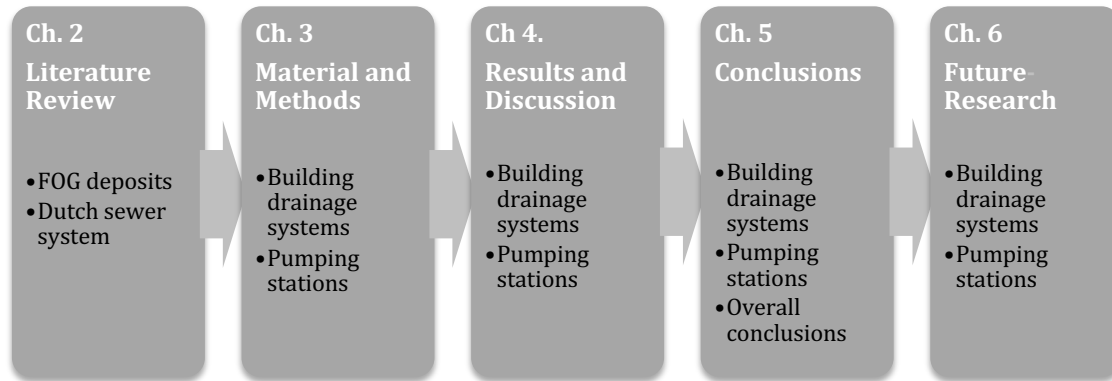


Figure 2 - Thesis outline

Chapter 2 contains a literature review on FOG deposits, and the problems caused by the accumulation of FOG throughout the Dutch sewer network.

The applied methods are presented in Chapter 3. For the part on the building drainage systems, this mainly comprises the chemical tests performed. For the pumping stations, it is discussed how the data was processed and how the accumulation of FOG in pump sumps was described using a generalized linear mixed model (GLMM). It also presents the model selection process.

The results and discussion sections are combined into one section, Chapter 4. The findings are discussed in the context of previous literature, and the reliability of the results and the used approach are evaluated.

Chapter 5 presents the conclusion and discusses to what extent the results support the hypothesis and answers the research questions. The implications of the findings in both sections are summarized.

In addition, an overall conclusion is offered, combining the outcomes of both parts and considering the accumulation of FOG at different locations within the sewer network as a whole.

Finally, based on the results and conclusions of both parts, the recommendations for future research are presented in Chapter 6.

2 Literature Review

This literature review gives an overview of the current knowledge on FOG deposits in sewer systems, and it discusses the accumulation of FOG throughout the Dutch sewer network.

2.1 FOG deposits

As stated by Butler and Davies (2004), FOG is 'a general term and comprises all fats, oils, greases and waxes of plant or food-based origin present in wastewater'; accordingly, FOG deposits are solids containing high levels of such FOG.

Recently, the field of FOG deposits in public sewer systems has received increasing attention. Various studies have been performed on the chemical and physical characteristics of FOG deposits (He et al., 2011; Husain et al., 2014; Keener et al., 2008; Shin et al., 2014; Williams et al., 2012). Additionally, the overall formation mechanisms (He et al., 2013), and the chemical and structural factors influencing the formation process (de Groot et al., 2015; Dirksen et al., 2012; Dominic et al., 2013; Iasmin et al., 2016, 2014) have been studied.

2.1.1 Chemical and physical characteristics

Previous studies collected samples from different locations within the sewer network (He et al., 2011; Keener et al., 2008; Shin et al., 2014; Williams et al., 2012). The samples showed a wide range in physical and chemical properties, suggesting different formation processes and accumulation mechanisms for different network locations (He et al., 2011; Williams et al., 2012).

Keener et al., (2008) analysed 27 FOG deposit samples taken from sanitary sewer pipes in the United States and showed that the deposits had a grainy, sandstone-like texture with high yield strengths. They described the layered structure of FOG deposits, with both layers of debris and layers of FOG, which is displayed in Figure 3. They suggested an intermittent formation process influenced by the fluctuating flow profiles of wastewater.

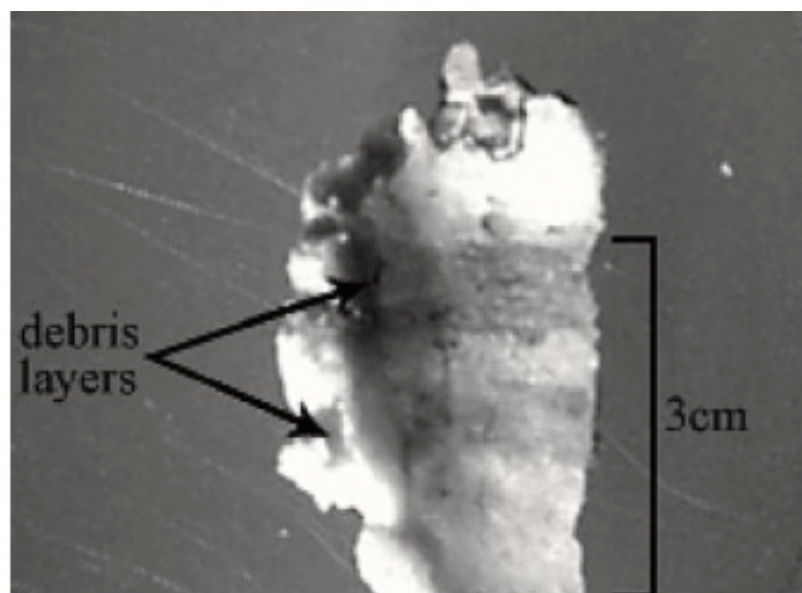


Figure 3 - FOG deposit sample showing layering (Keener et al., 2008)

They distinguished between two categories of deposits that contain FOG: the majority of the deposits (88%) were thought to be metallic salts of fatty acids, as this predominantly contained calcium and saturated fatty acids; the other 12% of the deposits were presumed to solely result from lipid accumulation. Since most of the FOG deposits examined had a high saturated fat content and high levels of calcium, the study suggested that the deposits were the result of saponification.

2.1.2 Saponification

Saponification is a reaction between fats and alkalis that is used to produce soap; in other words, it is the hydrolysis of an ester under basic conditions to form an alcohol and the salt of an acid (Levitt, 1951).

Figure 4 displays the saponification reaction of triglyceride, three molecules of fatty acids attached to a single molecule of glycerol, with calcium hydroxide. Common cooking oils, animal fats and human fats are all composed of triglycerides. When such fats are treated with basic solutions, hydrolysis occurs; the ester bond is split, thereby releasing three deprotonated fatty acids and glycerol. The hydrolysis is an equilibrium reaction; however, metal salts are formed due to the presence of positive metal ions and the equilibrium shifts to the right, thereby producing soap.

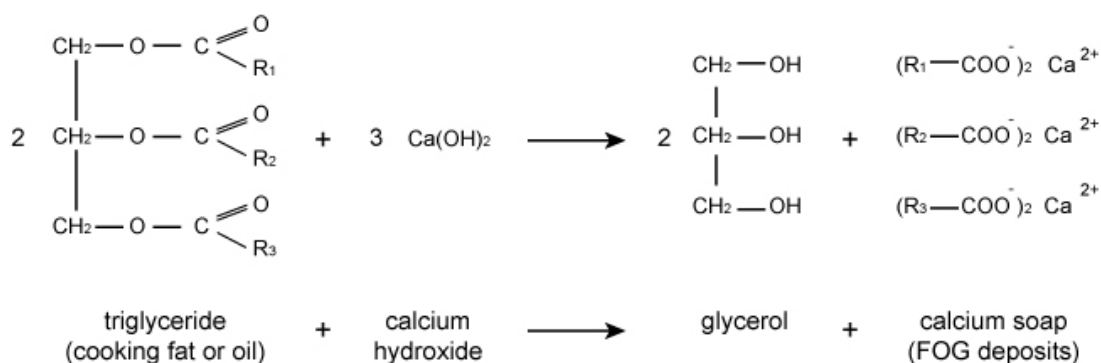


Figure 4 - Saponification of triglyceride with calcium hydroxide, resulting in glycerol and calcium soap molecules (FOG deposits). The R represents the carbon chain of fatty acids.

In soap manufacturing, calcium ions, which are naturally present in wastewater, are reported to be preferentially selected over sodium ions. Thus, after hydrolysis has taken place, calcium ions react with free fatty acids (FFAs) to form FOG deposits (Levitt, 1951).

2.1.3 FTIR spectrometry

He et al. (2011) compared FOG deposit samples collected from sanitary sewer pipes, with FOG deposits produced under laboratory conditions. They performed Fourier transform infrared (FTIR) spectroscopy to provide evidence that both were the calcium salts of fatty acids, formed as a result of saponification. The theoretical background on this FTIR technology is described in Appendix A.

The approach of He et al. (2011) was based on a study conducted by Poulenat et al. (2003), who identified four infrared spectral band regions that are attributable to the formation of calcium soaps: region 1: 4000-3000 cm^{-1} , region 2: 1800-1350

cm^{-1} , region 3: $1350\text{--}1180\text{ cm}^{-1}$ with an additional sideband near 720 cm^{-1} , and region 4: near 665 cm^{-1} . Each region is attributable to a particular bond or functional group, of which a brief overview is displayed in Table 1.

Table 1 - Characteristic FTIR band regions of calcium soaps in the mid-infrared region (4000 to 650 cm^{-1}), as presented by Poulenat et al. (2003). Abbreviations: asym= asymmetric; symm= symmetric; st= stretch; sc= scissors; r= rock; b= bend; tw= twist; and w= wag.

Charac. Region	Bandwidth [cm^{-1}]	Functional group	Assignments	Characteristic absorptions [cm^{-1}]	Type of vibration
1	4000-3000	O-H	Hydrogen bonds, water	3400	st
2	1800-1350	C=O	Carbonyl group, ester bond in TG	1745 (disappearance)	st
		COO-	Carboxylate group, ionized in Ca soap	1577, 1541	asym st
		COO-	Carboxylate group, ionized in Ca soap	1468, 1435, 1422	sym st
3	1350-1180	CH ₂	Methylene group, aliphatic chains	1278	tw, w
		C-O	Ester bonds, glycerol	1111, 1042, 993, 930, 854	st
	720	CH ₂	Methylene group, aliphatic chains	722	r
4	± 665	Ca-O	Calcium-oxygen bond, Ca soap	665-680	st

Region 1: ($4000\text{--}3000\text{ cm}^{-1}$). The broad absorption band around 3400 cm^{-1} is attributable to the presence of different types of hydrogen bonds, following from the many oxygen atoms in the polar head of the soap molecule and the hydrated water (Poulenat et al., 2003).

Region 2: ($1800\text{--}1350\text{ cm}^{-1}$). In addition, the saponification reaction was followed by the disappearance of the stretching vibration at 1745 cm^{-1} , attributing to the frequency of the ester bond in TG, and the appearance of two stretching vibrations of the carboxylate group instead (Poulenat et al., 2003). The stretching vibrations are split into three and two bands (symmetric stretching vibration, ν_1 at 1468, 1435, and 1422 cm^{-1} and asymmetric stretching vibration, ν_2 at 1577 and 1541 cm^{-1}) and show that the calcium-oxygen bonds have an ionic character (Mehrotra and Upadhyaya, 2010).

Previous studies also observed other bands in the second region of the spectra that derived from FOG deposits; it was suggested that they were the result of accumulated FFAs (He et al., 2011; Shin et al., 2014). He et al. (2011) subjected palmitic, oleic and linoleic acids to FTIR analysis and found peaks in their spectral

signatures around 1470, 1464, 1460, 1430, 1411 cm^{-1} . Additionally, three strong intensity bands at 1690, 1704 and 1704 cm^{-1} were observed in the spectra of palmitic, oleic and linoleic acids.

Region 3: (1350-1180 cm^{-1} with an additional sideband near 720 cm^{-1}). The third characteristic region is the spectral region of the aliphatic chains. The first bands, with weak intensities, could be assigned to the wagging and twisting of successive methylene groups of calcium soaps, and the second band, with strong intensities, to the rocking of successive methylene groups of the calcium soaps (Poulenat et al., 2003).

Region 4: (near 665 cm^{-1}). The absorption band around 665 cm^{-1} represents the calcium-oxygen bond, which is present between the calcium ion and the ionized carboxylate group of the fatty acids (Figure 5) (Poulenat et al., 2003).

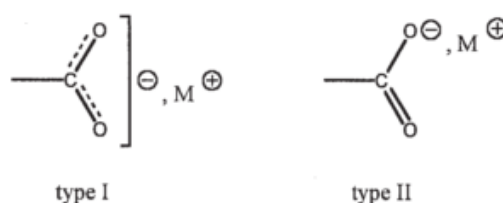


Figure 5 - The ionized carboxylate group in a metal soap; type I displays the symmetric stretching vibration, type II the asymmetric stretching vibration (Poulenat et al., 2003)

In addition to the characteristic bands, Poulenat et al., (2003) described the appearance of absorption bands which are characteristic of glycerol between 1150 and 850 cm^{-1} in the FTIR spectra of calcium soaps obtained from the saponification of TG. Since glycerol is a product derived from oil hydrolysis, these bands did not appear in the spectra of pure soaps obtained from fatty acids.

2.1.4 Proposed formation mechanisms

He et al. (2013) proposed a model to represent the overall mechanisms of FOG deposit formation in sewer systems, which is shown in Figure 6.

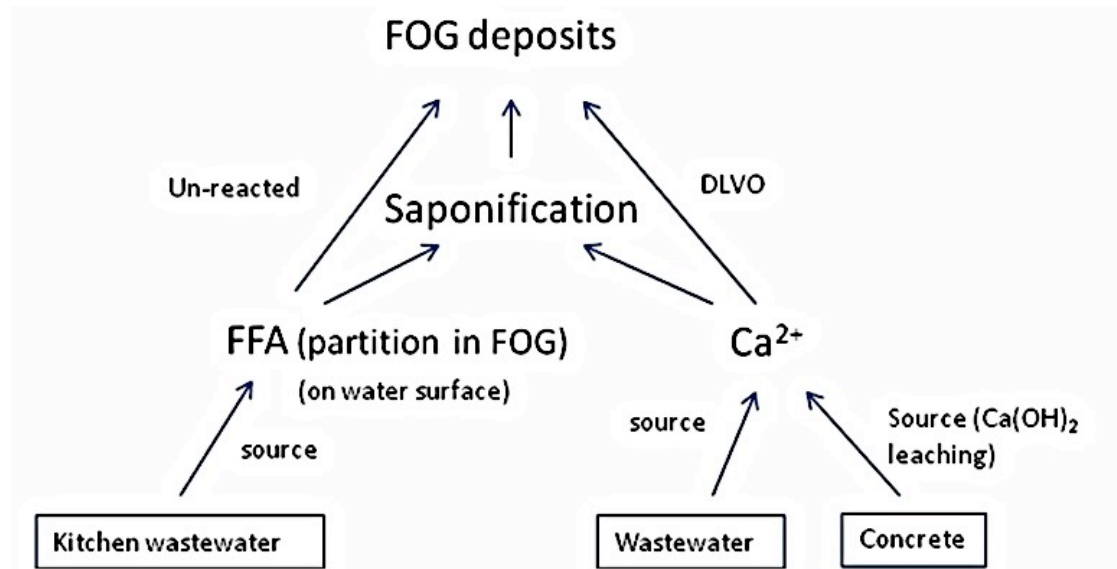


Figure 6 - Model representing the overall formation mechanism of FOG deposits in sewer systems (He et al. 2013)

This model demonstrated that four major components are required to form FOG deposits on concrete in sewer systems: FOG, water, FFAs and calcium:

FOG: FOG, in the presence of triglycerides, enables the partition of FFAs and transports these to the oil/water or oil/concrete interface.

Water: water enables the saponification reaction to take place, and He et al. (2011) showed that in the absence of FFAs, FOG deposits were not formed.

FFAs: FFAs in wastewater originate from various sources. Matsui et al. (2005) mentioned microbial driven hydrolysis, and Iasmin et al. (2016) hypothesized four different types of alkali-driven hydrolysis of FOG as possible sources, depending on the specific location in the sewer system. The oxidation reactions of oils during deep-frying or ordinary frying is another possible source of FFAs (Husain et al. 2014). The oxidation reaction is a radical chain reaction that results in FFAs and runs fast at high temperatures. When FFAs and calcium are both present, saponification occurs at a fast rate at the oil/water or oil/concrete interface, thus forming FOG deposits (He et al., 2013). Unreacted FFAs also aggregate in FOG deposits (He et al., 2011).

Calcium: calcium is present in municipal wastewater, but it is also thought to be released by corrosion from concrete pipes (He et al., 2013). FOG deposits contain calcium both in the form of calcium soaps and calcium ions, resulting from the saponification process (Williams et al., 2012) and following the DLVO theory (He et al., 2011), respectively.

The Derjaguin, Landau, Verwey, and Overbeek (DLVO) theory (Derjaguin and Landau, 1941; Verwey and Overbeek, 1946), describes the balance between two forces in colloidal suspensions: electrostatic repulsion and Van der Waals attraction. Electrostatic repulsion is related to the electrical double layer of molecules. It increases when two particles approach each other and their electrical double layers interfere. The Van der Waals force is caused by the attractive electrostatic interaction between the negative carboxylic ends of FFAs and the positive calcium ions. The repulsion force can be decreased, thus making the particles subject to attractive forces and enabling agglomeration. He et al. (2011) suggested that, following the DLVO theory, calcium ions may accumulate around the negative carboxylic ends of fatty acid micelles, where charged double layers are decreased, and saponification may take place.

Figure 7 explains the build up of FOG deposits, as proposed in a study by He et al. (2013) and following the DLVO theory: saponified solids are presumed to act as the FOG deposit matrix towards which counter-charged particles, i.e. positive calcium ions or the slightly negative carboxylic chains of FFAs, are drawn (He et al., 2011, 2013). Additionally, debris accumulates in the deposits. He et al. (2013) suggested that this is attributable to the adhesive character and surface charge of FOG deposits. Keener et al. (2008) explained the accumulation of debris on the basis of its settling characteristics and flow restrictions.

FOG deposit Formation Mechanism

Based on model proposed by He et al. (2013)

Stage 1: FOG deposit matrix attracts counter-charged particles

Stage 3: Saponification occurs on the (growing) core matrix

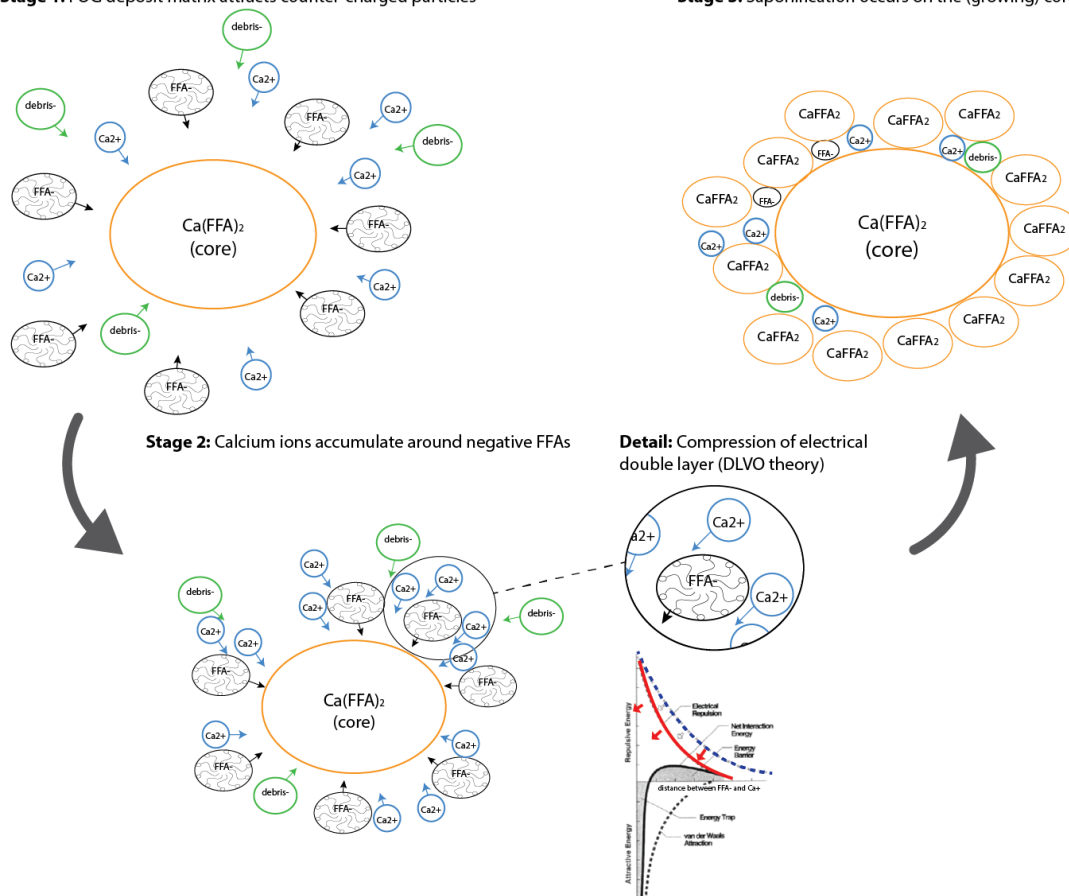
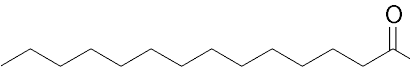
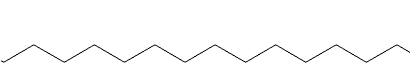
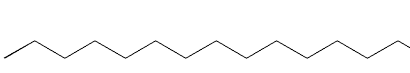
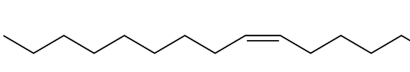
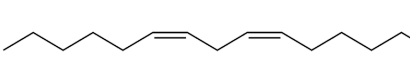


Figure 7 - Different stages of FOG deposit build up, as proposed in the study by He et al. (2013) and following the DLVO theory

2.1.5 Fatty acid composition

Analyses of the deposit's fatty acid profiles from previous studies revealed that most long-chain fatty acids (LCFAs) were between C14 and C18 (He et al., 2011; Keener et al., 2008; Williams et al., 2012). Table 2 presents an overview of such LCFAs.

Table 2 - Chemical characteristic of typical LCFAs that are present in FOG deposits.

Trivial name	Lipid Num. (C:D)	Chemical formula	Chemical structure
Myristic acid	14:0	C ₁₄ H ₂₈ O ₂	
Palmitic acid	16:0	C ₁₆ H ₃₂ O ₂	
Stearic acid	18:0	C ₁₈ H ₃₆ O ₂	
Oleic acid	18:1	C ₁₈ H ₃₄ O ₂	
Linoleic acid	18:2	C ₁₈ H ₃₂ O ₂	

The saturated palmitic acid (C16:0) appeared to be the most common acid, followed by the monounsaturated oleic acid (C18:1). FOG deposits showed a saturated fat content ranging from 20-90% (He et al., 2011; Keener et al., 2008; Williams et al., 2012). This is well above the values found in typical cooking oils and fats, as shown in Table 3. Cooking oils predominantly contain unsaturated fatty acids oleic and linoleic acid (C18:2). The amount of saturated fat in animal fats is limited to around fifty per cent of the total weight.

Table 3 - Fatty acid content of typical cooking oils and animal fats; margarine composition based on the typical margarine products sold on the Dutch market (Nutrition Information Centre, 1997)

Fat/oil type	C14:0 (%)	C16:0 (%)	C18:0 (%)	C18:1 (%)	C18:2 (%)	C18:3 (%)
Canola oil	-	4	2	60	21	10
Line oil	0	6	4	21	13	56
Palm oil	1	44	5	39	11	-
Olive oil	0	11	3	76	8	1
Sunflower oil	0	6	4	22	65	-
Margarine	2	17	12	24	22	1
Butter	11	30	10	20	2	1
Beef fat	4	26	20	35	3	-
Lard	3	25	21	32	7	1

Williams et al. (2012) showed that there was a strong inverse relationship between the palmitic and oleic acid in the deposits. The proportions of the two FFAs differed significantly between the studied network locations. They therefore suggested that biodegradation of unsaturated fatty acids takes place, resulting in the predominance of saturated fatty acids, which is possibly related to the ageing of deposits in the sewer network. Keener et al. (2008) suggested that beta-oxidation caused by microorganisms may account for these in-sewer transformations, which is supported by the findings of Matsui et al. (2005).

Iasmin et al. (2014) demonstrated that, although saturated fatty acids were dominant in the FOG deposits, unsaturated fats tended to be more active in the forming of saponified solids. They proposed that saturated fractions might increase due to the solidification of saturated fat and the subsequent accumulation within the FOG deposit matrix. Another explanation might be the compression of the charged double layer (DLVO theory), which enables the attraction of counter ions, respectively calcium ions and FFAs, within the deposit matrix (He et al., 2011, 2013). In addition, Iasmin et al. (2014) suggested that the influence of high-temperature cooking could be relevant, converting unsaturated fat to saturated fat.

2.1.6 Locations vulnerable to FOG accumulation

FOG deposits are known to accumulate in the following general locations within the sewer network:

- In lateral house connections, FOG deposits appeared to be the dominant failure mechanism. Post et al. (2016b) conducted a statistical analysis of lateral house connections for the Netherlands and showed that FOG was responsible for more than one third of all failure events.
- In sewer pipes, FOG deposits tend to accumulate in a specific position in the pipe cross-section, typically slightly above the air-water interface. This is displayed in Figure 8 (de Groot et al., 2015; Keener et al., 2008; Williams et al., 2012).



Figure 8 - Accumulation of FOG above the low-flow watermark in Arnhem (source: Municipality of Arnhem)

- Dirksen et al. (2012) conducted an analysis on FOG deposits in sagging sanitary sewers in Amsterdam and also found deposits that were formed on the soffit of sewer pipes (see Figure 9). They suggested that this was the result of blockages downstream or pump failures, causing water levels to reach the soffit.



Figure 9 - FOG deposits in Amsterdam sewer pipes, located on the soffit (Source: Waternet)

- Both Dominic et al. (2013) and Dirksen et al. (2012) identified sagging sewers in particular being vulnerable to the accumulation of FOG, due to the low flow velocities, which enable reaction and accumulation processes to take place.
- Other structural configurations that influence flow conditions, such as manholes, could also accelerate the FOG formation process. De Groot et al. (2015) focused on inverted siphons in the city of Amsterdam and showed that declining parts of inverted siphons are particularly prone to FOG blockage. They suggested this was the result of localized presence of air pockets.
- At pumping stations, FOG deposits with three different appearances were described in literature:
 - Franke et al. (2011) mentioned the floating layers of FOG, accumulating on the walls of pump sumps, which is also displayed in Figure 10. These layers potentially interfere with the functioning of level regulators in the pump sump (Bowen, 2006), depending on the type of level regulators.
 - Williams et al. (2012) collected FOG samples in the shape of 'fat balls' from the water surface of pumping stations (see Figure 11).
 - Dirksen et al. (2012) mentioned the occasional detachment of bar-shaped deposits in sewer pipes, causing blockages downstream. These could also end up in pump sumps, as such bar-shaped

deposits are observed in pump sumps during the site visits conducted for this study (see Figure 11).



Figure 10 - Thick floating layer of FOG at the large pumping station Amelandseplein in Rotterdam (source: Municipality of Rotterdam)



Figure 11 - FOG deposits in the small pumping station Millingenhof in Amsterdam, apparent as floating layers attached to the walls, floating balls and in bar shape.

Such FOG deposits in pump sumps entrap wipes, clothes and other dirt. This may clog impellers, potentially resulting in pump failures. Therefore, FOG deposits in pump sumps are removed in case the accumulation becomes severe.

- At wastewater treatment plants, excessive FOG could inhibit treatment processes. Cammarota and Freire (2006) mentioned the reduction in the cell-aqueous phase transfer rates, sedimentation hindrance due to the development of filamentous microorganisms, development and flotation of sludge with poor activity, clogging and the emergence of unpleasant odors.

2.1.7 Formation kinetics

A recent lab-scale study focused on factors that may affect the physical, chemical, and rheological properties of FOG deposit formation, including the types of fats used in cooking processes, environmental conditions such as temperature and pH,

and the source of calcium in sewer systems (Iasmin et al., 2014). Based on these results, Iasmin et al., (2016) proposed a kinetic model of the formation process. The study was performed on a lab-scale and the model has therefore not yet been validated on full-scale sewer systems.

2.1.8 FOG problems in the Netherlands

In 2012, Dutch municipalities reported fifteen blockages per 100 kilometres of main sewers per year and in ten per cent of all cases, this caused flooding and water ponding in streets (RIONED Foundation, 2013). It is unknown to what extent FOG accumulation contributes to sewer blockages. The Amsterdam water company, Waternet, estimated that fifty per cent of all blockages are related to FOG (Waternet, 2009). Additionally, Post et al. (2016b) showed that, for the Netherlands, more than one third of all failure events in lateral house connections were related to FOG, based on a statistical analysis of failure mechanisms in lateral house connections. Dirksen et al. (2012) stated that in the Netherlands, hydraulic jet cleaning is the most common cleaning method for the removal of FOG deposits attached to pipe walls.

Pumping stations are prone to failure and such failures significantly decrease the overall sewer serviceability, as they may cause combined sewer overflows or flooding (Korving et al., 2006). The Netherlands is a relatively flat delta area, which explains why the gravity sewer systems contain many pumping stations. In 2012, 49,700 pump failures were reported in Netherlands, which corresponds to 3.6 failures per station per year (RIONED Foundation, 2013). It is unknown to what extent FOG accumulation contributes to pump failures. According to the municipalities that were interviewed for this study, FOG deposits entrap wipes, clothes and other dirt, causing pump failures. Therefore, FOG deposits are removed in case the accumulation becomes severe.

2.2 Responsibilities in sewer management

According to the Environmental Law ('Wet Milieubeheer' in Dutch), municipalities have the obligation (duty of care) to collect wastewater from properties and transport it to wastewater treatment facilities (Environmental Law, 1979). They are responsible for providing sufficient drainage capacity (and so for clearing blockages), or for solving pump failures.

Regarding building drainage systems and connected laterals, the combination of the exact failure location and the particular municipality determines who is charged and has the responsibility of maintaining free-flowing pipes. In most municipalities, property owners are responsible for the maintenance of blocked pipes within the boundaries of properties or blockages that are located in the pipes up to the inspection openings (IOs). In some municipalities, however, property owners are responsible for the entire lateral up to the connection to the public sewer line.

Households and industries are not allowed to dispose of wastewater that impedes the effective functioning of the sewer system, thereby implying that the disposal of FOG is not allowed. According to the Environmental Activities Decree ('Activiteitenbesluit' in Dutch), FSEs and establishments that pack or process meat or fish are obliged to purchase and maintain grease interceptors (Activities Decree, 2007). There are no regulations, however, controlling the total amount of FOG discharged.

Water boards are responsible for wastewater treatment in the Netherlands.

3.1.2 Sample collection

For this experimental study, a non-random and convenience sampling method was used: the research population was composed of households with FOG blockages and they were all living in the area covered by the RRS service engineers. Only in the case that the service engineers identified FOG as failure mechanism, a sample of clogging material was collected.

For the lateral house connections, the blockage location together with the construction of the building drainage system determined the manner of sampling. If the FOG blockage was close to the IO, a jar was filled directly. When the blockage was not visible directly from the IO, the service engineers used high-pressure water jetting, equipped with jetting nozzles facing backward and forward. Due to the backward facing jets, the unit propelled forwards and detached FOG deposits flew towards the IO, where a sample could be collected.

The clogged kitchen drains were cleared by mechanic drain rodding. After removing the water trap, the kitchen drain was entered with the flexible cable on a rotating drum. The detached FOG deposits were collected using a wet vacuum cleaner, and then put in a jar.

The samples were stored in the sewer inspection car and at the end of the day refrigerated at 5°C for further analyses within seven days. Because of technical difficulties, fatty acid profiles of the samples 4, 5 and 6 were measured twice. After it was noticed that lab results were three orders of magnitude smaller than fatty acid contents of prior samples, the samples were submitted to the laboratory for a second analysis. Only the lab results of the second analysis are reported in this thesis.

For every sample, the service engineers were asked to provide information on the particular clogging, the manner of sampling and the structural conditions of the building drainage system. Also, the type of sewer system downstream was noted, since storm water of roof drainage systems may alter the flow conditions.

3.1.3 Chemical and physical testing

Chemical and physical tests were carried out by the AL-West laboratory that focuses on soil, waste and (waste)water analyses (AL-West B.V., Deventer, the Netherlands).

The kitchen drain samples were filtered prior to analyses, since they contained both wastewater that could not pass the blockage and clogging material. Analyses were performed on the residues, after filtration through a 0.25mm filter (see Table 4). The samples from lateral house connections only contained clogging material and did not require filtration. Both the samples from kitchen drains and lateral house connections were homogenized prior to analyses.

Table 4 - Filtration characteristics of kitchen drain samples; volume prior to filtration and weight of the residues

Sample	Total volume (L)	Weight Residue (g)
1	0,825	480
2	0,516	114
3	0,908	177
4	0,516	278

Dry matter and water content were analyzed gravimetrically by drying and heating, according to a method equivalent to NEN-ISO11465 and conform AS3000, AS3200 and NEN-EN 12880.

The calcium concentration was determined with Inductivity Coupled Plasma-Massa Spectrometry (NEN 6966) and after destruction with aqua regia (NEN 6961).

Using internal methods and conform NEN 6671, the oil and fat content was measured gravimetrically by ether extraction. Then, the following FFAs were analyzed by internal methods: hexanoic acid (C6:0), heptanoic acid (C7:0), octanoic acid (C8:0), nonanoic acid (C9:0), decanoic acid (C10), undecanoic acid (C11:0), undecylic acid (C11:1), dodecanoic acid (C12), tetradecanoic acid (C14:0), hexadecanoic acid (C16:0), octadecanoic acid (C18:0), octadecenoic acid (C18:1), octadecadienoic acid (C18:2), eicosanoic acid (C20:0), docosanoic acid (C22:0).

3.1.4 FTIR spectrometer analysis

Fourier transform infrared (FTIR) analysis was performed at the Chemical Engineering Laboratory at Delft University of Technology, using a Thermo Scientific Nicolet™ 6700 FTIR spectrometer. An attenuated total reflection crystal made of zinc selenide (ZnSe) was used to obtain infrared absorption spectra of the homogenized FOG samples. For every sample, independent analyses were performed on three sub samples.

Spectra were collected at the mid-infrared region (4000 to 650 cm^{-1}) and a total of 64 scans were performed per run at a resolution of 4 cm^{-1} . The spectra were subtracted against the background of an air spectrum. A new background scan was performed every thirty minutes, and after switching to a sample from a new lateral house connection. For data processing Omnic software was used.

3.1.5 Questionnaire

To collect information on disposal and cooking habits, a questionnaire was conducted by phone. The sewer cleaning company provided phone numbers if the households were willing to participate. Any adult member of the household who was capable of providing information on cooking and washing habits was considered to be suitable. The questionnaire was divided into four main sections:

- Disposal of FOG: the households were asked for their cooking, cleaning and disposal habits of fat, oil, savory sauces and dairy products. Both amounts and moments of disposal were asked for. Also, the types of cooking oils were considered.
- Drainage of debris: the disposal of food scraps flushed through the toilet and kitchen sink were studied, since the adhesive character of FOG may adsorb debris. Also, people were asked for the usage of kitchen sink grinders.
- Laundry- and dish-washing preferences: the soaps used for dishwashers and laundry machines were taken into account, as they may influence the saponification process due to their high alkalinity. Also, they may accumulate in the deposits.

- Observed sewer problems: to determine the severity of sewer problems of the particular household, the time of residence together with the frequency of drainage problems last ten years were considered.

An overview of the questions is included in Appendix B.

3.2 Pumping Stations

To acquire more information about the relationship between FOG disposal patterns of inhabitants and FOG deposits in the sewer network of the corresponding catchment, the severity of FOG accumulation at pumping stations was studied in relation to demographic data and system characteristics of the area upstream.

3.2.1 Site selection

The dataset consisted of pumping stations located in five relatively large Dutch municipalities that were all involved in the 'Knowledge Program Urban Drainage' (see Acknowledgments). Table 5 provides an overview of the participating municipalities and their general characteristics; they varied in demographics, type of catchments and pumping stations.

Table 5 - General characteristics of participating municipalities. The data is revealed from municipal sewer system management plans (Municipality of Almere, 2011; Municipality of Arnhem, 2009; Municipality of Rotterdam, 2011; Municipality of The Hague, 2010; Waterboard Amstel, 2010). Pumping stations were count as such when their corresponding (sub)-catchments were identified on the GIS data delivered by the urban drainage system.

Municipality	Number of inhabitants [-]	Pumping stations [-]	Length of DWF gravity sewers [km]		
			Total	Combined	Separated
Amsterdam	767,500	437	1358	525	833
Rotterdam	593,000	536	3311	1809	1502
The Hague	484,000	72	1091	845	246
Almere	188,000	178	595	0	595
Arnhem	147,000	22	464	178	286

Pumping stations were chosen as representative points for FOG deposits in sewer systems of the entire catchments upstream. Since pumping stations are the most downstream points in catchments, this location enabled to study the influence of disposal patterns that are shared by the population of a catchment.

The scope of this study was limited to domestic disposal patterns and their effect on FOG deposits. Therefore, only pumping stations in residential catchments were taken into account.

3.2.2 Data collection

The dataset of catchments was composed in close collaboration with the participating municipalities, resulting in binomial data on FOG accumulation in pump sumps of the selected catchments. First, a letter with further information about the research was sent to the heads of the sewer management departments of the participating municipalities (Appendix C). They provided the names of the employees responsible for the management of pumping stations. These employees were visited, both to give an explanation about the research and to obtain municipality-specific information of the sewer system.

For this study, a stratified sampling method was used. The research population was divided into two separate strata; pumping stations with and without severe accumulation of FOG, which both should be located in residential areas. As each stratum was sampled as an independent sub-population, the sampling was assumed to be random within the strata itself. The participating municipalities were asked to compose two list: the first list should include pumping stations that were known for their severe FOG accumulation; the second list should consist of pumping stations that were known to have hardly any accumulation of FOG in their pump sumps. The pumping stations should have a pumping capacity of at least $1 \text{ m}^3\text{h}^{-1}$. No requirements were given for the total number of pumping stations, as long as both lists were of approximately equal length.

Each observation is represented by one catchment, describing the presence or absence of severe accumulation of FOG in the pumping station downstream of this catchment. For Rotterdam and Amsterdam there was some, although limited, quantitative data available on the accumulation of FOG. As the observations from the five municipalities formed one dataset, however, it was not possible to use this quantitative information. The accumulation of FOG was therefore solely quantified by its presence or absence, as judged by the sewer employees.

In addition to the two lists of pumping stations, the municipalities were also asked to provide general information about their sewer system and the selected pumping stations. This included:

- GIS data of the urban drainage areas
- The municipal drainage scheme
- Physical properties of pumping stations (construction drawings, pumping capacities, design dry weather flows, type of sewer system)

Discrepancies between cities were prevented by discussing parameter definitions on forehand. For some pumping stations there was no consensus about the severity of FOG accumulation among the sewer employees; such observations were not included in the dataset. Also, if information on pumping stations was lacking, such as construction drawings, the observations were not included either.

3.2.3 Parameter selection

The parameters in the dataset represented general system characteristics and socio-demographic (from here on called ‘demographic’) characteristics that were potential indicators for the accumulation of FOG or FOG disposal patterns.

3.2.3.1 System characteristic data

The dataset contained six parameters that represented the geometry of the pumping stations and the system characteristics of the catchment, which are displayed in Table 6.

The parameters ‘city’ and ‘sewer system type’ were expected to reflect more general aspects of the sewer system conditions, and the other parameters were all, to some extent, related to the motion of water. The motion of water was

suspected to prevent the build-up of FOG by keeping the FOG particles in suspension and inhibiting the accumulation of FOG.

Table 6 - Selected system characteristic parameters and their characteristics

Parameter	Unit	Description
City	[-]	The city where the pumping station is located
Sewer system type	[-]	The type of sewer system
Gutters	[-]	The presence of gutters arranged in a zigzag pattern ('slingergoten' in Dutch) in pump sumps
Vertical velocity	[mh ⁻¹]	The average vertical velocity in the pump sump following from to the pumping capacity under dry weather conditions
Daily operation time	[hd ⁻¹]	The average operation time per day, based on DWF
Total kinetic energy	[Jm ⁻³ d ⁻¹]	Total incoming kinetic energy per unit of volume per day

No configuration details, such as the shape of the pump sump or the position of suction inlet were considered for this study, as the nature of statistical analysis does not allow for such details.

Simplifications and assumptions

The statistical analysis required one representative and comparable value per parameter per pumping station. For some observations and/or parameters, the values were therefore simplified and/or pre-processed.

Dry weather flow

The values for dry weather flow (DWF) as provided by the municipalities were considered to be representative and up-to-date. For Amsterdam and Rotterdam, measured DWFs were available. For Arnhem, Almere and The Hague, design DWFs were used, which are based on the number of inhabitants, peak disposal flow per inhabitant and disposal flows of local industrial facilities.

Hourly DWFs were derived from the hourly distribution percentages, as presented in the 'Guidelines for sewer systems computations and hydraulic functioning' (RIONED Foundation, 2004).

Pump operation details

Pump operation details concern the pumping capacity, and the switch-on and switch-off level. Since pumping stations run under dry weather conditions for eighty per cent of the time (Tukker et al., 2012), capacities corresponding to peak DWF were taken as representative values, both for areas served by a separated system and for areas served by a combined sewer system.

For some pump operation details, such as switch-on and switch-off levels or pumping capacity values, the values varied greatly among different reports and/or management systems of one municipality. According to the municipalities, such discrepancies might be induced by pragmatic changes in the field. In such

cases the most representative value, according to the municipality in question was taken.

Control systems enable alternating operation of two (or more) pumping units. It was assumed that only one pump was running under dry weather conditions. In case of varying pumping capacities of the pumping units that are running under dry weather conditions, the average pumping capacity was taken.

Some pumping stations in the dataset, located in Amsterdam, Almere, Rotterdam or The Hague, were controlled by a variable frequency drive (VFD). A VFD is an electronic device capable of controlling the rotation speed of a three-phase induction motor in a sewer pump. Such VFDs transform the standard three phase sinusoidal voltage levels of the power grid into a series of rectangular pulse form voltage levels, thereby controlling the rotation speed of the electrical motor and thus the speed of the pump. Depending on their control algorithm, VFDs are used to control the speed of the motor during the start and stop cycle, and/or to only deliver what the operation needs to function at optimal efficiency.

The operating schemes of the VFDs varied considerably among the municipalities. For Almere, Rotterdam and The Hague, the VFD systems were mainly used to prevent high inrush current of the pumps. Similar to conventional pumps, such VFD operated pumps switch-on and off several times during the day. Hence, the VFD systems did not considerably affect the overall pumping schemes and mainly affected the initial and final phase of the pumping cycle. For these pumps, the stabilized pumping capacity was taken as the representative value for pumping capacity.

For Amsterdam, the VFD systems had a different operation strategy, as they focused on maintaining a constant water level in the pump sump. This operation scheme entailed continuously operation of the pumps during daytime, and an on-off mode operation during the night. Compared with conventional pumps, the overall pumping capacities of such pumps were lower due to longer run times and the alternating operating speed. For these VFD operated pumps, the measured peak DWF was taken as a reference value for pumping capacity.

In addition to the variable speed operation, the VFD operated pumps in Amsterdam had flexible switch-on and switch-off levels. The minimum and maximum water levels that were measured during the night were used as representative switch-on and switch-off levels.

Pumping station geometry

The water level in between the switch-on and switch-off levels of the DWF pump was considered as the representative water level in the pump sump. Further values concerning the geometry of the pumping stations were determined under representative water level conditions.

The water depth, z , was defined as the water level with respect to the pump sump bottom. In case of sloped bottoms or varying bottom levels, the average bottom level of the pump sump was taken. For each pumping station, this water depth was assumed to be constant over time, following from the representative water level conditions. This water depth can be written as follows:

$$z = \frac{z_{on} + z_{off}}{2} \quad (1)$$

where z_{on} is the switch-on level and z_{off} is the switch-off level with respect to the pump sump bottom.

For the surface area of the pump sump, A_{sump} , the projected pump sump surface was taken. When gutters arranged in a zigzag pattern ('slingergoten' in Dutch) were present between the inlet and the pump basin, the contributing surface area of half-filled gutters was taken.

The values for the total storage capacity were based on the surface area and the representative water depth. For some pumping stations, invert levels were located beneath switch-on levels, increasing the actual storage capacity. Such in-sewer storage was not included in the total storage capacity.

Parameter derivations

The three parameters 'vertical velocity', 'daily operation time' and 'total kinetic energy' (Table 6) were no standard parameters and were derived from physical properties of the pumping stations and catchments.

Vertical velocity

The average vertical velocity v_{vert} , [$\text{m} \cdot \text{h}^{-1}$] represented the flow in the pump sump following from the pumping capacity, and was calculated as follows:

$$v_{vert} = \frac{Q_{pump}}{A_{sump}} \quad (2)$$

where Q_{pump} [$\text{m}^3 \cdot \text{h}^{-1}$] is the pumping capacity under dry water conditions, and A_{sump} [m^2] the surface area of the pump sump.

Daily operation time

The average daily operation time, $t_{operation}$, in hours per day was calculated as follows:

$$t_{operation} = \frac{Q_{dwf} \cdot t}{Q_{pump}} \quad (3)$$

where Q_{dwf} is the hourly DWF, t is the time, in this case 24 hours, and Q_{pump} is the pumping capacity under dry water conditions in [$\text{m}^3 \cdot \text{h}^{-1}$].

Total kinetic energy

The values for incoming kinetic energy per unit of volume per day, $E_{daypump}$ [$\text{J} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$], were based on the values for DWF as provided by the municipalities and the hourly distribution percentages (see page 24). For each pumping station, hourly values for the kinetic energy, $E_{kin,h}$, were summed over the day and divided by the representative water volume in the pump sump, V_{pit} ; which can be written as:

$$E_{daypump} = \frac{\sum_{t=1}^{24} E_{kin,h}}{V_{pit}} \quad (4)$$

The incoming kinetic energy, E_{kin} , was calculated as the kinetic energy at the invert level of the inflowing pipe(s), $E_{kin\ inv}$, and the potential energy, E_{pot} , of the inflowing water with respect to representative water depth in the pump sump. This leads to the following formula:

$$E_{kin} = E_{kin\ inv} + E_{pot} \quad (5)$$

where E_{pot} follows from the equation for potential energy:

$$E_{pot} = mgh \quad (6)$$

where m is the mass of the incoming water, g is the gravitational acceleration, and h the fall height of the incoming water, assuming a constant water level in the pump sump. $E_{kin\ inv}$ follows from the equation for kinetic energy:

$$E_{kin\ inv} = \frac{1}{2}mv^2 \quad (7)$$

where m is the mass of the incoming water, and v the flow velocity.

The velocities were derived from hourly values for the DWF, according to the hourly distribution percentages, and the cross-sectional area of flow:

$$v = \frac{Q_{dwf}}{A} \quad (8)$$

where Q_{dwf} is the hourly DWF, and A is the cross-sectional area of flow. The flow velocity, v , was assumed to be constant for every hour, and the incoming DWF was assumed to be equally divided among all inlet pipe. Pressurized pipes that drained wastewater from upstream pumping stations were considered to have the same (hourly) DWF distribution as gravity sewer inlet pipes.

The cross-sectional area depended on the water depth at the location of inlet during the particular hour, and was derived from the representative water depth in the pump sump, z_{repr} , the invert level of the inlet pipe, z_i , and the average water depth in the pipe at the location of inflow during the particular hour, d .

For the calculations of the cross-sectional area and thus the flow velocity and corresponding kinetic energy, three situations for representative water depths at the location of inlet were distinguished, which is visualized in Figure 13.

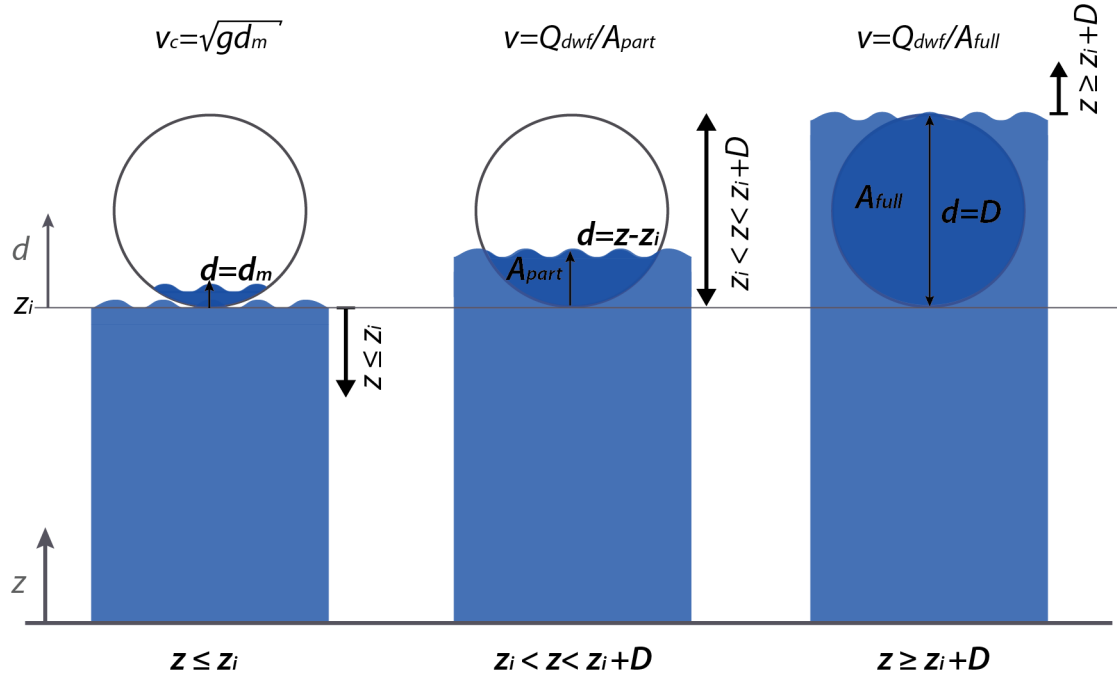


Figure 13 - Different representative water depth scenarios for calculating the kinetic energy. The figure shows the front view of the inlets.

1. $z \leq z_i$

For this situation the representative water level was below the invert level of the pipe. The outlet of this pipe was classified as a 'free outflow'. Close to the end of such pipes, flow conditions are critical, implying that the non-dimensional Froude number, F_r , is known and specified as:

$$F_r = \frac{v_c}{\sqrt{g \cdot d_m}} = 1 \quad (9)$$

where v_c is the critical flow velocity, g is the gravitational acceleration, and d_m is the hydraulic mean depth, specified as the cross sectional area of flow per flow width at the water surface. Following from this equation, the critical flow velocity can be written as:

$$v_c = \sqrt{g \cdot d_m} \quad (10)$$

Based on the following empirical equation of Straub (Straub, 1978), the critical depth, d_c , and with this, using geometric and trigonometric equations, the hydraulic mean depth, d_m , were determined:

$$\frac{d_c}{D} = 0.567 \cdot \frac{Q_{dwf}^{0.506}}{D^{1.264}} \quad (11)$$

where $0.02 < \frac{d_c}{D} \leq 0.85$ and where Q_{dwf} is the hourly DWF in SI units.

For one pumping station the value was slightly below the lower limit with $d_c/D = 0.007$, and for seven pumping stations this value was above the upper limit $d_c/D \leq 1.31$. In such cases d_c/D was assumed to be equal to the lower and upper limits, as the specified conditions were only violated for values of peak DWF and DWF during the night.

The possible influence of the tail water was neglected, and the water depth at the outflow was assumed to be equal to the critical depth, thus neglecting the drawdown effect.

The potential energy, E_{pot} , was calculated according to Equation (6), where the following specification of the fall height, h , was used:

$$h = (z_i + d_m) - z \quad (12)$$

The potential energy was equal to zero.

2. $z_i < z < z_i + D$

For this situation, the representative water level was between the invert level and the crown level of the inlet pipe. The following specification of the water depth in the pipe, d , was used:

$$d = z - z_i \quad (13)$$

where z is the representative water depth and z_i the invert level with respect to the pump sump bottom. The value for d was confined by d_c .

Using geometric and trigonometric equations, the value for the cross-sectional area of flow A was derived.

The potential energy was equal to zero.

3. $z \geq z_i + D$

For this situation, the representative water level was above the crown level of the inlet pipe, implying that there was full pipe flow. The value for the cross-sectional area of flow A followed from the geometrical equations for circles.

The potential energy was equal to zero.

Some pipes that drained wastewater from upstream pumping stations discharged their water via vertical pressurized pipes that were fully submerged. Such pipes were considered as horizontal inlets that were fully submerged, thus according to the third situation for the representative water depth ($z \geq z_i + D$).

For Rotterdam, some of the pumping stations had rectangle inlet pipes; such pipes were considered as round inlet pipes with an equivalent cross-sectional area.

3.2.3.2 Demographic data

Geographical data from Statistics Netherlands ('CBS' in Dutch) on neighborhood level was used to obtain weighted demographic data per catchment. The geographical maps were composed from data from the Key Registers Cadastre ('BRK' in Dutch) and regional data from Statistics Netherlands (Statistics Netherlands and Kadaster, 2012). Data from the year 2012 was used, as this was the most recent dataset that contained values for all desired parameters. Merging data from different years was unfeasible, due to changes in borders of administrative neighborhoods.

Table 7 provides an overview of the parameters that were selected from the database. Only parameters that were considered to be relevant for FOG accumulation, i.e. that were potential indicators for FOG disposal, were selected.

Table 7 - Selected demographic parameters and their characteristics, derived from geographical data on neighborhood level (Statistics Netherlands and Kadaster, 2012).

Parameter	Unit	Description
Population density	[km ⁻²]	Population per unit of area
Household density	[km ⁻²]	Total number of households per unit of area
Household size	-	Average number of inhabitants per household
Non-west. immigrants	[%]	The percentage of immigrants with non-western origin
Rental properties	[%]	Percentage of rental properties
Housing assoc. prop.	[%]	Percentage of rental properties owned by housing associations
Pers. income (total pop.)	[·1000€]	Average personal income based on total population
Pers. income (work. pop.)	[·1000€]	Average personal income based on people with an annual income
Low income pop.	[%]	Percentage of households belonging to the group with the 40% lowest disposable incomes
High income pop.	[%]	Percentage of households belonging to the group with the 20% highest disposable incomes
Below soc. minimum	[%]	Percentage of households belonging to the group that has an income below the social minimum as established in the political decision-making
FSE density	[km ⁻²]	Average number of restaurants, cafes and cafeterias within a travel distance of one kilometer for each inhabitant

Calculations were performed with Quantum GIS software, version 2.0.1-Dufour (QGIS, 2013). Using the Geoprocessing Intersect tool, a GIS layer with the contributing areas of neighborhoods in each individual catchment was created,

the process of which is displayed in Figure 14. The Intersect command creates a new feature based on the area of overlap between two layers, which enabled to deduce neighborhood-specific data for each individual catchment.

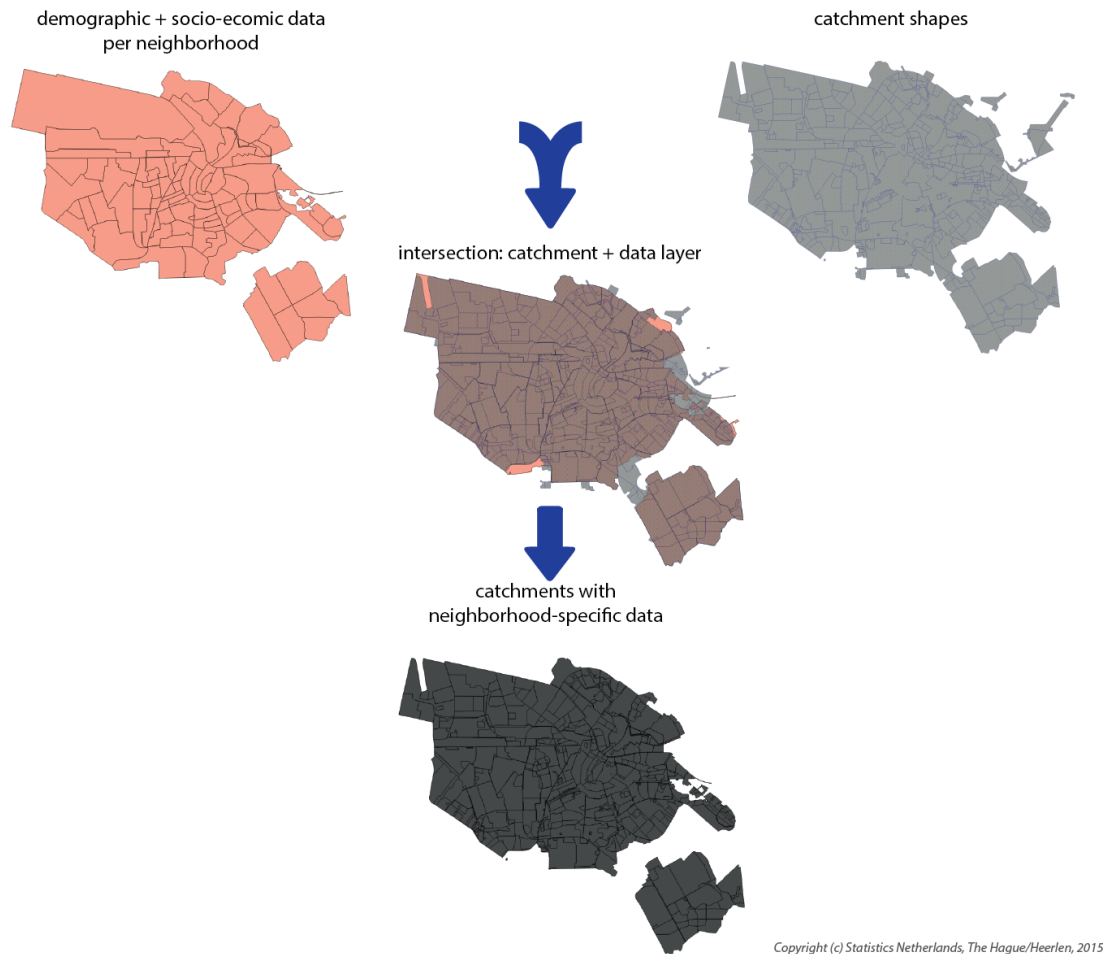


Figure 14 - Visualization of merging the demographic data, showing the catchment shapes for the municipality of Amsterdam.

Further data processing was performed using R statistics software, version 0.99.893 (R Core Team, 2016). The database contained some missing values; data points that were identified as ‘nihil’ were replaced by zero, and data points that were identified as ‘susceptible to reliability and secrecy’ were replaced by “NA” (not available).

The parameters ‘FSE density’ and ‘household density’ were not readily available from the geographical database, and were derived from other parameters. Also the number of inhabitants, which was required to determine representative values for each catchment, had to be computed:

- The total number of inhabitants for each neighborhood was calculated, based on the population density and the surface area of each neighborhood.
- Representative values for the presence of Food service establishments (FSEs) were derived by summing the average number of restaurants, cafes

and cafeterias that were present within a travel distance of one kilometer for the inhabitants (see Table 7 on page 30). This value was divided by the surface area.

- The household density for each catchment was calculated by taking the number of households divided by the surface area.

Estimations of the demographic characteristics per catchment were obtained by weighing the characteristics according to the catchment's population that the contributing neighborhoods contained. Using the catchment weights, characteristics per catchment were derived in proportion to their populations. The numbers of inhabitants per catchment were based on the population density of the neighborhoods and the contributing surface areas of the neighborhoods.

The larger pumping stations often received wastewater from various smaller pumping stations. The catchments of these smaller pumping stations are referred to as sub-catchments. To determine representative demographic characteristics for the catchments that contained sub-catchments, the sub-catchments were weighted by the same procedure in the computation of representative values of the sub-catchments.

After the pre-processing of the data, the database of the selected pumping and their system characteristics were merged with the demographic catchment data.

3.2.4 Dataset

Table 8 provides an overview of the data; the dataset consisted of 128 observations in total, spread over five cities. The number of pumping stations varied largely among cities. Of the entire dataset, 53 pumping stations were clean and 75 had severe accumulation of FOG in their pump sump. The explanatory variables represented factors related to general system characteristics (Table 6 on page 24) and demographics (Table 7 on page 30).

Table 8 - Overview of the dataset, showing the total number of observations, and the number of observations with and without FOG accumulation in the pump sump per city.

Municipality	Pumping stations in dataset [-]		
	Total	Clean	FOG
Amsterdam	53	21	32
Rotterdam	12	6	6
The Hague	25	7	18
Almere	26	12	14
Arnhem	12	7	5
Total	128	53	75

Following the research questions as presented on page 4, this study used a descriptive modelling approach; hence, the study focused on quantifying the relationship between catchment demographics and the presence of FOG in pump sumps, and whether the pump sump geometry influences such accumulation of FOG. The entire dataset was therefore used to develop the statistical model, so it

was not split into a train and test set to perform a (simulation-based) cross-validation.

3.2.5 Statistical data analysis

For the statistical analysis of the catchment data, the procedure as presented in Figure 15 was followed to obtain the final generalized linear mixed model (GLMM). The procedure, which is consistent with the procedure presented by Zuur et al. (2009), consisted of four steps: data exploration, model component selection, model selection, and model validation.

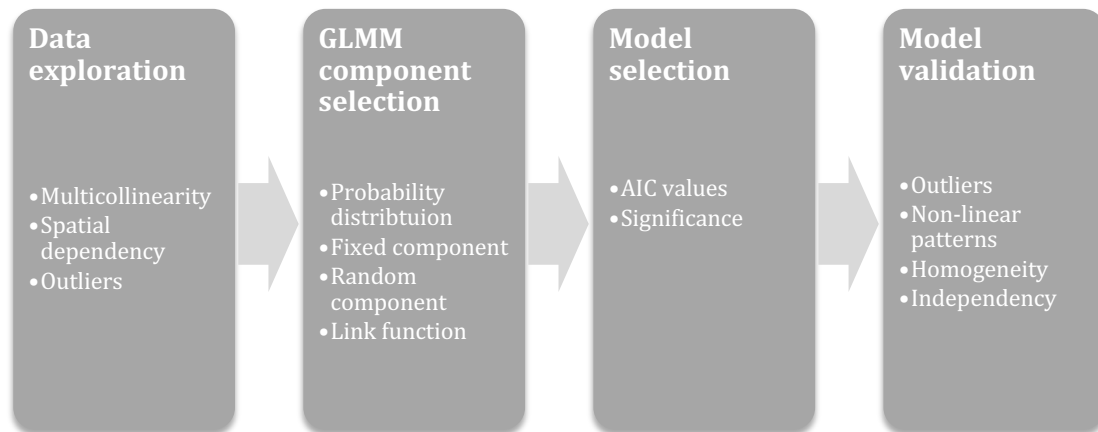


Figure 15 - Procedure for the GLMM model selection and validation process

3.2.5.1 Data exploration

A detailed data exploration was performed to identify collinearity, to check for spatial dependency, to detect outliers, and to reveal information on the relationship between the response variable and the explanatory variables.

First, collinearity was investigated by visual inspection and variance inflation factors (VIFs). Collinear variables were removed and, after information on the spatial dependency was revealed, a GLMM was applied on the remaining dataset. Based on this GLMM, outliers were detected.

Collinearity

Visual inspections gave a first impression for pairwise correlations. The type of the explanatory variables, whether the variable was of the categorical or of the continuous type, determined which tool for visual inspection was used.

For the relationships between two continuous variables, pairwise correlations were studied using pairplots and correlations coefficient. One pairplot (see Appendix D) was produced for all continuous variables at once. To study the relationship between categorical and continuous variables, boxplots of the continuous variables conditional on each individual categorical variable were produced. In the case of two categorical variables, tables were produced, in which the rows represented the category of one variable and the columns represented the categories of the other variable. The table specified the proportion of every combination.

In addition to visual inspection tools, which provide only information on pairwise correlations between explanatory variables, VIF values were used to examine

linear dependence among three or more continuous explanatory variables. The theory on VIFs is briefly discussed in Appendix E.

A threshold of 3 for the VIFs was used in combination with a maximum Pearson correlation coefficient of 0.65. One collinear variable at a time was removed until the values for the VIF and Pearson correlation were below the preselected thresholds. The criteria for selection of such a collinear variable were:

1. The number of missing values in the observations of the variable
2. The VIF value for the variable
3. The values for the Pearson correlation coefficients between the particular variable and all other variables
4. The ease of measuring the variable in terms of cost and effort (Zuur et al., 2009)

Since the dataset only contained variables that are thought to be relevant for the accumulation of FOG, all variables were considered to be of equal importance for the model.

For the categorical variables, only pairwise relations were studied. In case the tables and boxplots showed patterns for collinearity, variables were dropped.

Following this procedure, nine variables were dropped. An overview of the dropped variables and the reason for omission is given in Table 9. Although such variables were not included in the final model, they might be the variables that were driving the system, instead of the variables included in the model (Gjerdrum et al., 2008).

Table 9 - Collinear variables that were dropped, including the reason for omission. The order presented in the table is equivalent to the dropping order.

Dropped variable	Reason for dropping
Gutters	Small number of observations (8 in total, 7 of which located in Arnhem)
Below soc. minimum	High number of missing values (21 out of 128)
Personal income (based on work. pop.)	High VIF value (48.0) and highly correlated with the variable 'personal income' (based on total pop) ($r=0.96$)
Low income pop.	High VIF value (18.3) and highly correlated with variable 'renting properties' ($r=0.78$)
Non-west. Immigrants	Highly correlated with the variables 'housing assoc. properties' ($r=0.67$) and 'personal income' ($r=-0.69$)
Household density	Highly correlated with the variable 'population density' ($r=0.87$)
High income pop.	High VIF value (13.3)
Renting properties	High VIF value (11.6)
Daily operation time	Highly correlated with the variable 'total kin. energy' ($r=0.78$)

For the variable ‘sewer system type’, the level of ‘first flush systems’ (‘verbeterd gescheiden stelsel’ in Dutch) occurred rarely as it only contained five observations. If such a variable is included in the model, it may influence the model performance. Dropping the observations was not desirable either, since the dataset was relatively small. Their level was therefore transformed (Zuur et al., 2010).

It is thought that the presence of dirt and FOG, coming from the street and due to wrongly connected building drains, enhance the FOG deposit formation process in a way that resemble the situation in separated systems. Additionally, as first flush systems mainly contain domestic wastewater and only the first flush of storm water, the wastewater of such systems is less diluted compared with combined systems. The level of such observations was therefore changed to ‘separated systems’.

Spatial dependency

The data exploration indicated that there is spatial dependence; pumping stations located in the same city showed similarities in their characteristics. This nested data structure is visualized in Figure 16.

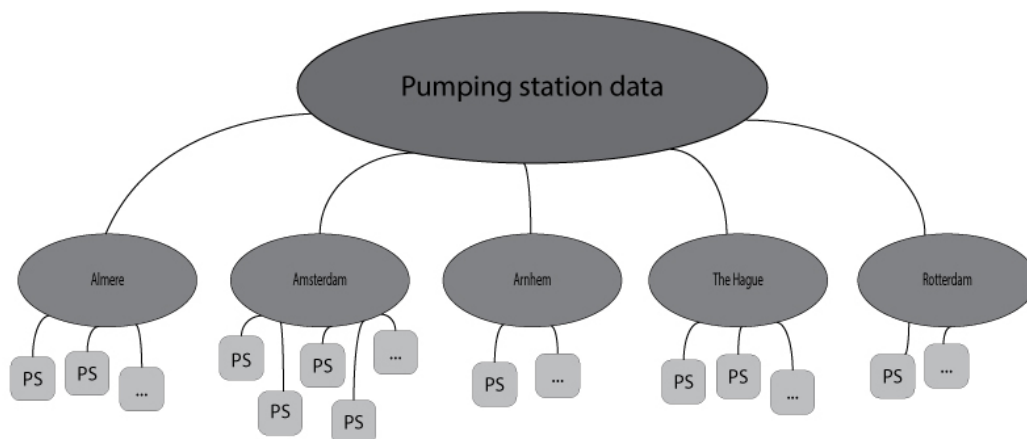


Figure 16 - Set up of the pumping station data. The pumping station data was collected in five different cities, and the observations of each city showed similarities in their characteristics, such as demographic characteristics of the catchment and sewer system pump sump geometry.

Figure 17 illustrates the city-effect in more detail; the conditional boxplots of the total incoming kinetic energy show a larger variation between cities than within cities. For Almere, the median kinetic energy is $1.6 \cdot 10^6 \text{ [Jm}^{-3}\text{d}^{-1}\text{]}$, which is three orders of magnitude higher than for Amsterdam, where the median value is only $2.5 \cdot 10^3 \text{ [Jm}^{-3}\text{d}^{-1}\text{]}$ (non-log-transformed).

In Amsterdam, the construction of most pumping stations is such that they have continuously submerged inlet pipes. This decreases the flow velocity in the inlet pipes considerable and hence, decreases the kinetic energy.

By contrast, in Almere, almost all inlet pipes are located above the representative water level, increasing the total kinetic energy. In addition, the Almere pump sumps are relatively small, which has a positive effect on the kinetic energy per unit of volume and time.

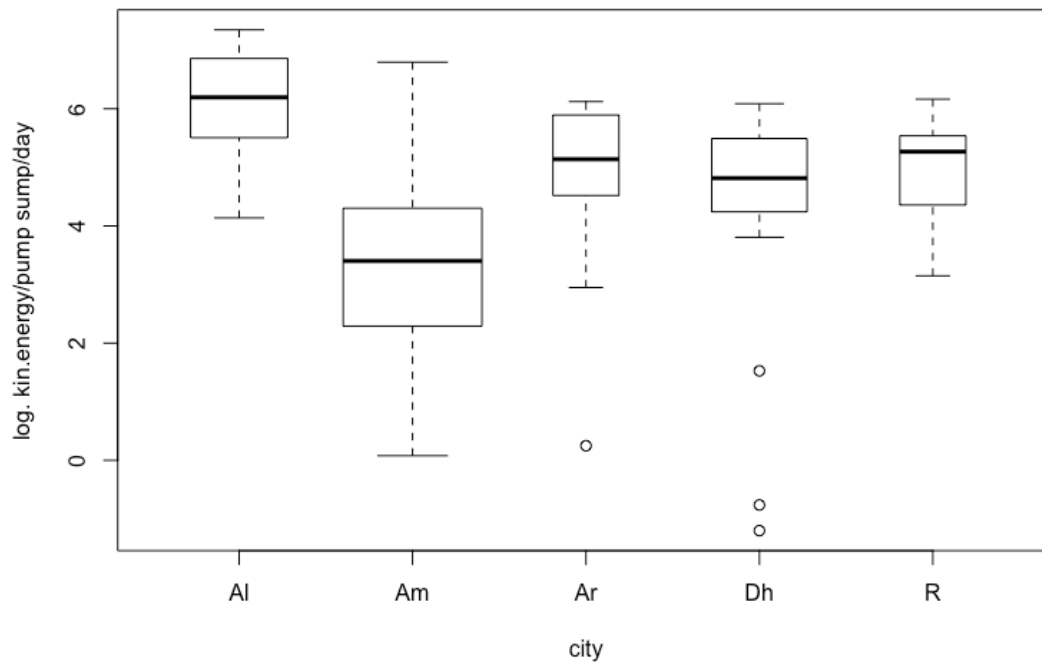


Figure 17 - Boxplots of the total kinetic energy per unit of volume per day (log-transformed with base 10), conditional on city. The width of the boxes is proportional to the number of observations per class. The horizontal line in each box is the median, the boxes define the hinge (25–75% quartile), and the wide dots represent extreme values (outliers).

This example illustrates that the predicted probability of FOG accumulation in a particular pump sump might be seriously affected by the city where the sump is located. It is therefore thought that each city holds its own building design philosophy; the design of more recent pumping stations might be based on designs of previously built pumping stations. In addition, it suggests that pumping stations might be built according to city-specific design requirements.

Knowing the exact nature of the city effect is of less interest, as the scope of this study is limited to the impact of behavioral and general structural conditions of catchments. To resolve non-independence without losing four degrees of freedom by adding city to the fixed effects, a random effect for city was added. This changed the model into a generalized linear mixed model (GLMM). The structure of such a mixed effect model allows the intercept to be *random* over cities and assumes a different reference probability of the accumulation of FOG for each city.

Based on the GLMM with the random component that accounted for the city effect, and the system component containing all variables that remained after removal of the collinear variables, the dataset was studied for the presence of outliers.

Outliers

Observations were considered as outliers when the values of the variables were extreme compared with the majority of the observations, or when the combination of values of explanatory variables was unique in terms of

‘environmental’ conditions (Zuur et al., 2009). If a particular explanatory variable has one or more values that are much larger or smaller than the other observations, these observations could strongly influence the estimates of the regression coefficients (Zuur et al., 2010).

For the response variable, the possibility for outliers was removed, as the variable only described the presence or absence of FOG in the pump sump.

Outliers in the explanatory variables were investigated exploiting Cleveland’s dot plots, and using Cooks Distance statistics (Cook, 1977), of which the theory is briefly described in Appendix E. As a Cooks Distance cut off, the value $\frac{4}{n-k-1}$ with n for the number of observations and k for the number of regression coefficients was set. The threshold value was used to enhance graphical interpretation, up on which the points identified were examined in more detail.

The visualization of the Cooks Distance statistics is presented in Appendix F. The calculated cut off value was 0.0342, and fifteen out of the 128 observations were above the threshold with values up to 0.4453. After further exploration of the marked observations, i.e. by inspecting construction drawings and catchment datasheets, the following two observations were removed:

- The first pumping station was located in The Hague. Its catchment was sparsely populated, the average income was low and the catchment had the highest percentage of houses from housing associations (84%). The combination of values for these explanatory variables was unique, influencing the values for the estimated regression coefficients. In addition, more than 25% of the design DWF of this catchment was attributed to industrial wastewater, while this study focused on domestic wastewater disposal patterns. On the base of these two aspects, the observation was removed from the dataset.
- The other station was located in Amsterdam, in the catchment with the third largest population (69661 inhabitants, which is around 9% of the entire population of Amsterdam). This pumping station showed high values for the vertical velocity in particular. It had two inlet pipes and a VFD pump with a representative DWF pumping capacity of $700 \text{ m}^3\text{h}^{-1}$, which is much higher than the overall average capacity of $176 \text{ m}^3\text{h}^{-1}$. For the calculations of the parameters related to the pumping station geometry, it was assumed that the incoming DWF was equally divided among all inlet pipes, and pressurized pipes that drained wastewater from upstream pumping stations were considered to have the same (hourly) DWF distribution as the gravity sewer inlet pipes. These assumptions were, however, violated for the particular pumping station: there were only two inlet pipes, one of which was a pressurized pipe that transported 72% of all incoming wastewater (Waternet, 2016), which is well above the estimated 50%. The invert level of this pressurized pipe was above the representative water level, while the other inlet pipe was fully submerged. This resulted in a calculated kinetic energy that was 2.8 times lower than the actual kinetic energy, which corresponds to an error percentage of 65%. In addition, the average vertical velocity, which equaled the DWF

pumping capacity divided by the pump sump surface, of this particular pumping is thought to be biased. For VFD pumps, the pumping capacity was considered to be equal to the measured peak DWF (see Section 3.2.3.1 on page 25), while for this pumping station the discharge pattern of the pressurized pipe is thought to mainly determine the actual pumping capacity. Since the assumptions for calculating the parameters were violated due to the deviating conditions, the observation was removed from the dataset.

For the thirteen remaining observations that had Cooks Distance values above the cut off value, no particularities in the pump sump geometry were found that would be largely affected by the assumptions. As the high leverage is thought to result from natural variation in pumping stations, and since the Cooks Distance values were still far below the frequently used cut off level of 1 (Zuur et al., 2009), no further observations were removed from the dataset.

After removal of the two outliers, the variables were checked for collinearity again. The removed outliers did not cause the VIF values and correlation coefficients to rise above the threshold values set.

3.2.5.2 GLMM components selection

Both the GLMM component selection and the model selection, which are represented by the two middle blocks in Figure 15, were based on the protocol for the top-down strategy for linear mixed models as recommended by Diggle et al. (2002) and applied in the book of Zuur et al. (2009). This protocol suggests to start with a model where the fixed component contains all explanatory variables and as many interactions as possible. In the second step the optimal structure of the random component is determined, and the third step focuses on obtaining the optimal fixed structure. First, the GLMM components that compose the model are discussed. More information on the theory of GLMMs can be found in Appendix G.

Conditional probability distribution

Conditional on the random effect b_i that accounted for the city-effect of city i where the pumping station j was located, the presence and absence of severe FOG accumulation Y_{ij} was assumed to be binomial distributed with probability $\pi_{ij}|b_i$. Thus, the presence and absence of severe FOG accumulation in the pumping stations can be described by the conditional probability distribution that is specified by:

$$\begin{aligned} E(Y_{ij}|b_i) &= \pi_{ij}|b_i \\ \text{var}(Y_{ij}|b_i) &= \pi_{ij}|b_i \times (1 - \pi_{ij}|b_i) \end{aligned} \quad (14)$$

Linear predictor

The linear predictor η contains both a fixed component and a random component, and follows the form of the linear regression model:

$$\eta(X_{ij}, Z_{ij}) = \boldsymbol{\beta} \times \mathbf{X} + \mathbf{b} \times \mathbf{Z} \quad (15)$$

where $\beta \times X$ accounts for the fixed effect and $b \times Z$ for the random effect. The fixed component is a linear function of the explanatory variables. β is the matrix containing the weights that are assigned to the explanatory variables, and X is the design matrix of the explanatory variables. The random component extends the linear function of the fixed component with a compound symmetrical correlation structure, adding a random intercept conditional on city to the fixed intercept.

Fixed component

The system component of the linear predictor is given by:

$$\eta_{system}(X_{ij1}, \dots, X_{ijM}) = \beta_0 + \beta_1 \times X_{ij1} + \dots + \beta_M \times X_{ijM} \quad (16)$$

where j is the pumping station in city i and M represents the total number of explanatory variables. β contains the coefficient corresponding to the particular explanatory variable X , and β_0 is the intercept term

Since the fitting algorithms of GLMMs require the explanatory variables to be on comparable scales (Zuur et al., 2009), all continuous explanatory variables were standardized prior to fitting, according to:

$$X_{ij,standardized} = \frac{X_{ij} - \mu_i}{\sigma_i} \quad (17)$$

where X is the explanatory variable, j the pumping station and i the city where the pumping station is located. μ_i is the mean value for the particular explanatory variable, and σ_i represents the corresponding standard deviation.

Random component

The random component that is added to the system component in the linear predictor resolves the violation of independence associated with the city effect; it models the inter-city variation and it allows for correlation between the observations of one city. It assumes the pumping stations in the same city to be equally correlated.

In addition to the city effect, no other nested data structures were revealed from the data exploration. More complex random effects, such as an additional random slope for each city, were not considered, as the number of observations was too low.

Link function

The relationship between the conditional mean and the explanatory variables is determined by the logistic link:

$$\pi_{ij} = \frac{e^{\eta(\beta_i, X_{ij}, b_i, Z_{ij})}}{1 + e^{\eta(\beta_i, X_{ij}, b_i, Z_{ij})}} \quad (18)$$

Model specification

The final model can now be specified as follows:

$$\ln\left(\frac{\pi_{ij}}{1 - \pi_{ij}}\right) = \boldsymbol{\beta} \times \mathbf{X}_{ij} + b_i \quad (19)$$

$$b_i \sim N(0, \sigma^2)$$

where π_{ij} is the probability that FOG accumulates in the pumping station j in city i . $\boldsymbol{\beta}$ is the vector representing the model coefficients, $\mathbf{X}_{ij}$ is the vector containing the explanatory variables for pumping station j , which is located in city i . b_i is the random intercept for city i .

3.2.5.3 GLMM model selection

As the probability distribution and random parts were specified, the model selection focused solely on the optimal structure of the system component.

Model selection process

A stepwise backwards selection approach was applied to find the optimal model. The first model contained all explanatory variables after which the terms were dropped one-by-one, until all terms were significant ($p < 0.05$).

Table 10 gives an overview of the model selection process and also presents the dropping order of the explanatory variables. This was based on the relative quality of models as judged by the Akaike's Information Criterion (AIC), and the significance of the model parameters. More information about this criterion is provided in Appendix E.

The variable that gave the largest drop in AIC if it was excluded from the model, was dropped first. For the final model, the p-values of the estimated regression coefficients should be stable, i.e. they should not change considerably if one of the variables is dropped.

Table 10 - Explanatory variables in the model selection process. The dropping order was based on the significance of regression parameter and the relative quality of the model. The AIC value is the AIC of the model containing all variables with a lower position in the table. If all model regression parameters were significant, this was indicated with a '+' in the last column. The variables indicated in bold were included in the final model.

Variable	Type	Dropping order [-]	AIC value [-]	Significance all model param. ($p < 0.05$)
Household size	continuous	1	133.62	-
Population density	continuous	2	131.89	-
Housing Assoc. properties	continuous	3	130.51	-
Total population	continuous	4	130.07	+
Sewer system type	categorical	5	131.29	-
Vert. flow velocity	continuous	6	132.58	+
FSE density	continuous	-		
Total kin. energy	continuous	-		
Personal income	continuous	-		

During the model selection process, the six variables 'household size', 'population density', 'housing association properties', 'total population', 'sewer system type' and 'vertical flow velocity' were dropped. The final model only contained the three continuous variables 'personal income', 'total kinetic energy', and 'FSE density'.

As shown in Table 10 the model in which the variables 'vertical flow velocity' and 'sewer system type' were still included, had a higher model quality than the final model, as judged by the AIC. In addition, all five estimated regression parameters of the model were significant. The model was, however, rejected as the optimal model, since the random intercept of the model was equal to zero, changing the GLMM structure into the structure of a classical GLM, and thereby suggesting overfitting.

Although such overfitting could not be revealed from the fitted GLM (dispersion coefficient=0.92), the model structure of a GLMM is thought to be more representative. GLMMs implicitly allow for the correlation between pumping stations that are located in the same city; hence, while the dropped variables 'vertical flow velocity' and 'sewer system type' might be able to explain some variety between cities, it is thought that they would not be able to explain all city specific elements.

Additionally, after the variable 'sewer system type' was dropped and the model was fitted again, the regression parameter of the variable 'vertical flow velocity' turned out to be non-significant anymore, supporting the hypothesis that the fitted GLM with five variables might be overfitted and/or unstable.

Final model

The final model only contained the explanatory variables 'personal income', 'total kinetic energy', and 'FSE density'. The glmer function from the lme package (Bates et al., 2014) was used for the Bernoulli GLMM, and the model was fit by the default maximum likelihood with a Laplacian approximation. As the GLMM likelihoods involve high order integrals that do not have closed form solutions, the true

likelihood values are approximated using numerical integration. Hence, to prevent numerical issues the variables were standardized prior to fitting according to Equation (17) on page 39.

Table 11 presents the estimated regression coefficients and model fits for this final GLMM. This model had a deviance, calculated at the sum of residual deviance, of 112.24, and an AIC value of 132.58 (see Table 10). Solely based on the dispersion coefficient, no over- or underdispersion could be detected for the model. This coefficient, calculated as the Pearson residual deviance divided by the residual degrees of freedom in which the mixed effects were calculated to be one degree of freedom, was 0.86, and thus, approximated 1 (Zuur et al., 2009).

Table 11 - Parameter estimates of the GLMM with standardized variables, containing both the random effects and fixed effects. The model estimates the probability of the accumulation of FOG in the pump sump.

Effects	Probability of FOG accumulation in the pump sump	
Fixed effects	Estimate $\pm$ SD	Pr ($> z $)
Intercept (average)	0.394 $\pm$ 0.513	0.4427
Personal Income	-1.652 $\pm$ 0.388	<0.0001
Total kinetic energy	-1.068 $\pm$ 0.468	0.0225
FSE density	1.749 $\pm$ 0.890	0.0493
Random effects	Variance	
City identity	0.820	

The regression parameter estimates were all significant at the 5% level. The variable 'personal income' had the smallest p-value and the parameter estimate was highly significant ($p < 0.0001$). The variable 'total kinetic energy' had a p-value of 0.0225.

The variable 'FSE density' was at the margin of significance with a p-value of 0.0493, using Wald Z-statistics. Comparable results were found when a GLM was fitted as a function of solely the variable 'FSE density', which gave a p-value of 0.0661. As the predictor FSE density was justifiable on theoretical grounds, it was decided to keep the variable in the final model. FOG blockages in sewer pipes frequently occur in the proximity of restaurant and bar areas, and most of the FOG deposits analysed were collected from sewer pipes downstream from FSE areas (He et al., 2011; Shin et al., 2014; Williams et al., 2012).

A larger sample size is required to obtain more information on the significance of this relationship; Schielzeth and Forstmeier (2009) showed that random intercept mixed models could give overconfident estimates, thus reporting significant results, while the relationships are actually caused by chance (type I error).

Given the parameter estimates from the GLMM with standardized variables as presented in Table 11 the model to estimate the probability of the accumulation of FOG in the pump sump model can now be specified as:

$$\ln\left(\frac{\pi_{ij}}{1 - \pi_{ij}}\right) = 0.394 - 1.652 \cdot \text{Income}_{ij} - 1.068 \cdot \text{Energy}_{ij} + 1.749 \cdot \text{FSE}_{ij} + b_i \quad (20)$$

$$b_i \sim N(0, 0.820)$$

where π_{ij} is the probability that FOG accumulates in the pumping station j , which is located in city i . Table 12 shows the random effects b_i and the estimated city-specific intercepts.

Table 12 - City-specific intercepts and the random effects of the final model with standardized variables

City	Random effect	Intercept
Arnhem	-0.841	-0.448
Rotterdam	-0.082	-0.475
Amsterdam	-0.007	0.387
The Hague	0.589	0.983
Almere	1.060	1.454

3.2.5.4 Model validation

Visual tools were used to verify the model assumptions for the final model. Deviance residuals were used for this model validation, as, compared with Pearson residuals, the distribution of deviance residuals is thought to be closer to the residuals from a Gaussian linear regression model, enhancing checking for the presence of patterns (McCullagh and Nelder, 1989).

The deviance residuals were plotted versus the fitted values for the response variable, and versus the explanatory variables in the model and the ones that were dropped during the model selection process. The Cooks Distance statistics were used to check for influential observations once again. No extreme observations could be discovered in this Cooks Distance plot in comparison to the first Cooks Distance plot.

Residual plots versus fitted values

Figure 21 shows the residuals plotted versus the fitted values, both for the entire dataset at once, and conditional on city. Such Bernoulli residual plots do not reveal much information, as the response data is either one or zero, generating two bands in the validation plots (Zuur et al., 2009).

The residual plots of the cities of The Hague, Almere and Amsterdam, show multiple observations with a similar relationship between the residual and the fitted values. Except this notice, no further information on patterns is revealed from these plots.

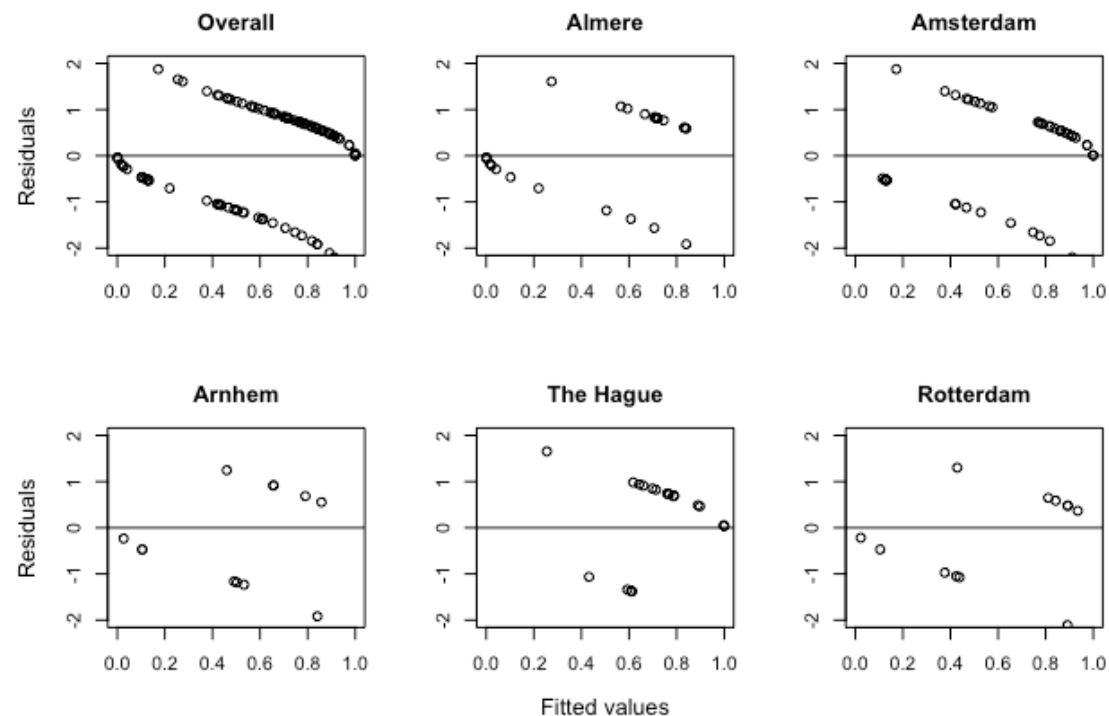


Figure 18 - Deviance residual plots for the fitted values, both for all observations at once and conditional on city. The y-axis shows the residuals, the x-axis the fitted values.

Residual plots versus explanatory variables

One overview was made containing all plots of the deviance residuals against the standardized explanatory variables, both the ones that were included in the model and the ones that were dropped during the model selection process.

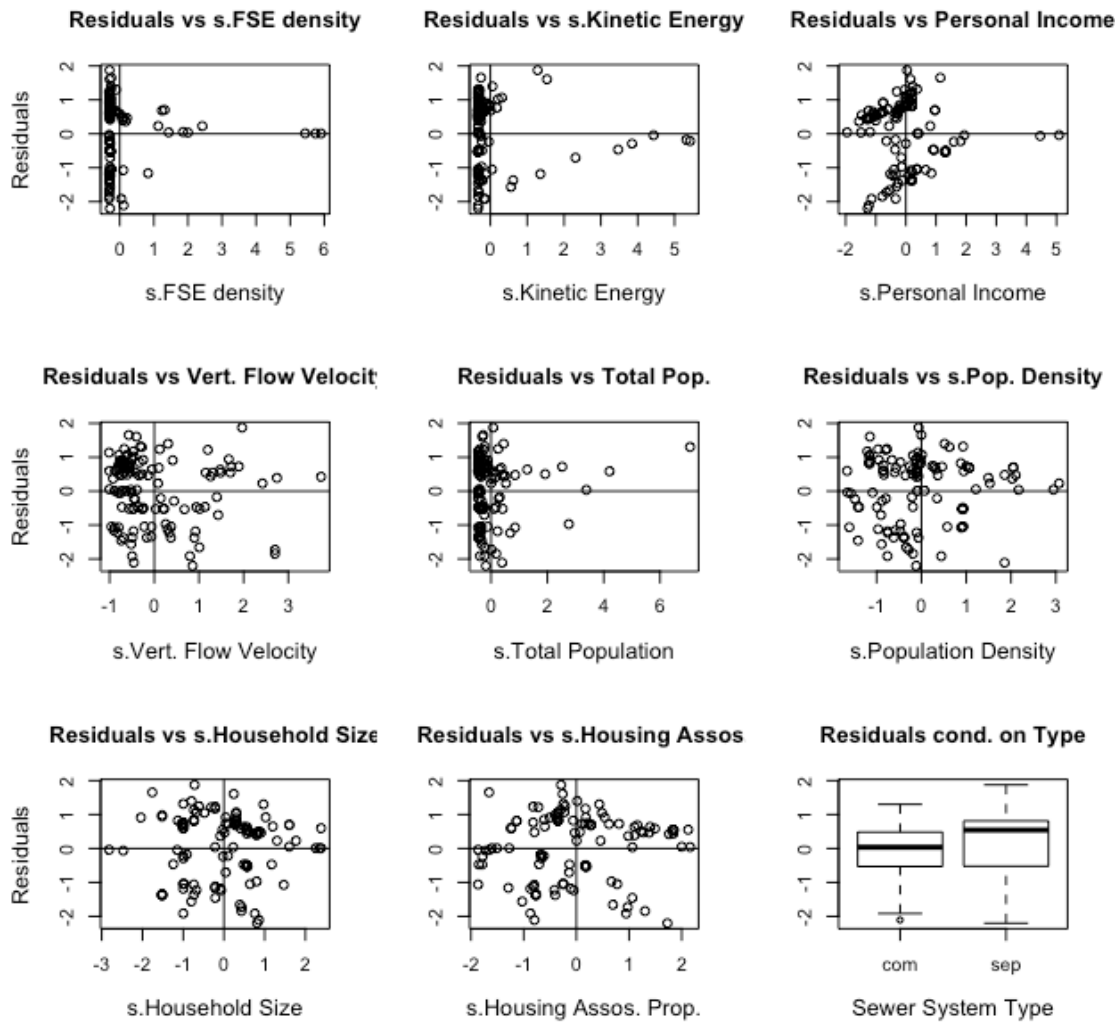


Figure 19 - Residual plots versus the explanatory variables. The y-axes show the residuals, and the values of x-axis the standardized variables. The upper row shows the variables that were included in the final model. The two lower rows show the variables that were dropped during the model selection process. The line $x=0$ represents the mean value of the corresponding explanatory variable, as the variables were standardized prior to fitting

To validate the model, the residual spread should be similar for all values of the explanatory variable, and no patterns should be present. For the binomial GLMM, the deviance residuals r_{ij}^D are defined as such, that for $Y_{ij}=0$, r_{ij}^D is negative, and for $Y_{ij}=1$, r_{ij}^D is positive.

The upper row shows the (standardized) variables that were included in the final model. For these variables, the spread was less for higher values, suggesting violation of the homogeneity assumption. Additionally, in the residual plot for kinetic energy, a pattern is observed; all residuals are negative for higher values of kinetic energy. Such patterns imply that residuals are correlated, thus one residual can be used to predict another residual, suggesting that predictive information might be missing (Zuur et al., 2009).

The small number of observations with higher values could also be the underlying reason for the observed heterogeneity patterns. As there were only a few

observations with higher values for kinetic energy, and as the residuals of such observations were small, it is thought that these observations had been weighty for the final parameter estimates.

Most of the (standardized) variables that were not included in the model did not show such strong patterns. The variables 'vertical flow velocity', 'household size', 'housing association properties', and to a certain extent 'sewer system type' displayed residual spreads that were approximately equal for all values of the variables. The variable 'population density' showed a weak pattern in the residuals; the residual spread was smaller for more dense populated catchments. For the variable 'total population', the spread was also slightly smaller for higher values of the total population. This might, however, also be caused by the fewer observations for larger populations.

In literature, different options for resolving patterns are mentioned, i.e. including dropped variables that show patterns in their residual plots, including quadratic terms or interaction terms, or applying a different model structure, like a generalized additive mixed model (Zuur et al., 2009). The base of such an additive mixed model is a fitted smoothing curve, in which the linear predictor depends linearly on unknown smooth functions of the explanatory variables.

Adding the variables 'population density' and/or 'total population' did not let the patterns disappear. A quadratic term or interaction terms did not improve the situation either. Since additive mixed models use complex solvers and require a large and/or strong dataset, such a model was not fitted to the dataset.

As the patterns could not be resolved, it is concluded that the assumption of independence and constant variance (homogeneity) were violated, implying that the results might be biased. Despite this violation, the reported results provide insights into important aspects of catchment demographics and pumping station characteristics that are related to the accumulation of FOG in pumping station.

4 Results and Discussion

4.1 Building Drainage Systems

This section reports on the composition of the FOG deposits collected from building drainage system, and discusses how such deposits relate to FOG deposits collected from public systems that have been collected in prior studies.

4.1.1 Sample collection

Eleven samples were collected from building drainage systems, four of which originated from kitchen drains and seven of which were collected from lateral house connections. Table 13 provides an overview of the sample site characteristics. The pipes of the kitchen drains were 70 or 75 mm, and the pipes of the lateral house connections were 110 or 125mm in diameter. The pipes collected wastewater from a single household, except for samples 8 and 10; due to particular constructions, these (private) pipes collected wastewater from two up to six households.

Table 13 - Sample site characterises, 'service engineer' indicates by whom the sample was collected. The average time between FOG blockages was based on the last 10 years. K=kitchen drain, L= lateral house connection, MR=mechanic rodding, VC= vacuum cleaner, WJ= water jetting, IO=inspection opening

Sample	Service engineer	Drain type	Diameter size [mm]	Sampling manner	Household size	Av. time between blockages [years]
1	A	K	75	MR + VC	2	3.3
2	A	K	70	MR + VC	5	10
3	A	K	75	MR + VC	2	2.5
4	A	K	75	MR + VC	1	5
5	A	L	110	IO	4	1
6	A	L	110	WJ+IO	3	1
7	A	L	110	WJ+IO	2	NR
8	A	L	125	WJ+IO	NR	NR
9	B	L	110	IO	1	1
10	B	L	125	MR+ IO	NR	NR
11	A	L	110	WJ+IO	NR	NR

For four out of eleven samples, information about cooking and disposal patterns was lacking. Subjects 6 and 11 refused to answer the questions. The samples 8 and 10 were collected from the drains that were connected to multiple households; no questionnaire was conducted in such cases, as the origin of the FOG was unknown.

4.1.1.1 Location of blockages

Since the blockages were not always visible from the IOs, exact blockage locations often remained unknown. Since the blockages were always located between kitchen sinks and IOs, they were in any case maximum thirty meters downstream from disposal locations.

The FOG blockages in this study were located closer to disposal locations than the FOG deposits described in previous reports. Keener et al., (2008) reported that FOG deposits were thought to form between 50 and 200 m downstream from foodservice establishments. This difference might be the result of the intermittent flow conditions in building drainage systems, as there are only pulses of water in building drainage systems (Walski et al., 2011). In between such pulses, deposits may settle (Staufer, 2011); hence, low flow velocity conditions might reduce the ability to wash out and transport accumulated FOG further downstream (Dominic et al., 2013).

4.1.1.2 Blockage frequencies

The average time between blockages that was revealed from this study was around five years for lateral house connections, and around one year for kitchen drains, as can be revealed from the information in Table 13.

The occurrence frequencies reported in previous studies were in the same order of magnitude. Keener, et al. (2008), for instance, reported an occurrence frequency of FOG blockages from 30 days up to 2 years. Based on the study of Post et al. (2016b), who performed a statistical analysis of failure mechanisms in lateral house connections and who used a database of the same sewer cleaning company, the occurrence frequency of FOG blockages in the particular case study is derived. The households in the case study had a FOG blockage approximately once every 7.5 years (Post, 2016b). For the lateral house connections in this dataset, the calculated average blockage rate was higher, and it is thought that the non-random sampling method that was used for this study contributed to the differences. The failure rates reported in this study were not normalized with respect to the total number of households; e.g., the building drainage systems in this study might have been more susceptible to clogging. This is consistent with the observations of the service engineers, as they mentioned explicitly the poor structural conditions for four households.

4.1.2 Sample properties

4.1.2.1 Visual characteristics

Figure 20 displays two FOG deposit samples. The appearance of the FOG deposit suspensions released from kitchen drains was very different to the appearance of FOG deposits collected from lateral house connections. As a consequence of the cleaning and sampling method, the samples from kitchen drains contained, in addition to clogging material, (dark) kitchen wastewater that could not pass the blockage. The samples were filtered prior to analyses. It is hypothesized that the flexible rotating cable had cut the larger deposits into smaller pieces, as most of the FOG particles were around 5-40 mm in diameter while the drains were 70 or 75mm in diameter. Additionally, fine sediment-like deposits were observed in the samples.

The samples from lateral house connections were directly collected via the IO; these samples did therefore not contain wastewater. The samples collected from lateral house connections were round or bar-shaped, and had a length up to 200 mm.

The deposits, both from kitchen drains and lateral house connections, had an overall white to grey colour. The deposits from lateral house connections predominantly had a soft, waxy consistency and fell apart when applying pressure. Samples 6 and 10 had slightly harder textures, despite their soft appearances, while samples 5 and 11 had more paste-like textures. The samples collected from the kitchen drains were harder and had more chalk-like, grainy, appearances.



Figure 20 - FOG deposit samples collected from kitchen drains (left) and lateral house connections (right), showing their appearance, shape and color.

Comparison of FOG deposits from the lateral house connections with deposits from main sewer areas, suggested that FOG deposits collected from public sewers had more variable appearances than deposits from lateral house connections. The appearance of deposits reported in a UK-study resembled the lateral house connection deposits (Williams et al., 2012), while samples collected in a study in the US appeared to be more grainy, with sand-stone like textures (Keener et al., 2008). This might be explained by different environmental conditions, as a study on the influencing factors for FOG formation mechanisms showed that, e.g., different calcium sources resulted in different FOG deposit appearances. They suggested that this could be attributed to the solubility of the calcium sources under the particular conditions (Iasmin et al., 2014).

4.1.2.2 Physical characteristics

An overview of characteristics of FOG deposits is shown in Table 14. The bulk density of the deposits both collected from kitchen drains and collected from lateral house connections was around 1.0 g/cm³. The FOG deposits showed a wide range in moisture content, with higher moisture content for kitchen drains (75-90%), compared with lateral house connections (54-81%). The relatively high moisture content for kitchen drain samples might be attributable to the manner of sampling, as these samples also contained wastewater that could not pass the blockage.

Previous studies that analysed FOG deposits collected from public sewer systems reported a wider range in moisture content compared with the lateral house connection deposits. In the US, values were reported between 6 and 86%; they suggested that moisture content was not a significant factor in the formation

process (Keener et al., 2008). A later study, which was conducted in the UK, reported values between 15 and 95%. They found significant differences in moisture content between different network locations (pumping stations, sewers and sewage treatment works), and suggested these may reflect the different sewer environments and the maturation of FOG in the network. They also reported a significant difference in the proportion of oil in solids for the different network locations. The writer of this report noticed an inverse relationship between the proportion extractable oils and the moisture content in these studies. It is suggested that this might be related to the amphipathic nature of free fatty acid (FFA) micelles, possibly affected by FOG disposal patterns. Such a relationship, however, was not found for the deposits collected for this study.

Table 14 - Characteristics of FOG deposits. Total fat content is measured as the mass percentage of extractable oil and fat in solids. NR=not reported.

Sample	Drain type	Bulk density [g/cm ³]	Moisture content [%]	Total fat content [%]	Calcium content [mg/kg DW]
1	K	NR	75.0	NR	149,000
2	K	1.1	82.1	15.0	32,400
3	K	1.0	84.6	22.0	54,200
4	K	1.0	90.2	9.2	27,400
5	L	1.0	54.4	110.0	9,400
6	L	1.0	52.5	88.0	1,500
7	L	0.99	77.1	66.0	37,000
8	L	1.0	60.4	56.0	17,800
9	L	NR	59.4	32.0	35,600
10	L	0.97	74.8	99.0	11,800
11	L	0.96	80.8	57.0	11,000

4.1.3 Total fat content

Table 14 also shows the total fat content of the samples. For the kitchen drain samples, the extractable oil and fat content ranged from 9 to 22%. For sample 1, no value was reported. Fat content of the lateral house connection samples ranged from 32 to 110%. Previous studies that analysed FOG deposits from main sewers found comparable results (He et al., 2011; Keener et al., 2008; Shin et al., 2014; Williams et al., 2012). Values greater than 100% resulted from the analyses method used. As the fat content equals the proportion of fat in solids, the total accuracy was affected by both the moisture content analysis and the extractable oil analysis. Because different subsamples were used for both analyses, spatial variability may account for the fat content values over 100%. For sample 11, the total fat content measured was higher than the FFA identified; this could also be the result of spatial variability.

The deposits from households 5, 6, and 10 showed the highest total fat content, which might be related to a large amount of FOG disposed, since these samples were collected from houses where most people were living (sample 5 and 6), or

from laterals that collected wastewater from 6 households (sample 10). However, no such conclusions can be drawn based on a sample size of eleven samples. Regarding the physical characteristics of FOG deposits, no relationship could be found between total fat and moisture content, nor could a link be found between total fat and the appearance of deposits.

4.1.4 Calcium content

Calcium content of FOG deposits collected from kitchen drains and lateral house connections ranged from 2.74 to 14.9% and from 0.15 to 3.70%, respectively (Table 14). The higher calcium content of the kitchen drain deposits was consistent with their more chalk-like appearance.

The calcium content of sample 1 (14.9%) was an order of magnitude higher compared with the other samples from kitchen drains. In addition, the total fat content of this sample was not reported and the sum of fatty acids recovered was minor (<2%); hence, based on the composition solely, one may suggest that sample 1 did not contain many FOG deposits and might be misidentified as FOG blockage.

Sample 6 had the lowest calcium content (0.15%) of all lateral house connection samples. Williams et al. (2012) found a correlation between drinking water hardness and calcium levels in FOG deposits. Since all samples were collected in the same drinking water district, however, softer water supplies could not account for the low calcium content. Additionally, it was thought that system characteristics, i.e., downspouts that are connected to building drainage systems, were comparable, since all households were located in catchments with combined sewer systems. The particular situations at the sampling sites were, however, not studied; residents might have disconnected their downspouts or blockages could have been located upstream from downspout connections.

Figure 21 on page 53 shows that the calcium levels in lateral house connection deposits were relatively high in comparison to the values measured in previous studies (He et al., 2011; Keener et al., 2008). It was not expected to measure high calcium levels in the deposits collected from the PVC, PE and cast iron lateral house connections, since several studies suggested concrete corrosion, possibly microbiologically induced, as an important calcium source for FOG deposits (Dominic et al., 2013; He et al., 2013; Iasmin et al., 2016, 2014). The results of this study suggest that concrete is not essential for the FOG deposit formation process in sewer systems. This is in line with the results of a Malaysian study that analyzed FOG deposits collected from vitrified clay pipes (Husain et al., 2014). The study, however, reported lower calcium values. Since building drainage systems do not contain concrete pipes, it is thought that solely background levels of calcium in drinking water and calcium released from food, i.e., dairy products, were accountable for the calcium present in FOG deposits.

Except for sample 6, the calcium levels in lateral house connection deposits were relatively high compared with deposits that were collected from public sanitary sewers in previous studies (He et al., 2011; Keener et al., 2008). Although He et al (2011) collected three samples from sanitary sewers that showed comparable calcium levels (0.09, 1.24 and 5.14%), another study reported a mean calcium concentration of 4255 mg/L based on 27 samples (Keener et al., 2008). The latter

study expressed calcium content in different units, since a different method for metal analysis was conducted. Nevertheless, as the particle density of the FOG deposit was around 1 (g/cm³), it is assumed that the calcium concentration in mg/L was comparable to the calcium content in mg/kg dry weight (Keener et al., 2008).

A probable explanation for the relatively high calcium levels might be the use of different methods of analysis. Compared with the US studies, this study used a method in which the spectrometer recorded at slightly different wavelengths (EPA, 1994; NEN, 2005).

Another explanation might be the different environmental conditions. It is hypothesized that structural conditions, the per capita water use, and the composition of both drinking water and wastewater differ per country, which could influence the composition of FOG deposits. Kitchen sink food waste disposers (FWDs), for instance, are widespread throughout the US, while their domestic usage is less usual in Europe. Such FWDs are thought to be an important source of calcium and FOG for the deposits (Mattsson et al., 2014a). Furthermore, the chlorine present in US drinking water, e.g., could affect the FOG formation process by decreasing the biological activity in sewer pipes (van der Wende et al., 1989).

Williams et al. (2012) found a positive relation between drinking water hardness and calcium levels in FOG deposits. Water hardness levels in Rotterdam and its surrounding area are around 150 mg/L CaCO₃ (Evides, 2016), which is generally considered as moderately hard (WHO, 2011). This is twice as high compared with the soft water levels (<60 mg/L CaCO₃) in the Southeastern part of the US, where most of the samples for the US studies were collected (Johnson, 2016; Orr, 2013). Williams et al. (2012) collected samples from combined sewer systems in the UK and measured calcium levels that were comparable to the calcium levels measured in this study. Solely based on water hardness levels, however, one would expect higher calcium levels in the UK study, since hardness levels are in the class of hard to very hard in the UK with values ranging from 140 to 300 mg/L CaCO₃, (DWI, 2009). A possible explanation for this observation might be the presence of rainwater in the combined sewers. Calcium concentrations in rain water are two orders of magnitude lower compared with drinking water (Junge and Werby, 1958) and might have decreased the background levels of calcium in wastewater. Additionally, storm water flow patterns could have affected the formation process of FOG deposits.

Another explanation might be related to the solubility of different calcium sources (Iasmin et al., 2014). This previous study performed lab experiments and showed that calcium chloride produced soft gel-like deposits, while calcium sulfate, which is a product of concrete corrosion, resulted in harder, granular deposits. In addition, calcium chloride based FOG deposits had higher calcium levels than calcium sulfate based FOG deposits. Hence, this suggests that the calcium source could be related to formation mechanisms and might account for both the higher calcium levels and the softer appearance of lateral house connection deposits.

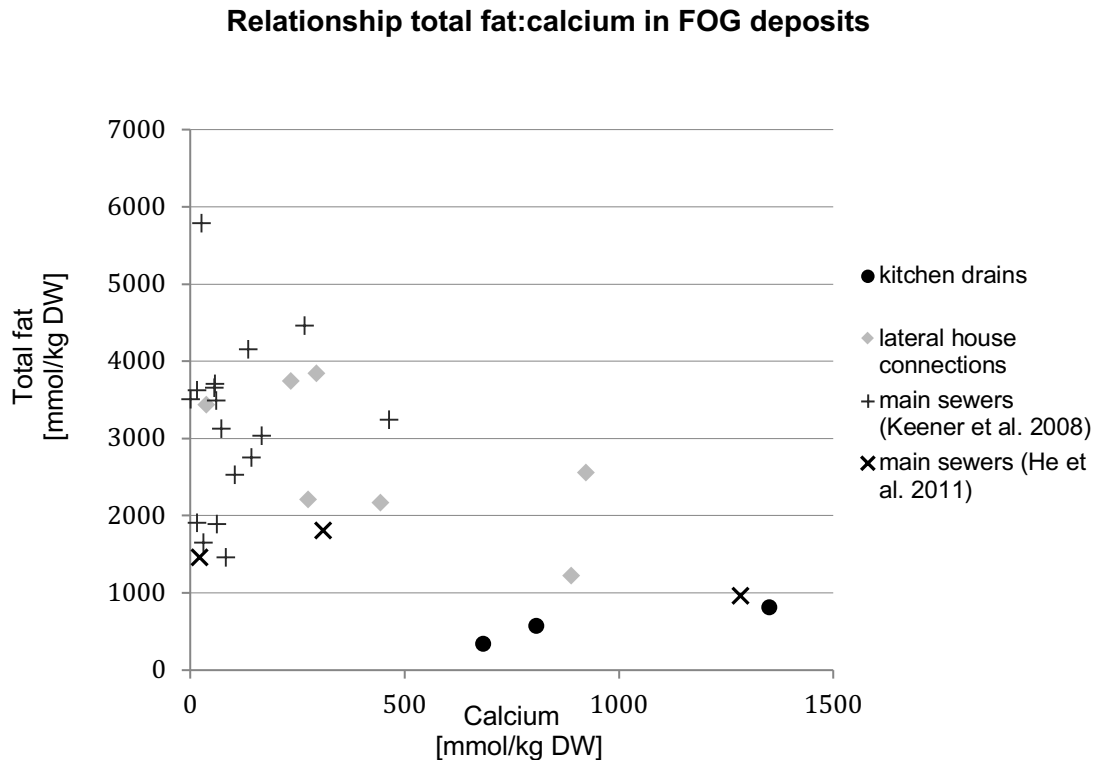


Figure 21 - Relationship between total fat and calcium content (in molecular weight, with the weighted average molecular weight of fatty acids in FOG). Deposits from this study (both kitchen drain and lateral house connection deposits) and separated public sewer deposits from previous studies (He et al., 2011; Keener et al., 2008) are displayed.

4.1.5 Total fat to calcium ratio

Figure 21 displays the relationship between the total fat content and calcium levels of FOG deposits. Total fat to calcium ratios were higher in deposits collected from lateral house connections than deposits collected from kitchen drains. According to the reaction stoichiometry of saponification, the molar ratio in calcium soaps should be 2:1 between FFAs and calcium. The kitchen drain deposits had lower values and the lateral house connections had higher values, except for sample 9 that had a total fat to calcium ratio of 0.59 (with 40.08 g per mol calcium and 260.50 as the weighted molecular weight of fatty acids in FOG).

The low total fat to calcium ratios and the large fraction of the deposits that remained unidentified for the kitchen drain deposits, suggests that other debris also accumulated in the deposits. The observation of fine deposits in the samples supported this hypothesis, and although their total fat content was low (see Table 14), the presence of FOG may enhance (further) accumulation of debris due to the surface charge and adhesive character of FOG deposits (He et al., 2013).

Figure 21 shows that for lateral house connections, the total fat to calcium ratios were of the same order of magnitude as main sewer deposits from sanitary sewers (He et al., 2011; Keener et al., 2008). Since the total fat to calcium ratio did not equal the stoichiometric ratio, it is suggested that the FOG deposits also contained excess calcium, fatty acids and/or debris. Due to compression of the electrical double layer (DLVO theory), counter-charged particles, respectively positive calcium ions or the slightly negative carboxylic chains of FFAs, were drawn within

the FOG deposit matrix (He et al., 2011, 2013), of which the process is also explained in Figure 7 on page 11. It is thought that the wide variety in fat and calcium levels might be the result of different reaction conditions, and so, differences in, among other things, the corresponding disposal patterns. The questionnaire, however, did not provide quantitative information on disposal patterns to support this hypothesis.

4.1.6 Fatty acid profiles

The FOG deposits were made up of predominantly long chain fatty acids (LCFAs). On average, over 96% of the fatty acids that were identified had an aliphatic chain ranging from fourteen up to eighteen carbon atoms.

4.1.6.1 Recovery rates

The recovery rates of fatty acid profiles for the kitchen drain samples ranged from 47 to 93% (Table 15). The recovery rate appeared not to be related to the total fat content. For sample 1, the total fat content was not reported and the identified fat content of this sample made up only 2% of total solids.

For the samples collected from lateral house connections, the recovery rates were between 42 and 121%. For sample 11, the total FFA content was higher than the total fat content reported. Similar to the total fat content of sample 5 that was greater than 100%, the high recovery is thought to result from the methods of analyses and spatial variability.

Table 15 - The FFA recovery of FOG deposits. Total fat content is measured as the percentage of extractable oil and fat in solids. NR=not reported. The samples 1 to 4 were collected from kitchen drains, and the samples 5 to 11 were collected from lateral house connections. * For sample 5, of which the total fat content measured was 110%, the fatty acid recovery was based on a total fat content of 100%. ** For sample 11, of which the FFA identified was greater than the total fat content measured, the fatty acid recovery was assumed to be 100%.

Sample	Total fat in solids [g/g]	FFA identified in solids [g/g]	FFA recovery [%]
1	NR	0.02	NR
2	0.15	0.07	47
3	0.22	0.13	61
4	0.09	0.09	93
5	1.10	0.81	81*
6	0.88	0.58	66
7	0.66	0.52	79
8	0.56	0.36	64
9	0.32	0.14	42
10	0.99	0.48	49
11	0.52	0.69	100**

Overall, the recovery rates of this study were lower compared with previous studies that analysed FOG deposits from sewer pipes, which reported average recovery rates of around 90% (He et al., 2011; Keener et al., 2008). Different methods of analysis might account for the differences, and the methods used for

this study might not have been able to detect particular forms of fatty acids. Keener et al. (2008) hypothesized that the unidentified fat in their study were epoxy, oxidized or polymerized FFAs to which the analysis method was not sensitive.

4.1.6.2 Fatty acid composition

For all FOG deposits, palmitic acid (C16:0) was the most common saturated acid, and oleic acid (C18:1) and linoleic acid (C18:2) were the most abundant monounsaturated and polyunsaturated acids (Table 16).

Table 16 - Fatty acid characteristics of FOG deposits. Fatty acids are shown as their proportions of the total fat. The samples 1 to 4 were collected from kitchen drains, and the samples 5 to 11 were collected from lateral house connections. * For sample 5, of which the total fat content measured was 110%, the fatty acid content was based on a total fat content of 100%. ** For sample 11, of which the FFA identified was greater than the total fat content measured, the fatty acid content was based on the fatty acid content.

Sample	Saturated fat		Monounsaturated fat		Polyunsaturated fat	
	Content [%]	Primary	Content [%]	Primary	Content [%]	Primary
1	NR	Palmitic	NR	Oleic	NR	Linoleic
2	38	Palmitic	4	Oleic	5	Linoleic
3	17	Palmitic	28	Oleic	17	Linoleic
4	44	Palmitic	37	Oleic	14	Linoleic
5	50*	Palmitic	10*	Oleic	21*	Linoleic
6	64	Palmitic	1	Oleic	1	Linoleic
7	78	Palmitic	1	Oleic	1	Linoleic
8	64	Palmitic	0	Oleic	0	Linoleic
9	42	Palmitic	1	Oleic	0	Linoleic
10	47	Palmitic	1	Oleic	1	Linoleic
11	97**	Palmitic	0**	Oleic	0**	Linoleic

Figure 22 shows the fatty acid profiles of all samples, except for sample 1; the identified fat content of this sample made up only 2% of total solids and the total fat content was not reported. For sample 1, palmitic acid was the most abundant fatty acid type, followed by linoleic acid, with respectively 48 and 30% of the total identified FFAs.

The other samples from kitchen drains showed a wide variety in their fatty acid profile. Sample 2 predominantly contained saturated fat, while the samples 3 and 4 had a higher unsaturated fat content. Myristic acid (C14) was low for all kitchen drain samples.

For the lateral house connection samples, palmitic acid predominated, as their proportion of total fat ranged from 32 to 67%. The unsaturated acids identified made up less than 3%, except for sample 5 that had an unsaturated acid content of 31% (see Table 16 on page 55). The proportion of myristic acid ranged from 3 to 14%. The samples 6, 8 and 10 had a relatively high myristic acid content (>8%) and also displayed other physical properties; they appeared to be more solid and

were harder compared with other lateral house connection samples. Sample 11, of which the myristic acid content was highest (14%), however, did not display such characteristics. Although this sample contained hard particles, it had a less solid appearance. This could also be related to the high moisture content of this sample (81%).

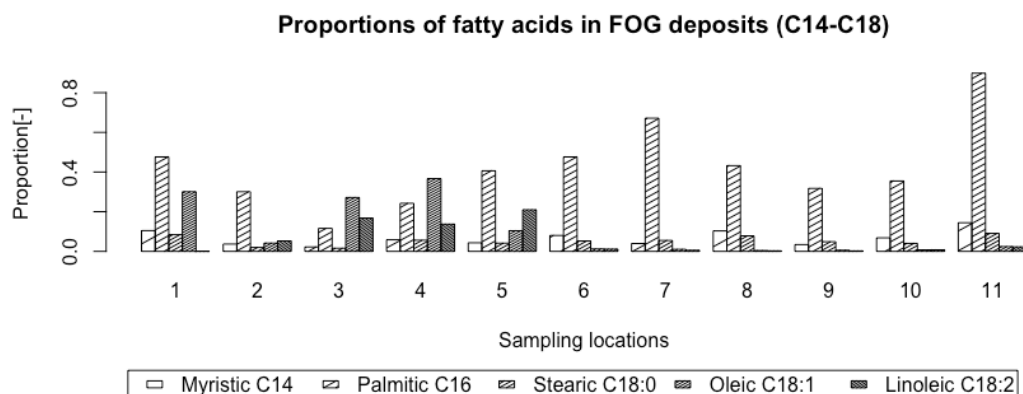


Figure 22 - Proportions of fatty acids in the FOG deposits for myristic, palmitic, stearic, oleic and linoleic acid. Values are reported as their proportions of total fat. The samples 2, 3 and 4 were collected from kitchen drains, and the samples 5 to 11 were collected from lateral house connections.

The higher unsaturated fat content in kitchen drain deposits support the hypothesis that debris accumulated in the kitchen drains, since it was shown that calcium soaps with unsaturated fatty acid profiles had a more adhesive character (He et al., 2013).

Compared with the deposits released both from kitchen drains and from public sewers, the lateral house connections were low in unsaturated fat: previous studies reported average values of unsaturated fat content of more than 20% (He et al., 2011; Keener et al., 2008; Williams et al., 2012), while for the lateral house connections the values were around 2%, except for sample 5.

4.1.6.3 Relationship between palmitic and oleic acid

In Figure 23 the two most common acids (palmitic and oleic acid) are plotted as their proportions of total fat. This plot suggests an inverse relationship between the two acids; i.e., if the oleic acid content is high, the palmitic acid content is low. In addition, this plot demonstrates the relatively low oleic content in lateral house connection deposits.

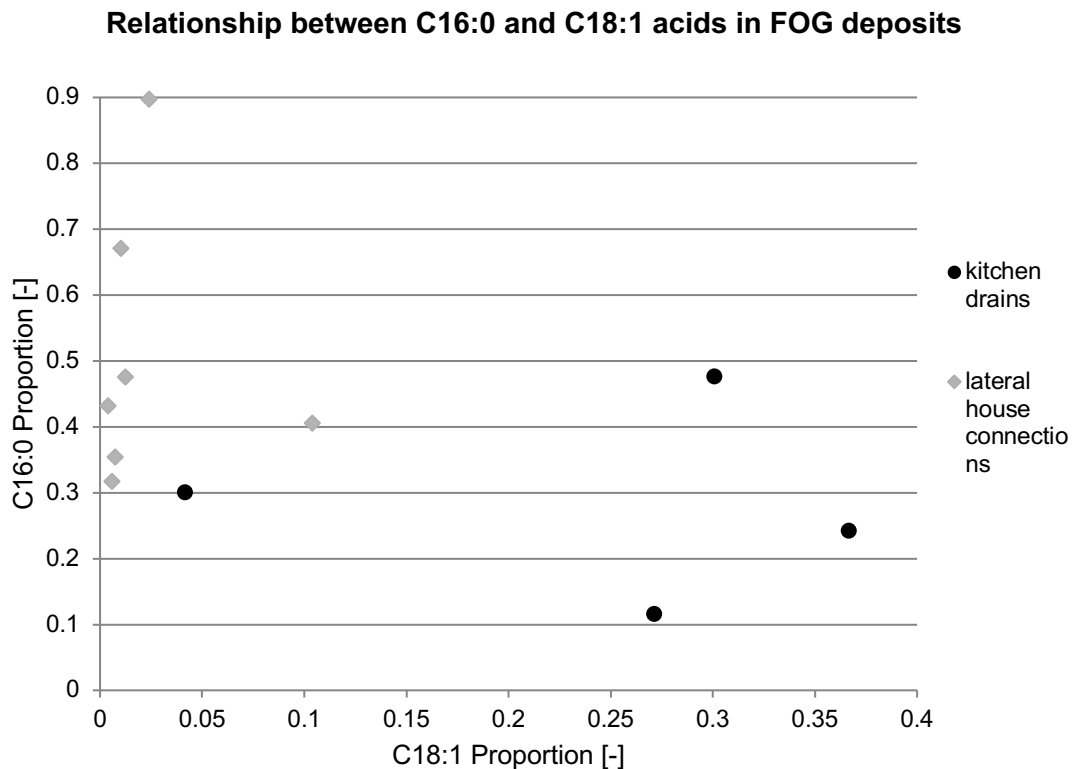


Figure 23 - Relationship between palmitic and oleic acid proportions for both kitchen drains and lateral house connections. Values are reported as their proportions of total fat.

The suggested inverse relationship is consistent with the results from Williams et al. (2012). They observed significantly different proportions of palmitic to oleic acid for different network locations too, and suggested this might be related to ageing, and hence in-sewer transformations from oleic into palmitic acid, or to formation mechanisms. They, however, reported a wider range in their proportions and measured overall higher oleic levels.

Keener et al. (2008) suggested that beta-oxidation caused by microorganisms might account for the in-sewer transformations. This is supported by several studies on anaerobic (treatment) processes that showed that during the treatment of oleic and linoleic wastewater, precipitates of calcium and palmitic acid were formed (Dereli, 2015; Matsui et al., 2005; Pereira et al., 2001). Palmitic and myristic (C14) acids were the most important intermediate LCFAs during the oleic acid and linoleic acid degradation (Lalman and Bagley, 2000). In the deposits collected for this study, myristic acid was also present. Since common cooking oils hardly contain myristic acid (Table 3 on page 12), it is thought that ageing and in-sewer transformations occur in building drainage systems. However, as the

average occurrence frequency of only the households 5, 6 and 9 is known ($\pm 1/\text{year}$) and since it is unknown if all deposits were removed during previous clearing activities, the particular process of ageing in building drainage systems remains unknown.

In addition to beta-oxidation, previous studies have suggested other situations that could have lead to the accumulation of palmitic acid in FOG deposits: Iasmin et al. (2014) proposed that the saturated fractions in FOG deposits could increase due to the solidification and accumulation of saturated fat within the FOG deposit matrix. He et al. (2011) suggested the DLVO theory (compression of the electrical double layer), since this might attract saturated FFAs. It is thought that one of these situations, or a combination of them, accounted for the accumulation of palmitic acid in the FOG deposits.

4.1.7 Cooking oils used

For the households 2, 3, 4, 5, 6 and 9, the fatty acid composition of the cooking oils and fats used in the households were compared with the fatty acid composition of the samples collected at these building drainage systems. Table 17 shows the cooking oils used by the households.

Table 17 - Cooking oils and fats used by the households. Only the households that provided information on their FOG disposal patterns are shown.

Household	Cooking oils and fats used
2	Sunflower oil
3	Olive oil, Fluid baking fat
4	Butter, Margarine
5	Sunflower oil, margarine
6	Olive oil
9	Olive oil, fluid baking fat

Figure 24 shows the fatty acid profiles of the FOG deposits and profiles of the cooking oils used, from the households of which information about their FOG disposal was known. The values for the cooking oils were derived from the questionnaires and the typical composition of the particular cooking oils (Table 3 on page 12).

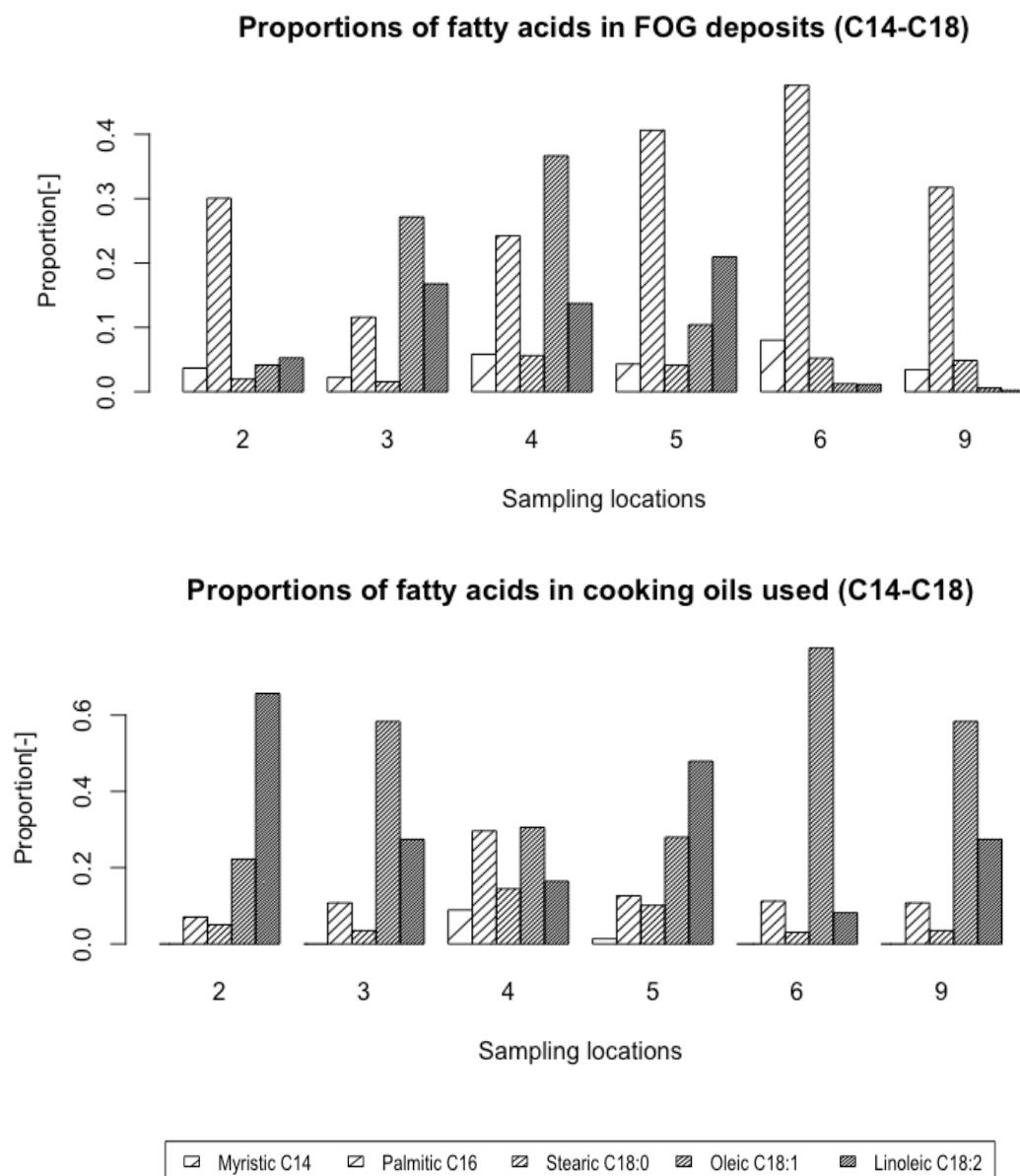


Figure 24 - Fatty acid profiles of FOG deposits and cooking oils used, reported as their proportions of total fat. Only the information for the household that provided information on their FOG disposal patterns are shown. The samples 2, 3 and 4 were collected from kitchen drains, and the samples 5, 6 and 9 were collected from lateral house connections.

Compared with the cooking oils used, all deposits had fatty acid profiles with higher saturated fat content and shorter aliphatic chains. In particular, the samples 2, 6, 7, 8, 9 and 10 showed high levels of palmitic acid. For these samples, no link between fatty acid profiles of FOG deposits and disposal patterns could be identified.

For the samples 3, 4 and 5, a link was observed between the fatty acid profiles of the deposits and the cooking oils. For all samples, the palmitic acid content was higher compared with their content in cooking oils, nevertheless the levels of oleic

and linoleic acid remained substantial. For samples 4 and 5, the ratios oleic to linoleic in the deposits also remained of the same sign; i.e., if the linoleic content was greater than the oleic content in the cooking oils, this was also the case for the samples.

Comparing the fatty acid profiles of the deposits from this study with the profiles from public sewer deposits, the most common acid was also palmitic (He et al., 2011; Keener et al., 2008; Williams et al., 2012). Previous studies showed, however, that calcium soaps produced under laboratory conditions had the same FFA profiles as their fat sources (He et al., 2011; Iasmin et al., 2016). Since cooking oils predominantly contain unsaturated fatty acids (Table 3, page 12) the full-scale FOG deposits did not reflect the composition of commonly used fats. In addition, Iasmin et al. (2014) demonstrated that, although saturated fatty acids were dominant in the FOG deposits, unsaturated fats tended to be more active in the saponified solid formation process. Based on these findings, one would expect higher unsaturated fat content in the deposits.

It should be mentioned, however, that only fatty acid profiles of cooking oils were taken into account for this study, thus assuming that disposed cooking oils are the sole source of the fatty acids observed in wastewater. According to the Dutch National Food Consumption Survey, however, only 26% of the total 88 grams fat per day originates from fat, oil and savoury sauces, while, for example, 18% originates from dairy products and 18.5% from meat products (Voedingscentrum, 1998). Animal fats contain significantly more saturated fat (Table 3, page 12), and hence, frequent spilling of e.g. rendered fat, could have significantly affected the fatty acid profiles of FOG deposits. Nevertheless, the saturated fat content measured for FOG deposits was still much higher compared with the typical values of animal fats and dairy products.

The transformation of the fatty acid composition due to cooking processes could also have contributed to higher saturated fat content. Williams et al. (2012), however, showed that for beef tallow and vegetable oil, the increase in saturated fats was minor, suggesting that this could not have solely accounted for the high saturated fat content of the lateral house connection deposits.

For the kitchen drain deposits the unsaturated acid contents were higher; different formation mechanism might have caused these higher values. Based on the findings of Iasmin et al. (2014), who performed a study on deposits formed under laboratory conditions, it is suggested that these deposits were the product of calcium, and FFAs, that had undergone fast alkali-driven hydrolysis, e.g. due to contact with moisture during cooking processes and/or with high alkaline detergents in dishwashers for instance. This may have resulted in calcium based fatty-acid soaps with comparable fatty acid profiles to their fat source.

4.1.8 FTIR spectrometry

In this study, FTIR spectrometry was used to compare spectra of FOG deposits collected from building drainage systems to deposits collected from main sewers (He et al., 2011; Shin et al., 2014), deposits formed under laboratory conditions (He et al., 2011, 2013, Iasmin et al., 2016, 2014) and pure fatty acid profiles (He et al., 2011). These comparisons enabled to study (the stage of) saponification of deposits in building drainage systems and revealed information on probable formation processes.

The absorption bands reported represent the mean bands obtained from triplicate samples. Individual bands of one sample were comparable and differences in absorbance intensities measured might be the result of spatial variation in the FOG deposits.

No FTIR analysis was performed on sample 2, since there was no sample material left after the chemical and physical were performed. The spectra of samples 7 and 9 showed negative absorption values. For these samples, it is thought that the crystal might not have been properly cleaned when the background spectra were collected. Despite their negative absorption values, relative absorption intensities displayed distinctive absorption bands and their wavenumbers were comparable to those of other lateral house connections; their values were therefore reported in this study.

Figure 25 and Figure 26 show the spectra of sample 4 and sample 11.

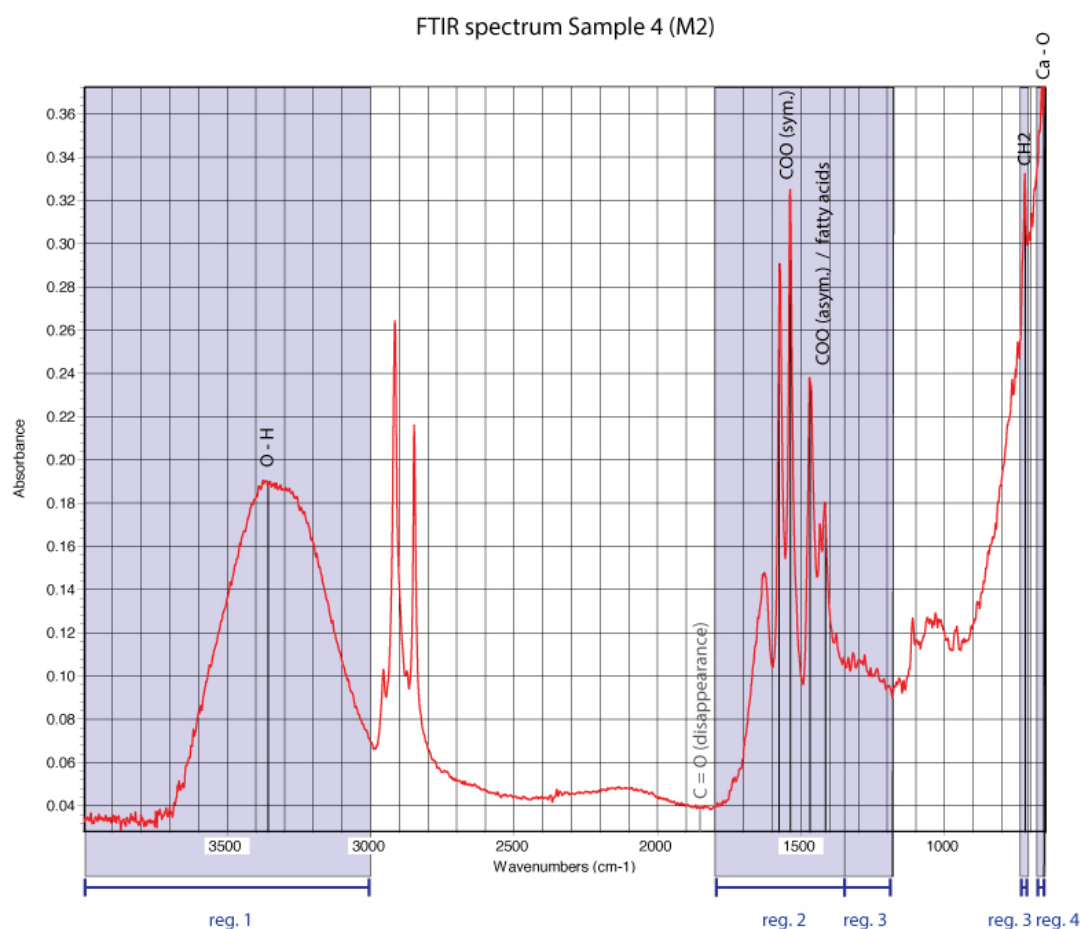


Figure 25 - FTIR spectrum of sample 4, measurement 2, collected from a kitchen drain. The blue boxes indicate the characteristic soap regions and the black lines the characteristic functional group, bond or the assignment.

FTIR spectrum Sample 11 (M3)

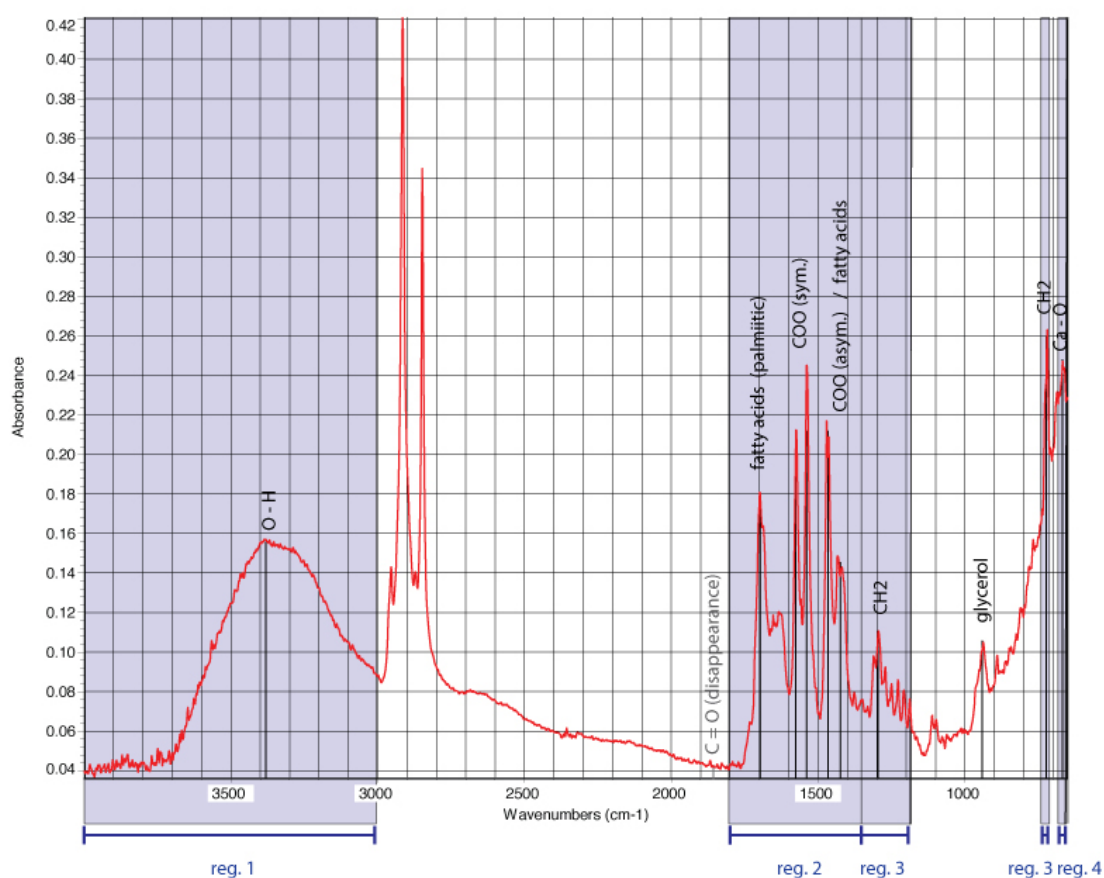


Figure 26 - FTIR spectrum of sample 11, measurement 3, collected from a lateral house connection. The blue boxes indicate the characteristic soap regions and the black lines the characteristic functional group, bond or the assignment.

The four infrared spectral band regions that are attributed to the formation of calcium soaps (Poulenat et al., 2003) are explained in more detail in Table 1 on page 8.

4.1.8.1 Region 1: 4000-3000 cm^{-1}

The broad absorption band around 3400 cm^{-1} that is attributable to the presence of different types of hydrogen bonds, was found in FTIR spectra of all deposits collected for this study, and all spectra of deposits reported in the previously mentioned studies.

4.1.8.2 Region 2: 1800-1350 cm^{-1}

If triglyceride (TG) is hydrolyzed, the stretching vibration at 1745 cm^{-1} that is attributed to the frequency of the ester bond disappears, and two stretching vibrations of the carboxylate group appear instead; the symmetric stretching vibration ν_1 at 1468, 1435 and 1422 cm^{-1} , and asymmetric stretching vibration ν_2 at 1577 and 1541 cm^{-1} .

The single band of 1745 cm^{-1} did not appear in the spectra of deposits collected for this study, nor did they appear in the spectra of FOG deposits reported in previous studies. This suggests that TG was not present in the FOG deposits.

All kitchen drain spectra and five out of seven lateral house connection spectra showed medium strong absorption bands at around both 1574 and 1538 cm^{-1} . The spectra of samples 6 and 10, both samples with high total fat to calcium ratios, displayed a weak absorption band around 1538 cm^{-1} and for sample 6, also a weak peak was observed around 1574 cm^{-1} . It is suggested that both samples contained a high amount of unreacted fatty acids, and hence less calcium soaps.

With respect to the symmetric stretching vibration, the spectra displayed some mutual similarities, but differed slightly from the characteristic soap bands. All spectra showed absorption bands at around 1471 and 1435 cm^{-1} . In addition, the samples from lateral house connections showed peaks at around 1464 cm^{-1} , except for the sample 6 and 11, and the spectra of kitchen drain deposits 1 and 4 showed bands around 1417 cm^{-1} .

Previous studies that subjected main sewer FOG deposits to FTIR analysis observed comparable bands in region 2 (He et al., 2011; Shin et al., 2014). He et al. (2011) suggested that the differences with the characteristic metal soap regions could be attributed to other materials accumulating in the FOG deposits, potentially leading to the overlap of absorption bands. They subjected palmitic, oleic and linoleic acids to FTIR analysis and found peaks around 1470, 1464, 1460, 1430, 1411 cm^{-1} in their spectral signatures. Hence, the bands observed in the region of 1471-1417 cm^{-1} could be attributed to both the presence of FFAs and the presence carboxylate ions. The spectra of the pure fatty acids, however, did not display any bands at around 1577 and 1541 cm^{-1} , while these characteristic bands were observed in the spectra of the FOG samples. This supports the hypothesis that the FOG deposits in building drainage systems contain calcium soaps and have ionized carboxyl groups.

In addition to the presence of calcium soaps, the presence of FFAs is suggested for all samples collected from lateral house connections, since all the spectra showed strong intensity absorption bands at around 1698 cm^{-1} , except for sample 5 that showed an absorption band around 1703 cm^{-1} . He et al. (2011) found three strong intensity bands at 1690, 1704 and 1704 cm^{-1} in the spectra of palmitic, oleic and linoleic acids, respectively. Based on these findings, it is suggested that palmitic acid accounted for the observed peaks at 1698 cm^{-1} in the lateral house connection spectra, and oleic and linoleic acid accounted for the observed peak at 1703 cm^{-1} in the spectrum of sample 5. This was consistent with the fatty acid profiles of the samples, since sample 5 was the only sample from lateral house connections with substantial unsaturated fatty acid content. In addition, the observed bands in the region of 1470-1411 cm^{-1} of the FFA spectra may have masked the characteristic soap bands at around this region.

All spectra from kitchen drain deposits and the spectrum of sample 11 showed peaks around 1630 and 1635 cm^{-1} in the second region. These bands have not been previously noticed in samples collected from main sewers, however, they have been noticed in linoleic and oleic based FOG deposits that were prepared under laboratory conditions (He et al., 2013; Iasmin et al., 2014). These studies suggested band shifting from 1630 cm^{-1} to 1577 cm^{-1} to occur, as a consequence of the formation of carboxyl group of soaps, indicating an incomplete saponification process. The particular samples had the highest proportions of

unsaturated fatty acids, supporting the findings of both previous studies. The lateral house connection sample 5, however, did not show a band around 1630 cm^{-1} , although it consisted for 39% of unsaturated acids. The alkene double bond ($\text{C}=\text{C}$) stretching vibration at $1680\text{--}1620\text{ cm}^{-1}$ (Coates et al., 2000), or the bending vibration in water molecules (Brubach et al., 2005) could also be attributed to the bands observed in the samples collected from kitchen drains.

4.1.8.3 Region 3: $1350\text{--}1180\text{ cm}^{-1}$ with a sideband near 720 cm^{-1}

The third characteristic region is the spectral region of the aliphatic chains and is split in two bands. In all lateral house connection samples, except for sample 11, both bands were visible.

The spectra of the kitchen drain deposits and sample 11 did not show bands in the region of $1350\text{--}1180$, however, they all showed peaks at 720 cm^{-1} . This was consistent with the FTIR spectra of main sewer deposits from He et al. (2011).

4.1.8.4 Region 4: near 665 cm^{-1}

The absorption band around 665 cm^{-1} represents the calcium-oxygen bond. For the kitchen drain deposits, the spectra displayed weak bands at around 660 cm^{-1} . The narrow peaks in fourth region were positioned on a broad peak at around 675 cm^{-1} , which is thought to be attributed to the librational motions of water molecules present in the sample (Brubach et al., 2005). This was consistent with the spectra obtained by He et al. (2011) and Iasmin et al. (2014).

In the FTIR spectra of samples 7, 8 and 11, narrow peaks were visible at around 665 cm^{-1} and for the remaining four samples from lateral house connections, these bands were found around 686 cm^{-1} .

He et al. (2011) suggested that difference in observed vibration band (686 instead of 665 cm^{-1}) might be the result of other materials accumulating in the FOG deposits. They mentioned that FFAs have absorption bands around 680 cm^{-1} that possibly overlap with the absorption band of calcium oxygen bonds at 665 cm^{-1} and hence, cause the observed difference in spectral peak position.

Yet, other Ca-O bonds, i.e., in CaSO_4 , could be responsible for absorption bands in this region too (Iasmin et al., 2016). Typical values of sulfate in Dutch drinking water are around 50 mg/L (Evides, 2016). Since the kitchen drain deposits had relatively high calcium levels and a large fraction that remained unidentified, the presence of such bonds is suggested. Furthermore, previous lab results showed that a significant amount of solid soaps in the FOG deposit matrix was necessary for the visibility of the Ca-O band in the spectra (He et al., 2011). Hence, the accumulation of other bonds might have led to the overlap of absorption bands and, in addition, lower concentrations of calcium soaps, could have decreased the measured intensities (Coates et al., 2000).

Nevertheless, since the observed bands in region 2 support the hypothesis that ionized carboxyl groups of soap molecules were present, it is thought that kitchen drain FOG deposits, though in small quantities, contained calcium soaps of fatty acids that were formed as a result of saponification. It is suggested that calcium salts in kitchen drains were the product of a fraction of fat that undergoes fast hydrolysis and reacts with the available calcium. Iasmin et al., (2016) proposed

five types of hydrolysis that may influence FOG deposit formation, depending on the location in the collection system. It is suggested that the hydrolysis in kitchen drains is the result of two types of alkali-driven hydrolysis: moisture during cooking processes and high alkaline detergents when doing the dishes.

4.1.8.5 Additional interesting absorption bands

In the spectra of lateral house connection deposits, interesting bands at around 938 cm^{-1} were observed in addition to the four characteristic regions of calcium soaps. The bands have not prior been observed in main sewer spectra, and were thought to be attributed to glycerol, which is a product of oil hydrolysis. In spectra of laboratory-based deposits (He et al., 2013) and pilot-scale system deposits (Dominic et al., 2013), these bands have been observed around 970 and 930 cm^{-1} , respectively. The presence of glycerol suggests different formation processes in lateral house connections compared with both main sewers and kitchen drains. Also, it indicates that hydrolysis might not be completed yet when wastewater is discharged and that saponification processes were ongoing in lateral house connections. This is consistent with the results from Iasmin et al. (2014), who suggested that solid fats, which are fluid when they are disposed due to high temperatures, might solidify above the solid soap matrix when they cool down in sewer systems. After solidification close to or within the FOG deposit matrix, oil hydrolysis occurs. It is thought that compared with kitchen drains, slower hydrolysis processes might have played a role. Microbial driven hydrolysis (Iasmin et al., 2014) and alkali-driven hydrolysis due to prolonged contact between un-reacted fat and high moisture (Iasmin et al., 2016) might have taken place.

The spectra of the subsamples of sample 11 showed different absorption intensities, although the locations of the bands were similar: the spectrum of the first subsample showed high peaks around 938 cm^{-1} and lower peaks around 1574 and 1538 cm^{-1} ; and, instead, the spectra of the second and third subsamples showed lower absorption intensities around 938 cm^{-1} and higher intensities around 1574 and 1538 cm^{-1} . This supports the hypothesis that glycerol is an intermediate during the soap formation process and that, after oil hydrolysis has taken place, the concentration of calcium soaps, which posses an ionized structure, increases.

The small bands in the region of $3000\text{-}2800\text{ cm}^{-1}$ represented the frequencies of the aliphatic chains of the soap. These bands do not provide information on the stage of saponification, since no significant modifications take place in this region during the saponification reaction.

4.1.9 Formation mechanisms

Based on the findings in this study, different formation mechanisms are proposed for kitchen drains, lateral house connections and main sewers.

4.1.9.1 Kitchen drains

The FTIR spectra of the deposits collected from kitchen drains showed bands that have not been previously observed in samples collected from main sewers. Nevertheless, these bands did have been found in laboratory based deposits with

unsaturated fatty acid profiles (He et al., 2013; Iasmin et al., 2014), and hence, comparable formation processes for both deposits are suggested.

It is thought that the deposits were the result of a reaction between unreacted calcium ions and a finite amount of FFAs. This was supported by the composition of the deposits: the deposits had high calcium levels and a low total fat content. Since the unsaturated fat content of the deposits was relatively high, and unsaturated fatty acids were thought to be more active in saponification processes (Iasmin et al., 2016), it is suggested that kitchen drain FOG deposits were the product of a fraction of fat that had undergone fast hydrolysis and reacted with the calcium ions that were present in kitchen wastewater. The FTIR spectra support this hypothesis, as they did not show absorption bands that are attributed to glycerol, a product of oil hydrolysis. Iasmin et al., (2016) proposed five types of hydrolysis that may influence FOG deposit formation and may depend on the location in the collection system. It is suggested that the hydrolysis that preceded the reaction between fatty acids and calcium ions was the result of two types of alkali-driven hydrolysis: moisture during cooking processes and high alkaline detergents when doing the dishes. Because of these alkaline driven hydrolysis conditions, the unsaturated acid content in kitchen drain deposits could have been of substantial amount.

Additionally, accumulation of debris in the deposit matrix is suggested for the kitchen drain deposits, because of the relatively high calcium and low total fat contents, together with the large fraction of the deposits that remained unidentified. The unsaturated acid content might have enhanced the accumulation of debris in the voids as they have shown to have an adhesive character (He et al. 2013).

4.1.9.2 Lateral house connections

In the FTIR spectra of lateral house connection deposits, the absorption bands attributed to glycerol are observed, indicating that saponification was ongoing. These bands have not prior been observed in main sewer spectra, and it is thought that oil hydrolysis has taken place close to or within the FOG deposit matrix, potentially related to the cooling of fats within lateral house connections.

In addition, it is thought that the flow patterns have influenced the accumulation of FOG. As the flow in building drainage systems is intermittent, there are only pulses of water (Walski et al., 2011). In between such pulses, deposits settle, until the arrival of the next pulse of water (Staufer, 2011), and this could enhance the accumulation of FOG. This is consistent with previous FOG deposit studies (Dirksen et al., 2012; Dominic et al., 2013) in which sagging sewers were identified as being particularly vulnerable to the accumulation of FOG. They suggested that low flow velocities enable reaction and accumulation processes to take place.

Compared with kitchen drain deposits, slower hydrolysis processes are suggested, consistent with the higher saturated fat content of the lateral house connection deposits (Iasmin et al., 2014). Alkali driven hydrolysis due to prolonged contact between un-reacted fat and high moisture (Iasmin et al., 2016), might have taken place.

Compared with deposits collected from main sewers, the calcium levels, the total fat content and the saturated fat content showed relatively high values. The FTIR spectra revealed that unreacted fatty acids accumulated in the FOG deposits. He et al. (2013) proposed that both excess calcium and unreacted fatty acids might accumulate in the FOG deposit matrix, due to compression of the electrical double layer (DLVO theory), which enables to draw counter-charged particles, respectively calcium and FFAs, on the FOG deposit matrix. The presence of glycerol and the suggested slow hydrolysis support this hypothesis; slow hydrolysis processes that take place close to the FOG accumulations might have enabled the continuous transport of excess calcium and FFAs to the FOG deposits (He et al., 2011).

4.1.9.3 Main sewers

Although no samples from main sewers were collected, the results of this study, together with the results of previous studies on FOG deposits in main sewers, provided new insights into the formation processes of these deposits.

FOG deposits from public sewers had variable appearances and some deposits were reported to be more grainy, with sand-stone like textures (Keener et al., 2008). The results of this study, together with the results of Iasmin et al. (2014), suggested that concrete corrosion, and the calcium sulfate released in this process, might account for the more grainy characteristics of main sewer deposits.

In addition, the FTIR spectra of main sewer deposits did not display absorption bands that are attributable to glycerol, and both total fat content and calcium levels were relatively low. It is thought that faster oil hydrolysis might account for these differences, e.g. due to concrete corrosion or prolonged contact between fat and high moisture (Iasmin et al., 2016). Nevertheless, more research is required to identify what the differences between main sewer and building drainage system deposits and their formation mechanisms are.

4.1.10 Data limitations

This section discusses the limitations of the study that directly followed from the research methods used, i.e. the manner of collecting disposal information and the sampling method.

4.1.10.1 Questionnaire

The questionnaires that were conducted to collect information on the cooking oils used and FOG disposal habits could have induced biases; responses may be influenced by the manner of phrasing questions via telephone or as a consequence of denying undesirable traits.

A literature review on under-reporting in dietary intake studies showed that foods with a negative health image, are susceptible to be under-reported (Macdiarmid and Blundell, 1998). This might have influenced the collected information on the amount and type of cooking oils used.

Besides, as it is prohibited by law to discharge wastewater that impedes the effective functioning of the sewer system in the Netherlands (Activities Decree, 2007), households may have denied their draining of FOG. Additionally, the occurrence of a FOG blockage can have served as an antecedent stimulus for

denying FOG disposal; people may started realizing that disposal of FOG is an example of improper use of the sewer system.

4.1.10.2 *Sampling method*

As a consequence of the convenience sampling method, one may doubt the external validity of this study; the results cannot be directly generalized across other locations in the sewer system network, or even other building drainage systems.

The service engineers only collected a sample when FOG was identified as the failure mechanism, and if they were able to catch the deposits. This suggests that FOG blockages with less typical FOG-appearance, had a higher chance to be excluded from the analysis. In addition, the service engineers only collected samples when the deposits were close to the IOs or if they were jetted towards the IOs during clearing; FOG blockages occurring at different positions were not sampled, while their substances and/or their formation mechanisms may be significantly different. Additionally, the particular building drainage systems might have been more susceptible to the accumulation of FOG, suggesting that these locations might not be fully representative. Nevertheless, although this atypicality of the sampling locations, the samples were thought to be representative of sites with severe FOG accumulation, and thus enabled to study the relationship between FOG disposal patterns and FOG deposits.

4.2 Pumping Stations

4.2.1 Model output

The final model and the model selection process is described in Section 3.2.5.3. As a recapitulation, the specification of the final GLMM with standardized variables is represented here:

$$\ln\left(\frac{\pi_{ij}}{1 - \pi_{ij}}\right) = 0.394 - 1.652 \cdot \text{Income}_{ij} - 1.068 \cdot \text{Energy}_{ij} + 1.749 \cdot \text{FSE}_{ij} + b_i \quad (21)$$

$$b_i \sim N(0, 0.820)$$

where π_{ij} is the probability that FOG accumulates in the pumping station j , which is located in city i , and b_i is the city-specific intercept.

4.2.1.1 Estimated regression coefficients

The estimated regression coefficients were all significantly different from 0 at a 5% level, as is displayed in Table 11 on page 42. Figure 27 provides an overview of the model; for the variables ‘personal income’ and ‘total kinetic energy’, the weight of the coefficient was negative, and for the variable ‘FSE density’ this weight was positive.

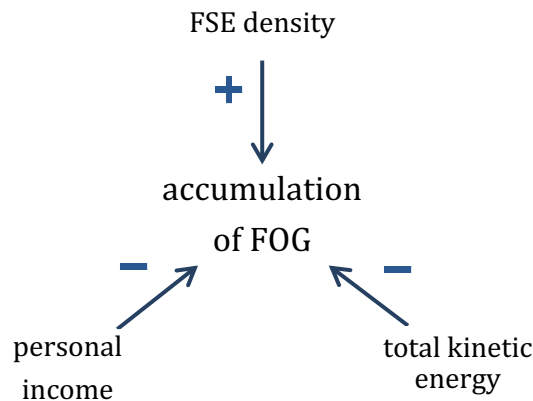


Figure 27 - Overview of the final model, showing the relationship between the explanatory variables and the response variable.

Personal Income

The variable ‘personal income’ was highly significant and had an estimated regression coefficient of -1.652, thus catchments with a lower average income had a higher probability of accumulation of FOG in their pumping stations.

This variable is the only variable representing population characteristics, and thus the only variable that could explain the relationship between demographic factors and FOG deposits; the main focus of this study. Since income, cannot directly influence the accumulation of FOG, it is thought that income is related to FOG disposal patterns (Ashley et al., 2004). This implies that people of one income-group shared particular FOG disposal patterns. In other words, if income varies considerably between catchments, FOG disposal patterns will also vary

considerably between catchments, explaining the variety of the FOG accumulation severity between catchments.

No previous studies explicitly focused on the relationship between income and FOG deposits, nor did any study explicitly focus on the relationship between domestic FOG disposal patterns and FOG deposits in full-scale sewer systems. Nevertheless, a recent study revealed that FOG deposits were the dominant failure mechanism in lateral house connections (Post et al., 2016b), and another recent study focusing on factors influencing the spatial variation of lateral house connection blockages, revealed that the neighbourhood mean income was an important factor with respect to this spatial variation (Post et al., 2016a). Hence, the combination of the two studies supports the findings of this study.

With respect to FOG disposal patterns and its impact on FOG deposits, most studies solely focused on FSEs (Dominic et al., 2013; He et al., 2011; Williams et al., 2012), and fishing and meat industries (Camarota and Freire, 2006; Mattsson et al., 2014b). None of these studies, however, contradicted the possible contribution of domestic disposal patterns to the accumulation of FOG.

One study analysed two FOG deposit samples from an apartment area, suggesting that private users also contribute to the severity of FOG deposit problems (He et al., 2011). In addition, a Swedish study, which held a survey among Scandinavian sewer operators, reported that around one third of the respondents experienced FOG-related problems in residential areas (Mattsson et al., 2014b). In addition, they mentioned explicitly the severity of FOG accumulation in areas with high-rise apartment buildings and a relatively high number of immigrants. No such significant relationships could be revealed from this study though; high-rise apartment buildings were not included as such in this study, and population density turned out to be a non-significant variable. The, on the basis of multicollinearity, dropped covariate 'percentage of immigrants with non-western origin', however, was highly correlated with the variable 'average personal income' ($r=-0.69$), suggesting that this covariate may be related to the accumulation of FOG too.

The interviews that were conducted for this study also indicated that the accumulation of FOG was more severe in areas with lower incomes. The interviewed sewer operators hypothesized that this might be related to differences in diets and/or in the disposal habits of FOG.

Influence of dietary and disposal habits

No previous studies explicitly focused on the relationship between particular diets or FOG disposal patterns and its impact on FOG deposits in full-scale sewer systems.

One study, however, focused on the different types of cooking oils and its effect on FOG formation mechanisms (Iasmin et al., 2014), as is also discussed in Section 4.1.7. The study demonstrated that although saturated fatty acids were dominant in the FOG deposits, unsaturated fats tended to be more active in the saponified solid formation process. Based on these results, it can be expected that the occurrence of FOG deposits is higher in areas where diets rely predominantly on

cooking oils such as olive oil and sunflower oil. It must be noted, however, that this study solely focused on cooking oils, thus assuming that disposed cooking oils are the sole source of the fatty acids observed in wastewater. The Dutch National Food Consumption Survey reported, however, that only 26% of the total 88 grams fat per day originates from fat, oil and savoury sauces (RIVM, 2011a). According to this survey, dairy products (18%) and meat products (18.5%) also significantly contribute to the fat consumption, suggesting that these product categories need to be taken into account in order to further study FOG formation mechanisms.

The same study reported on the intake of fat, subdivided into educational level (RIVM, 2011b), of which the results are presented in Table 18.

Table 18 - Actual fat intake by Dutch adults (19-69 years) weighted for socio-demographic factors, season and day of the week, reported as median values. No standard deviations were given in the report. (RIVM, 2011b)

Educational level	Total fat consumption [g/day]
Low education	82.7
Moderate education	86.6
High education	82.0
Overall median	84.0

The outcomes do not support the findings of this study, as they reveal that people with a moderate educational level have the highest fat consumption on average, 86.6 g/day. The fat consumption of people with a low educational level and a high educational is comparable and differs only 0.7 grams per day. As the level of education and the average income are strongly correlated (Statistics Netherlands, 2016b), the results suggest that catchments where people live that have a moderate income, would have most severe FOG disposal (assuming that fat consumption and fat disposal are proportionally).

Because the relationship between income and educational level in this study remains unknown, and the results do not provide information on disposal habits of FOG, it cannot be unequivocally concluded that the correlation between income level and severity of FOG deposit problems is related to fat consumption and disposal patterns.

The statement that the severity of FOG accumulation is related to non-western immigrants (Mattsson et al., 2014b) is not supported by other studies. Moreover, a Dutch governmental study on food habits and lifestyle contradicted the statement, and reported a lower fat intake for Turkish and Moroccan immigrants, both in comparison with groups with low socioeconomic status (SES), and with the overall mean of the Dutch population (RIVM, 2002). The study, of which the results are displayed in Table 19, was based on an earlier edition of the aforementioned national population survey, and specified the fat intake for specific target groups, such as migrant populations and groups with low SES.

Table 19 - Average fat intake of specific target groups among the Dutch population, such as migrants and low SES groups. Saturated fat was reported as their proportion of the total fat. No standard deviations were given in the report.(RIVM, 2002)

Group	Percentage of energy from fat [%]	Saturated fat [%]
Low SES groups	37	40
Turkish and Moroccan population	33	33
Dutch population (overall mean)	36	38

These results (Table 19) suggest that severe FOG accumulation is more likely to occur in catchments where groups with low socio-economic status are overrepresented, than in catchments where there is a high population density of non-western immigrants. However, even so for this situation, one has to realize that a high fat intake does not necessarily imply that one also disposes a lot of fat. In addition, the Turkish and Moroccan population in the Netherlands represent only around 36% of the entire population that has non-western origins (Statistics Netherlands, 2016a), thus based on the results of this survey, no conclusions can be drawn on the fat intake for the entire group of non-western immigrants. Furthermore, it is unknown whether the Turkish and Moroccan populations with low incomes were subtracted from the group with low socio-economic status; an overlap between the two groups was expected, since this study found a strong correlation between the variables 'below social minimum' and 'percentage of immigrants with non-western origin' ($r=-0.69$).

Regarding the different types of fat, which may influence the FOG deposit formation processes, Table 19 reveals that Turkish and Moroccan populations consume less saturated fat. In comparison with both the overall Dutch population and the low SES groups, the Turkish and Moroccan diet is thought to be more unsaturated-fat-based. Hence, this may affect the severity of the accumulation of FOG, as a lab-study revealed that unsaturated fats tended to be more active in the saponified solid formation process (Iasmin et al., 2014).

Influence of disposal moment

In addition to particular diets and disposal habits, the moment of FOG disposal could have a causal link with the accumulation of FOG. Different demographic groups may have different FOG disposal moments, possibly affecting the formation of FOG deposits. For instance, while Dutch people traditionally serve their dinner in the early evening, in other cultures it might be more common to have dinner in the later evening. As cleaning commonly occurs after dinner, the moment of FOG disposal could differ between catchments, depending on the average dinnertime of households connected to the catchment.

After nine o'clock in the evening, the hourly DWF is less than 2.5% of the daily DWF, according to the Dutch standard hourly distribution percentages (RIONED Foundation, 2004). This suggests there is no or little continuous flow, and in particular in the more upstream areas of catchments there might be only pulses of water (Walski et al., 2011). In between such pulses, (FOG) deposits settle, until the arrival of the next pulse of water (Staufer, 2011), thereby enhancing the

accumulation of solids. This hypothesis is supported by previous FOG deposit studies Dominic et al. (2013) Dirksen et al. (2012), in which sagging sewers were identified as being particularly vulnerable to the accumulation of FOG. They suggested that low flow velocities enable reaction and accumulation processes to take place.

Thus, with respect to the differences in FOG accumulation among areas, one may expect that disposal of FOG outside peak disposal moments, which might be more likely to occur in catchment with more non-Dutch citizens, results in more FOG deposits throughout sewer systems. As these studies focused solely on sewer pipes, it is unknown what the effects are on the accumulation of FOG in pump sumps.

As this study only took into account the demographic variables that were freely accessible via the database of Statistics Netherlands (Statistics Netherlands and Kadaster, 2012), it is thought that an important demographic factor might be overlooked. Reflecting on the outcomes of this study and the related literature, one cannot simply state that people with a lower income eat more FOG, dispose more FOG, and hence have more accumulation of FOG in the pump sump downstream of their catchment. The aforementioned aspects may provide a direction for important factors, and further research is required to obtain insights in how particular diets, cleaning habits and FOG disposal patterns may influence the accumulation of FOG.

Total kinetic energy

The regression parameter of the standardized variable 'total kinetic energy' had an estimated regression coefficient of -1.068. This implies that the probability of the accumulation of FOG decreases, when the amount of kinetic energy per unit of volume per day of the incoming water increases.

Influence of flow velocities

Both for pump sumps and for sewer pipes, the relationship between kinetic energy and the accumulation of FOG has not yet been reported. Nevertheless, flow velocity, which is directly proportional to the square root of kinetic energy, has been studied in relation to FOG deposits (Dirksen et al., 2012; Dominic et al., 2013). Such studies often focused on the accumulation of FOG in structural configurations that are known to block frequently and that have low flow velocities.

For instance, a study on the impact of sagging sewers on FOG deposits revealed that sagging sewers are more vulnerable to the accumulation of FOG if their filling degree is 40% or more (Dirksen et al., 2012). These results were in line with the results of a later pilot-scale study, which focused on particular sewer structural configurations, such as manholes and sagging sewers (Dominic et al., 2013). The study revealed that low flow velocities enhance FOG accumulation, and suggested such conditions to enhance the deposition of solids, as they have less capability to transport the FOG deposits further downstream. Meanwhile, the FOG deposits accumulate, and saponification reactions can take place.

Following the outcomes of these studies, it can be predicted that in pumping stations where the total kinetic energy of the incoming water per unit of volume is higher, the accumulation of FOG is lower.

The variable 'daily operation time', which was, on the basis of multicollinearity, dropped during the data exploration phase, was correlated with kinetic energy ($r=0.78$). Although the variable was partly based on other parameters than kinetic energy, as is described in Section 3.2.3.1, it also relates to the motion of water and the energy that the water possesses due to this motion. The exact effect on the motion of water due to the daily operation time remains unknown; a higher pumping capacity decreases the daily operation time and thus the time that there is motion due to the pump, but increases the average vertical velocity, of which the formula is given in Equation (2). Although the particular effect of the variable 'daily operation time' is unknown, its positive correlation with kinetic energy implies that a higher daily operation time could decrease the probability of the accumulation of FOG.

Inverse situation: Grease Interceptors

While the amount of information on kinetic energy in relation to the FOG deposit formation in pumping stations is limited, the inverse situation has been studied in the context of Grease Interceptors (GIs). There, the relationship between GIs and the accumulation of FOG was investigated to improve solids and FOG separation performance (Ducoste et al., 2008).

The impact of different GI inlet configurations were studied, performing experiments on a pilot-scale and making computational fluid dynamics simulations, in which kinetic energy was a determining parameter. Their simulations revealed that GI configurations that facilitated a gentle upward velocity pattern improved GI performance levels, showing that small geometric changes could have a large impact on the separation of FOG. It was suggested that such configurations allowed for an improved contact between the oil particles and the floating FOG layer. With respect to pumping stations, this may suggest that pumping stations with a low kinetic energy enhance the accumulation process, as this allows for contact between the oil particles and the floating FOG layer. In addition, the outcomes revealed that, apart from kinetic energy, velocity patterns might be an important factor. For this statistical study, various simplifications on the pump sump geometry had to be made, and many parameters that influence such velocity patterns, e.g. the shape of the pump sump, the inlet position and the location of the suction inlet, were therefore not considered.

As the scope and approach of the GI study differed from this study, the outcomes cannot be directly translated to the context of pumping stations. Nevertheless, the outcomes may provide some insights into aspects that are related to kinetic energy and that may have a causal link with (the prevention of) FOG accumulation. Their results demonstrated that many other aspects, such as velocity and flow patterns, have to be studied in more detail. In addition, FOG is known to accumulate at different places within the pump sump, since each of these appearance might have different formation mechanisms, they might also be differently influenced by the flow patterns.

FSE density

The regression parameter of the standardized variable 'FSE density' is highest (1.749) of all parameters (-1.068 and -1.652), implying that there is a strong

positive relationship between the FSE density and the accumulation of FOG in pump sumps.

Several studies mentioned the contribution of FSEs to FOG deposits in sewer systems; FOG blockages in sewer pipes frequently occur in the proximity of restaurant and bar areas (Dominic et al., 2013; He et al., 2011; Williams et al., 2012). Other studies reported on the malfunctioning and poor maintenance of GIs that FSEs are obliged to have, causing large quantities of FOG to be drained into the sewer system (Aziz et al., 2011; Ducoste et al., 2008; Williams et al., 2012).

4.2.1.2 Random effect

Figure 28 illustrates the GLMM predicted probabilities of the accumulation of FOG in pump sumps, along standardized personal income values, based on a population mean for the variables 'FSE density' and 'total kinetic energy'. The thick curve represents the population average, and the two dashed curves represent the inter-city variation; 95% of the values for b_i are estimated to fall between these two curves.

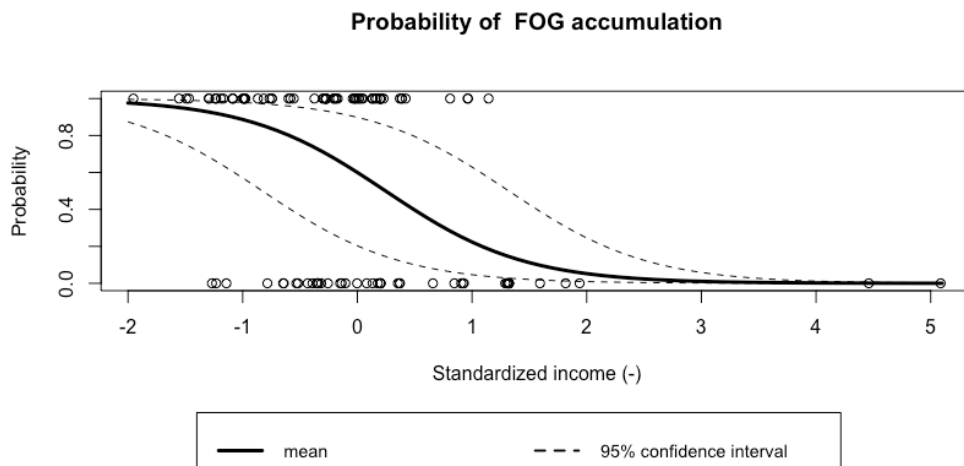


Figure 28 - GLMM predicted probabilities of FOG accumulation along standardized personal income values, for catchments with a mean FSE density and for pumping stations with a mean total kinetic energy. The thick middle line represents the predicted values for the entire sample of pumping stations. The confidence interval shows the variation of the predictions between the cities.

The graph illustrates the variation that is explained by the random intercept of the GLMM. If one goes to a representative city, thus a city representing the entire population ($b_i = 0$), and samples a catchment where people have an average income, so the standardized income equals zero, then the predicted probability that FOG accumulates in this pumping station is approximately 0.6. The confidence intervals reveal, however, that there is a substantial inter-city variation; for the majority of the cities (95%), the probability can be any value between 0.2 and 0.9.

City effect

To explain the variation between the five participating cities in more detail, a plot of the predicted probabilities of accumulation of FOG per city was made (Figure 29). This plot shows the predicted probabilities along the standardized values for personal income; for the other variables the mean values for each city individually were calculated. No prediction intervals were added to this graph; the response variable has a binary character, implying that for all values for the variables, the response value is restricted to 0 and 1.

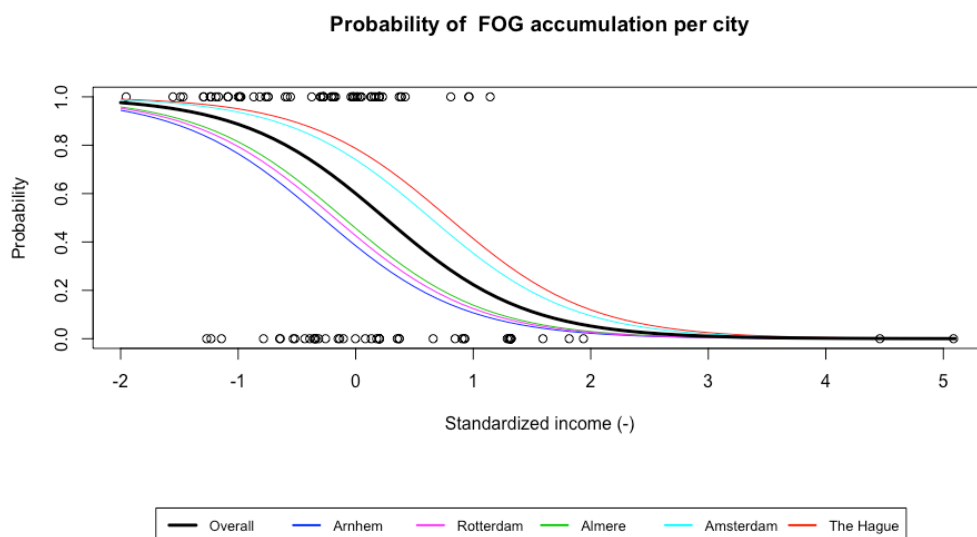


Figure 29 - GLMM predicted probabilities of FOG accumulation per city along standardized personal income values, for catchments with both mean values for the variables 'FSE density' and 'total kinetic energy' of the particular city. The thick middle line represents the predicted values for the entire population. The coloured lines represent the predicted values for each city. Prediction intervals were not added, as this does not provide valuable information for logistic regression.

The graph clearly illustrates that each city has very different intercepts. For a representative pumping station in Arnhem, thus a pumping station with mean values for all variables for the city of Arnhem, the predicted probability that FOG accumulates in this pumping station is approximately 0.4, while for Amsterdam, this probability equals 0.8.

This suggests that pumping stations in Amsterdam are more prone to the accumulation of FOG. This is also thought to be affected by the relatively low values for kinetic energy in Amsterdam and high mean value for the FSE density, making the pumping stations more prone to the accumulation of FOG.

Both Figure 28 and Figure 29 illustrate the large inter-city variation and validate applying a GLMM on the pumping station data. If a common GLM had been applied instead, containing the same explanatory variables and the variable city, four more degrees of freedom would have been used. Moreover, while a common GLM only allows making a statement on relationships per city, the GLMM allows making a statement on the relationships for cities in general. Lastly, the GLMM introduces the compound symmetrical correlation structure. This brings along that the probability of the accumulation of FOG in one pumping station is correlated to the accumulation of FOG in another pumping station that is located in the same

city. This suggests that the GLMM is able to account for city-specific factors that were not included in the current model.

4.2.2 The role of kinetic energy

Kinetic energy is the only non-demographic variable in the model, and its manipulation provides a possible approach to preventing the accumulation of FOG. For example, for catchments with a low average income and a high FSE density, a high kinetic energy per unit of volume may prevent the accumulation of FOG in the pump sump.

The significant role kinetic energy may play is demonstrated in Figure 30, which shows the probability of FOG accumulation along the standardized variable for kinetic energy, for three different income classes. The continuous variable 'personal income' was discretized into three values by creating intervals. The observations were equally divided among the intervals and the mean value for the observations within one interval was taken as the representative interval value (Gelman and Park, 2009).

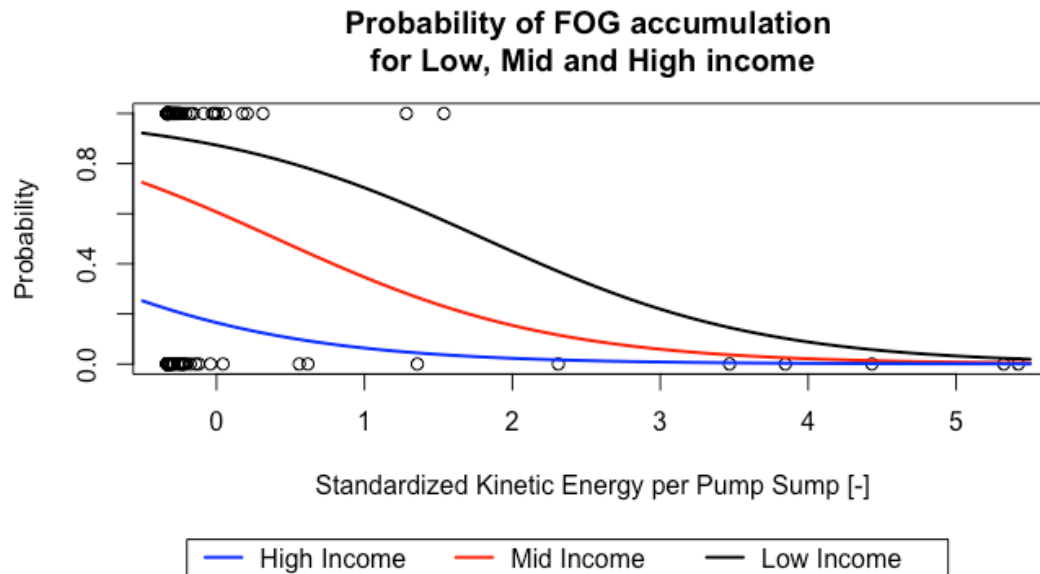


Figure 30 - Predicted probabilities for different income classes for the 'population of cities' ($b_i=0$), and along standardized kinetic energy values. For the variables 'FSE density' and 'personal income', mean values for the population were taken. The three income classes were based on the intervals of the continuous income variable. The observations are plotted as dots; the 0 stands for absence and the 1 for presence of FOG. Prediction intervals were not added, as this does not provide valuable information for logistic regression.

The plot demonstrates the importance of kinetic energy for catchments with lower incomes. The black line in Figure 30 shows that if one goes to a representative city, thus a city representing the entire population ($b_i = 0$), and samples a pumping station that is located in a catchment that belongs to the low income class, with a mean value for kinetic energy (thus the standardized kinetic energy equals zero), the predicted probability of FOG accumulation is approximately 0.9. For a pumping station that is located in the same catchment, but with a different geometry, resulting in a value for the standardized kinetic energy of 4, this probability would be only 0.1. As for a probability $\pi_{ij} < 0.5$, the

pump sump is more likely to be clean than filthy, this example illustrates the influence of kinetic energy on preventing the accumulation of FOG in pump sumps for catchments with a low income population.

In contrast, for catchments that belong to the high income class and that have an average FSE density, the model suggests that kinetic energy is of little importance. It can be revealed from the plot, that even for pumping stations with low kinetic energy values, the predicted probability of the accumulation of FOG remains below 0.3. It has to be realized, however, that this plot is based on the population intercept, while most pumping stations with high values for kinetic energy were located in Almere. For Almere, the random intercept was highest (see Table 12 on page 43), implying that the actual predictions were higher than the ones shown in Figure 30.

4.2.2.1 FOG accumulation versus air entrainment

The discretization of the income variable illustrates that for catchments where the demographics are such that the probability of FOG accumulation is high, one may desire pumping stations of which the kinetic energy is higher. Such pumping stations could decrease costs associated with severe FOG accumulation, i.e. costs of pump replacements, pump repairs, maintenance work such as periodic FOG removal activities and pump inspections, but also costs of flooding and sewer overflows. Hence, for municipalities, the outcomes of the model may justify the higher construction or remodelling costs of pumping stations for areas with lower income.

When considering the correlation between kinetic energy and FOG accumulation in pump sumps, one has to keep in mind that higher values for kinetic energy could increase the risk of air entrainment. When air bubbles are present in the reservoir, they may be sucked into the pump, thereby increasing the risks of pump failures (Smit, 2007). The study of Kranendonk and Pothof (2007) focused on the impact of various pump sump constructions on air entrainment. They did not study, however, how such constructions influence the accumulation of FOG.

In the 'Hydraulics handbook for pressurised wastewater mains', which was part of the CAPWAT ('capaciteitsverlizen in afvalwaterpersleidingen' in Dutch and written out in full) research project by Deltares and Delft University of Technology, four criteria for an optimal pump sump design are mentioned (Tukker et al., 2012):

- An optimal storage capacity with respect to the required number of pump starts
- No air entrainment in the pump
- Discharge of sediment and floating layers of debris
- Optimal water flow towards the suction inlet

These requirements clearly demonstrate that the design of pumping stations involves balancing between different aspects; e.g., on the one hand, preventing the entrainment of air in the pump, and on the other hand, discharging the

accumulation of FOG and other floating debris. Hence, further investigation is warranted to design pumping stations that fulfil these requirements best.

4.2.3 Newly developed areas

Figure 18 on page 44 showed that for The Hague, Almere and Amsterdam multiple observations displayed a similar relationship between the residuals and the fitted values. This suggests that for these observations, the linear predictor and the observed Y_i (absence or presence of FOG) were similar, implying that there are catchments for which the demographics and their pumping stations show comparable characteristics.

It is thought that such catchments might be located in newly developed areas. Figure 31 shows the observations in three different newly developed areas (Leidschenveen, Wateringseveld and IJburg). As such areas were often developed at once, the pumping stations and their sewer system upstream are thought to show comparable characteristics. In addition, the demographics of these catchments are thought to be relatively homogenous, as the areas are popular among young families that have an above average income (Statistics Netherlands and Kadaster, 2012). In Figure 31, the fitted values are plotted against the variable 'personal income'. In Figure 31, the fitted values are plotted against the variable 'personal income'.

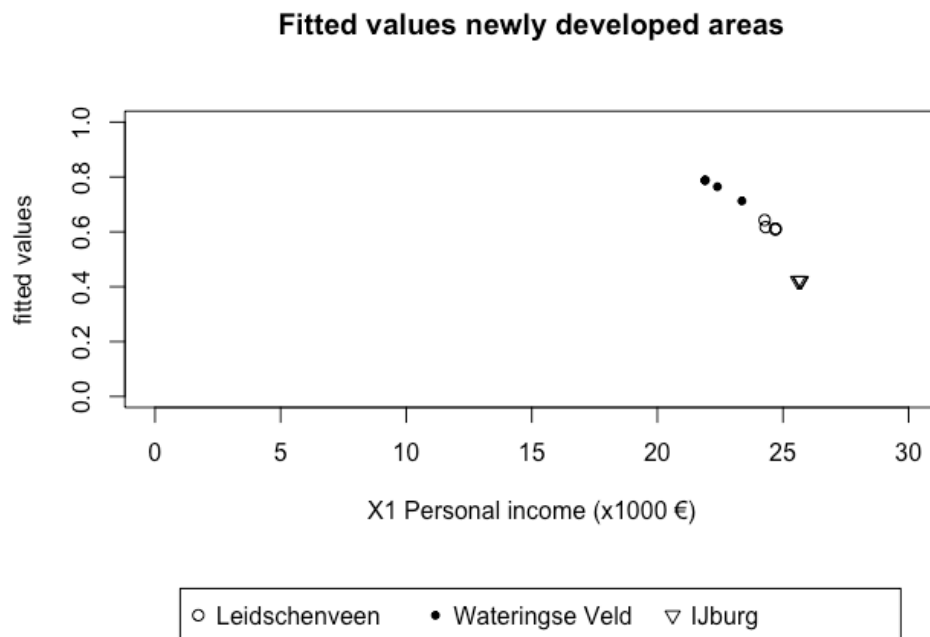


Figure 31 - Fitted values versus the variable 'personal income' for the newly developed neighbourhoods Leidschenveen, Wateringseveld, and IJburg. No prediction interval was added, as this does not provide valuable information for logistic regression.

For each area, between five and six observations were made. The plot clearly illustrates that the observations for the explanatory variables in each newly developed area are comparable, and therefore their fitted values are comparable. Hence, the observations from such areas are spatially correlated and cannot be considered as independent. This situation is displayed in Figure 32.

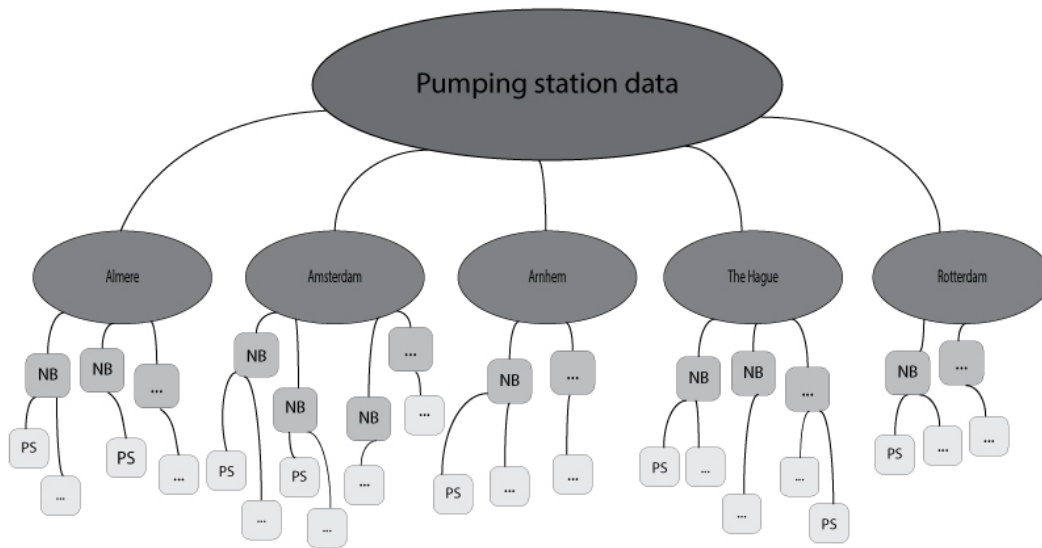


Figure 32 - Actual set up of the pumping station data. In addition to the city effect, there might also be a neighbourhood effect; i.e., the observations of one neighbourhood might show similarities in their characteristics, such as demographic characteristics of the catchment and sewer system pump sump geometry.

To a certain extent, the GLMM resolves this spatial correlation by implementing a random intercept term for each city. Mixed models allow for the compound symmetrical correlation structure, implying that the probability of the accumulation of FOG in one pumping station in Amsterdam is correlated to another Amsterdam pumping station. The models, however, consider the pumping station within one city to be equally correlated with each other, while Figure 31 illustrates that the intercept term may not fully account for the spatial correlation. An additional random intercept term for neighbourhood-type might solve the spatial correlation, however, this would also require a much larger sample size. Applying a residual autocorrelation structure might also solve the spatial correlation; however, the correlation is not solely induced by proximity. No such a structure was included in this model, since the coordinates of the pumping stations were not incorporated in the dataset.

4.2.4 Sewer system type

The interviews with the municipalities indicated that separated systems are thought to be more vulnerable to FOG deposits. No such findings could be revealed from this study, however.

The variable 'sewer system type' was excluded from the model, as the type of sewer system was very much dependent on the particular city, the building philosophy and state of the art at the time the sewer system was built (see Figure 17 on page 36). For example, for Almere and Amsterdam, the dataset contained hardly any catchments with combined sewers. The variable would therefore influence the random effect.

Table 20 provides an overview of the catchments with separated sewers, indicating that 79% of the observations employed separated sewer systems. For

the entire Netherlands, however, it is known that only 27% of Dutch households is connected to a separated sewer system (RIONED Foundation, 2013).

Table 20 - Observations with separated systems, expressed as the proportion of the entire dataset.

Observations (pumping stations)	Separated or combined systems [%]	Separated systems [%]
Full dataset	100	79
Of which clean	41	39
Of which contain FOG	59	61

The figures do not suggest that separated sewers were more prone to the accumulation of FOG; hence, the theory of the sewer managers was not supported by the data.

4.2.5 Omitted covariates

It could be observed from the residual plots (Figure 19 on page 45) that the assumption of independence was violated. Such violation of independence often means that important covariates are overlooked, and thus, that predictive information is missing in the model (Zuur et al., 2009). None of the dropped variables showed patterns in their residual plots, suggesting that these variables did not contain the predictive information; hence, it is thought that the initial dataset did not contain all influential factors.

Based on previous studies (de Groot et al., 2015; Dirksen et al., 2012; Dominic et al., 2013; Post et al., 2016a, 2016b), this section provides a discussion of the important factors, both factors related to demographics and general system characteristics, that might have been overlooked. It has to be realized, however, that while some of such factors were not included in this study as they were not readily available, others might be yet unknown.

4.2.5.1 Demographic factors

The relationship between the accumulation of FOG and demographics on a catchment scale has not been investigated thus far. Therefore, little is known about which demographic factors possibly influence the accumulation of FOG.

Section 4.2.1.1 elaborated on the variable ‘personal income’, and showed that although the analysis revealed a relation between FOG deposits and personal income, it is not thought that income is causally related to the accumulation of FOG. It is suggested that FOG disposal patterns are shared by individuals of one income-group, implying that the accumulation of FOG is affected by FOG disposal patterns, which comprise aspects such as particular diets, cleaning habits, and the moment of fat disposal.

In addition, the section highlighted the dropped variable ‘percentage of immigrants with non-western origin’ as it was correlated with the variable ‘personal income’. This suggests that the proportion of non-western immigrants

might also be related to one of the aforementioned factors or other influential factors not yet identified, which cause the severe accumulation of FOG.

For the variable 'FSE density', apart from the poor performance of GIs, no such influential factors were mentioned. Various studies showed that FSE density plays a role in the causation of FOG blockages and it is generally known that FOG blockages often occur downstream from restaurants and bars.

4.2.5.2 Sewer system characteristics

Kinetic energy was the only variable remaining in the final model representing sewer system characteristics. Previous studies revealed, however, many more sewer system characteristics and particular configurations that are thought to be related to the accumulation of FOG in sewer systems. Therefore it can be expected that such aspects also affect the accumulation of FOG in pump sumps.

Sagging sewers and soil settlement

Dirksen et al. (2013), who studied the influence of sewer sags on FOG blockages, reported that FOG deposits in main sewer sags were the main contributor to blockages in Amsterdam. According to the Amsterdam study, such sags are the consequence of unequal settlement, suggesting that also soil settlement is an important factor for predicting the accumulation of FOG. The results were in line with the results of a later pilot study, which focused on particular sewer structural configurations, such as manholes and sagging sewers (Dominic et al., 2013). Both studies suggested that low flow velocities could enhance the accumulation processes, as they enable reaction and accumulation processes to take place.

Inverted siphons

Another study focused on inverted siphons ('zinkers' in Dutch), in which FOG is known to accumulate in large quantities (de Groot et al., 2015). The study showed that declining parts of inverted siphons are particularly vulnerable to FOG blockage, and suggested that this was the result of localized presence of air pockets. Such inverted siphons might function as in-system grease interceptors, thereby preventing the accumulation of FOG in pump sumps and causing the FOG to accumulate upstream of the pumping station. In the case that the model would predict a large amount of FOG, the pump sump could be clean due to the capture of FOG in the inverted siphons.

As the same holds for sagging sewer, one may doubt if the current study is competent to study the relationship between FOG deposits in the sewer pipes of catchments and FOG disposal patterns, as the value for the response variable may not fully represent the severity of FOG accumulation in the entire catchment sewer network.

Storage in submerged inlet pipes

For some pumping stations, the invert levels were located beneath the switch-on levels of the pumps, thereby increasing the storage capacity of pumping stations ('pendelberging' in Dutch).

These conditions were typical for Amsterdam, as 47 out of the 58 pumping stations with such (partially) submerged inlet pipes, were located in Amsterdam.

Additionally, many of these pumping stations were designed such that the most downstream pipes were located deeper than the rest of the system ('verdiepte laatste streng' in Dutch). Such designs aim to prevent damage to the sewer pumps from being switched on too frequently and decrease the required storage capacity of the pump sump.

The municipality of Amsterdam mentioned such in-pipe storage at pumping stations to be problematic for the accumulation of FOG as this creates a large air-water interface and little water movement, i.e. it causes low flow velocities which could have enhanced the accumulation process (Dirksen et al., 2012; Dominic et al., 2013). In addition, the in-pipe storage entails that although the values for kinetic energy were already relatively low for Amsterdam (Figure 17), their actual values are even lower.

The in-sewer storage constructions were not considered for the statistical analysis, as little was known on the actual construction and its storage capacity. Nevertheless, it is expected that this might be an important factor for predicting the accumulation of FOG.

Construction year of the properties

A recent study focusing on factors influencing the spatial variation of lateral house connection blockages, revealed that the construction year of the properties, which was strongly correlated with construction year of the main sewers, was an important factor with respect to this spatial variation (Post et al., 2016a). As another study revealed that FOG deposits were the dominant failure mechanism in lateral house connections (Post et al., 2016b), it is thought that construction year of properties might be an important factor for predicting the accumulation of FOG throughout the sewer network.

4.2.6 Model performance

For this study, no (simulation-based) cross-validation was performed to compare model predictions against observed data, and the entire dataset was used to build the model. As the main question of this study is whether there is a relationship between the accumulation of FOG in pump sumps and demographics (FOG disposal patterns), and whether the pump sump geometry influences the accumulation of FOG, the study set up was solely designed to reveal information on these relationships.

Table 21 shows the confusion matrix of the model, assuming a cut-off value of 0.5. The model accuracy is specified as such:

$$Accuracy = \frac{TP + TN}{TP + FP + TN + FN} \quad (22)$$

where the T stands for true, the F for false, the P for positive, and the N for negative. This gives a model accuracy of 0.78.

Table 21 - Confusion matrix of the entire dataset, based on a cut-off value of 0.5

Observations	Predicted values	
	P(<0.5)	P(>0.5)
Clean	33	19
FOG	9	65

The final model performs better than the baseline model, in which all pumping stations are predicted to be filthy, resulting in an accuracy of 0.59. As the model performance is, however, solely based on the comparisons of model predictions and observation of the response variable from the data that was used to fit the model, the predictive performance of the model is expected to be overestimated (Zuur et al., 2009).

Table 22 presents the model accuracies per city. For each city, except for Arnhem that had an accuracy of 0.67, the model accuracy was around 0.8. The lower accuracy for the city of Arnhem might result from the relatively low number of observations (12) in this city.

Table 22 - Accuracy of the model per city

Observations	Accuracy [-]
Overall	0.78
Almere	0.81
Amsterdam	0.79
Arnhem	0.67
The Hague	0.75
Rotterdam	0.83

4.2.7 Implications

As municipalities are responsible for providing sufficient drainage capacity (Environmental Law, 1979) and thus for preventing and solving pump failures, findings from this study may provide useful information to prevent the accumulation of FOG, and/or make municipal maintenance strategies more effective. In this study, FSE density and kinetic energy have been shown to be directly related to the accumulation of FOG. Adjusting these parameters could therefore be a possible approach to reducing the accumulation of FOG, and therewith the undesirable health, environmental and financial costs associated with FOG accumulation.

FSE density is expected to be an important factor contributing to the amount of FOG, and thus the accumulation of FOG in pump sumps. Reducing the density of FSEs or applying a zoning strategy, i.e. restricting land use, solely based on the severity of the accumulation of FOG might, however, not be feasible.

A more realistic approach to reducing the severity of FOG accumulation could be through improved regulations for GIs and GI performance levels. FSEs and meat and fish processing establishments are obliged to purchase and maintain GIs

(Activities Decree, 2007). However, the responsibility for proper functioning lies with FSEs (Activities Decree, 2007), and according to the sewer operators that were interviewed for this study, inspections do not take place on a regular basis. This may result in poor GI maintenance and thus a high FOG disposal; hence, creating an incentive for local governments to change the inspection procedures or set particular effluent limits to reduce the amount of FOG discharged into sewer systems. Additionally, as the amount of FOG disposal could vary among particular restaurant types and/or individual FSEs, local governments may want to adapt regulations and inspection strategies accordingly.

Furthermore, as it was shown that the removal efficiency of GIs heavily depends on GI geometry, and can be easily improved by making small geometric changes (Ducoste et al., 2008), governmental institutions could decide to improve the standard GI design and/or replace GIs that are malfunctioning.

The average income of the catchment is correlated to the accumulation of FOG in pump sumps, suggesting that individuals within an income-group shared FOG disposal patterns. Changing user behaviour to prevent severe FOG disposal could prevent the accumulation of FOG. Little is known, however, about the particular aspects of disposal patterns that influence the FOG accumulation. Additionally, one may doubt the effectiveness of measures focused on preventing the accumulating of FOG, as it involves changing user behaviour. Hence, other measures to prevent the accumulation of FOG are thought to have a larger impact.

The incoming kinetic energy mainly depends on structural configurations and does not involve changing user behaviour, suggesting that this parameter might be easiest to influence. In particular, for catchments with a low average income and a high FSE density, one may desire a pumping station of which the kinetic energy is high to prevent the accumulation of FOG.

It follows from Equation (4) on page 27 that decreasing the storage capacity, or increasing the flow velocity, increases the total kinetic energy per unit of volume per day. For existing pumping stations, changing such parameters could be (economically) unfeasible; changing operational values, i.e. switch-on and switch-off levels, might be more feasible. To increase kinetic energy significantly, the levels should be set such that the invert level is above the representative water level, allowing inlet pipes to discharge freely. Nevertheless, the geometry of the pumping stations should allow such settings; e.g. there should be sufficient storage capacity.

In addition, one has to keep in mind that higher values for kinetic energy could increase the risk of air entrainment due to the presence of air bubbles in the reservoir (Smit, 2007). As discussed in Section 4.2.2, the design of pumping stations involves balancing between several requirements. Further investigation is needed to find the most appropriate balance between the prevention of FOG accumulation and the prevention of air entrainment.

The variable 'daily operation time', for which 'pumping capacity' is an important parameter, was correlated with the variable kinetic energy, and hence, could have also been driving the accumulation of FOG.

Waternet is currently experimenting with 'flushing regimes' to prevent severe accumulation of FOG. For such a flushing regime, the pumps are turned off for a

particular time, saving up water in the pump sump, after which they are turned on again and run at full capacity, flushing pump sumps, impellers and the pressurized pipes. Multiple-speed pumps or multiple pumps could simulate such flushing regimes. However, they also bring along higher investment costs. In addition, pumps have a particular operation point, and running outside the operation region might result in pump damage and could decrease the service life of pumps.

It has to be realized, however, that if FOG will be discharged by pumps, it may accumulate in pressurized pipes or it ends up at wastewater treatment plants, where it could inhibit treatment processes (Cammarota and Freire, 2006). FOG is known to accumulate at various locations within the sewer network; this implies that if its accumulation will be prevented at one place, it is likely to accumulate at another place. As there is currently limited knowledge available on the formation of FOG deposits, the associated costs for its removal from different locations within the sewer network, and possible solutions to prevent the accumulation of FOG, biodegradation for instance (He et al., 2015), further research is required.

Furthermore, the statistical analysis performed in this study did not enable any optimization; it only revealed relationships between the accumulation of FOG and user-based and system-based characteristics. This implies that the precise impact of higher or lower values for the variables remains unknown. The effects could, for instance, be limited by a maximum, and the optimum parameter values remain unknown. Further research is needed to improve knowledge of the identified relationships and of particular properties that may contribute to a more robust pumping station design that prevents severe accumulation of FOG. This may justify higher construction costs or remodelling costs, if this lowers the overall costs.

4.2.8 Generalization

After removal of outliers, the dataset comprised of 126 pumping stations in relatively large Dutch municipalities. It is uncertain whether these pumping stations are representative for pumping stations in other large Dutch municipalities, and moreover, to what extent they are representative for pumping stations in the rest of the Netherlands.

First, as the model assumptions that are inherent to GLMMs were not fully met, one has to interpret the model output with care, implying that one cannot draw inferential conclusion directly from the model. Second, both the catchments and pumping stations from different cities, and even from one city, showed a large variation in their characteristics: drainage schemes, system type and pumping station geometry differed per pumping station. It is therefore expected that the pumping stations are not representative for pumping stations in other large cities. Nevertheless, although these aspects largely decreased the predicting performance of the model and its external validity, the model revealed information on several important factors related to the accumulation of FOG. Since the GLMM structure accounted for the city-effects, the model does allow making a statement on the relationships in general.

For small municipalities, however, the model is thought to be less representative. The values for FSE density deviate in smaller municipalities compared with large cities. Additionally, a study on the benchmark of Dutch sewer system from 2013 showed that smaller municipalities (<20.000 inhabitants) had 44% more sewer system length compared to large municipalities (>100.000) (RIONED Foundation, 2013). This suggests that the FOG load per mean main sewer length is, for instance, higher for larger municipalities. Additionally, as shown in Section 4.2.4, 79% of the entire dataset consisted of catchments with a separated sewer system, while for the entire Netherlands this is only 23%. It is unknown how such significant differences in sewer systems influence the model performance.

In addition, it is unknown to what extent the accumulation of FOG in pump sumps represents the accumulation of FOG throughout the sewer system upstream of the pumping station. The statistical model solely focused on the accumulation of FOG in pump sumps, and assumed this location to be representative for the FOG disposal of the entire area upstream. When the kinetic energy in the pump sump is high, for example when there are many restaurants and the income of household connected to the catchment is low, one may observe a clean pump sump, while there is much FOG accumulated throughout the entire network.

Furthermore, there might be overlooked covariates, such as inverted sagging sewers or inverted siphons (Section 2.1.6 on page 13), that may prevent the FOG to reach the pump sump, resulting in false positive values. Hence, one may doubt the representativeness of this location for the entire catchment.

4.2.9 Data limitations

Despite careful data collection and extensive evaluation of the data, this study faced some limitations following from the sampling method, the data collection and the statistical analysis.

4.2.9.1 Sampling method

The residual plots in Section 3.2.5.4 revealed that for higher values, there were fewer observations and less spread of the variance, violating the homogeneity assumption. In addition, the residual plot of kinetic energy suggested non-independence of the observations.

The sampling method that was applied within the subgroups of clean and filthy pumping stations is thought to be partly responsible for the observed patterns. As there were not many observations with higher values, the sampling was unbalanced, which might have caused the heterogeneity in the variance (Zuur et al., 2010). This implies that the relatively small sample size could also have attributed to the observed heterogeneity.

The sampling method that was applied within the two strata brought along more data limitations. Although the sampling method was assumed to be random within the two strata, the probability of being chosen was not the same for each pumping station. As the dataset was mainly composed on the basis of employees' personal experiences, pumping stations were more likely to be included in the dataset if they were under attention of such employees, for example, if they were recently visited. In addition, the employees might have composed the dataset based on their own expectations; in other words, they could have selected certain

catchments, because they *expected* that these catchments would dispose a small or a large amount of FOG, without knowing the actual amount of FOG accumulation in the pump sumps.

In general, Dutch pumping stations are visited in case of malfunctioning, thus after registration of pump failures. While some municipalities also organize preventive cleaning activities that are solely focused on FOG and debris removal, most cleaning activities occur after registration of pump failures. The general opinion is hold that FOG mainly causes pump failures indirectly when wipes, clothes and other dirt get entrapped in the FOG. This is consistent with a study of the RIONED Foundation, which reported that disposable wipes were the main cause of pump failures for the Netherlands (RIONED Foundation, 2007).

It follows from this working practice, that 1) pumping stations that have fewer failures, although their accumulation of FOG is severe, may not have been identified as filthy, and 2) pumping stations that receive many wipes and get clogged frequently, are visited more frequently and may be cleaned regularly, preventing them from becoming filthy.

While it was impossible to identify what pumping stations belonged to the first category, at least one pumping station was identified that belonged to the second category. This pumping station was located in Almere and received water from eight pumping stations upstream that were all known for their severe FOG accumulation and the high amount of disposable wipes they receive. According to the company responsible for the maintenance of the pumping stations, the pumping station downstream was that often clogged by disposable wipes from pumping stations upstream, that it had to be frequently cleaned, preventing it from becoming as filthy as the pumping stations upstream. As the pump sump of this station still had an above average level of FOG accumulation, it was identified as filthy.

4.2.9.2 Data collection

Both the response variable and the explanatory variables faced some limitations that followed from the data collection.

Response variable

The response variable described the presence or absence of severe accumulation of FOG in pump sumps. Although the binary character of this variable removed the possibility for outliers, misidentification of the presence of FOG could have occurred.

Definition of severe accumulation

The dataset is mainly based on personal perceptions of employees, and during the interviews with the municipalities it was noticed that there was not always agreement on the state of FOG accumulation among the different employees. In addition, it is thought that there might have been differences in perceptions among the different municipalities. As none of the municipalities recorded the accumulation of FOG systematically, and since there is always some FOG present in pump sumps, there is no absolute boundary between the two levels. This made the response variable sensitive to perception.

Varying appearances

Furthermore, this study did not take into account the different appearances of FOG deposits, which could have affected the estimated model parameters.

FOG is known to accumulate at different places within the pump sump, i.e. in the form of floating layers that stick to the walls, as floating balls and/or as bar-shaped pieces (Figure 10 and Figure 11 on page 15). For this study, a sample of FOG deposits with each of these appearances was analysed (the values of which are not reported here). As only one sample of each was collected, the results should be interpreted with care. Nevertheless, the variability in the chemical composition and appearance of the samples was large, and it is thought that the appearance depends on, among other things, particular FOG disposal patterns and FOG formation processes. This suggests that the binary character of the response variable might have oversimplified the situation, possibly affecting the values of the estimated parameter coefficients.

Explanatory variables

The explanatory variables represented demographic and socio-economic characteristics, and factors related to general system characteristics. Most of the variables were pre-processed, thus increasing the probability of deviations from the actual values.

Demographic data

Representative values of the demographic variables per catchment were obtained by weighing the characteristics according to the catchment's population that the sub-catchments contained. This approach assumes that people living in a more upstream sub-catchment have the same impact on the accumulation of FOG as the people living in a more downstream catchment. It is likely, however, that FOG that was disposed more downstream and thus closer to the pumping station, had a larger impact on the accumulation of FOG. FOG that was disposed in more upstream catchment areas may have already been accumulated elsewhere, preventing it from reaching the downstream pumping station.

As the drainage schemes and pumping station configurations varied greatly among the municipalities, the municipalities are thought to be differently affected by the assumptions. The Rotterdam urban drainage system, for instance, is divided into several large catchments; smaller sub-catchments discharge their water to one large pumping station downstream of the catchment, from where it is discharged to other large pumping stations or to waste water treatment plants. The observations from Rotterdam only consisted of such large downstream pumping stations, which made the observations prone to have biased values.

On the contrary, the Almere drainage network consists of small catchments and their network is less hierarchical. This suggests that the observations from Almere are less affected by these assumptions.

Total kinetic energy

For the variable 'total kinetic energy', many assumptions had to be made to obtain one representative value per pump sump.

Both for combined and separated systems, the energy calculations were solely based on DWF, while for combined systems, storm water flows might have been more determining for the (prevention of) the FOG accumulation process.

In addition, the assumption that all pipes, both pressurized and gravitational pipes, had a similar and constant flow per hour could have largely affected the results. In Section 3.2.5.1 on page 36, it was shown that the assumption caused a particular observation to be an estimated 65% off from the actual value.

City-specific system characteristics

The availability and reliability of the information on sewer system characteristics differed greatly per city. For Amsterdam and Rotterdam, for instance, measured DWFs were available, while for the other cities only design DWFs were available for most observations. The latter may deviate greatly from actual DWFs, due to e.g. wrong connections or the inflow of groundwater.

As the deviations very much depended on the particular city and particular sewer system context, no estimations were made on the possible effects of such deviations.

In addition, although parameter definitions were thoroughly discussed with the municipalities, there might have been differences in interpretations of such parameter definitions, affecting the comparability of the observations due to discrepancies. The differences in configurations of pumping stations, drainage schemes and/or system layout could also have greatly affected the differences between observations from one city. For instance, for Almere most pumping stations had a rectangular cross section, and the network consisted of separated sewers, while the pumping stations in Rotterdam had arbitrary designs and the network predominantly contained combined sewers.

It is thought that the random intercept mixed effects model accounted for most of such discrepancies, provided that they were due to a systematic error, thus inherent in the city.

Information availability

As most of the pumping station dimensions were not readily available, construction drawings of each pumping station were to be read and evaluated. Despite thoroughly checking and evaluating these values, construction drawings might have been read erroneously and typing errors could have been made. Since some construction drawings were analogous and thereafter scanned, the legibility of such drawings was low, increasing the probability of errors. In addition, as such construction drawings were often rather old and the pumping stations could have been remodelled over the years, the drawings could have become obsolete.

Variability in operational values

For some operational values, the values varied greatly among different reports and/or management systems of one municipality. The most representative value, according to the concerned municipality, was taken.

For the switch-on and switch-off levels, for instance, this could have changed the water level to be above or below inlet pipes, largely affecting the calculated incoming kinetic energy per unit of volume (see Section 3.2.3.1). Based on the situation in which the pipe is fully submerged instead of half full, and given that the flow velocity is inversely related to the cross-sectional area of flow, and the kinetic energy is proportional to the squared velocity, this implies the following: for a pumping station with a 500 mm diameter inlet pipe, and a switch-on level

that is reported to be 0.25 m above the actual level, the calculated value for kinetic energy would be four times lower compared with the actual value.

4.2.9.3 Statistical analysis

As the statistical analysis required one representative value per catchment, many simplifications of pump sump geometry had to be made; various physically relevant parameters could therefore not be taken into account. For instance, the shape of the pump sump, the position of the inflow of wastewater and the position of the suction inlet were not considered.

Hence, it is thought that the value for kinetic energy could not solely explain the difference in the accumulation of FOG for two catchments with similar demographic conditions; although this variable was the only significant variable that represented system characteristics.

Some parameters required many pre-processing steps. No sensitivity analysis was performed to study the uncertainty of the assumptions that these pre-processing required. As most of the uncertainties were thought to be inherent in the city, a sensitivity analysis was in practice also rather complicated.

Lastly, for the statistical analysis, the data was assumed to follow a Bernoulli distribution, thus a probability distribution of a random variable which has a pure binary character. Since there is no absolute boundary between the two levels 'severe accumulation' and 'hardly any accumulation' of FOG, it might not be possible to assign one of the two classes to each pumping station. It is unknown how this assumption has affected the outcome of the model.

4.2.9.4 Overall assessment

Despite all the aforementioned limitations, the dataset did enable the study of the relationship between FOG disposal and FOG deposits on a catchment scale. Thus, although the limitations might have decreased the external validity of this study, it did enable to reveal some important factors that influence the accumulation of FOG.

5 Conclusions

5.1 Building Drainage Systems

The first part of this study was designed to answer the sub-questions one through three as presented in Section 1.4. It presents a method to analyze FOG deposits in sewer systems in relation to individual FOG disposal patterns, i.e. the cooking oils and fats used by households. In addition, this thesis provides new information about the physical and chemical characteristics of FOG deposits in building drainage systems and about the variation in FOG deposits that emerge throughout the sewer network.

The relationship between FOG disposal patterns and FOG deposits in building drainage systems

This research shows that FOG deposits in building drainage systems are, to some extent, related to domestic FOG disposal patterns. Three out of the eleven samples displayed a fatty acid composition that was comparable to that of the cooking oils used; the amount of oleic and linoleic acid present was considerable. For two of these three samples, the entire distribution of fatty acids was comparable.

The other samples did not display such relationships and mainly contained saturated fat. While typical cooking oils are predominantly made up of unsaturated fatty acids, the deposits collected from lateral house connections had a maximum unsaturated acid content of two per cent. The spilling of animal fats and dairy products, which were not considered for this study, could have contributed to the higher saturated fat content; however, their saturated fat content was still much lower than the average values that were found in the FOG deposits.

The characteristics of FOG deposits in building drainage systems and how such deposits differ from main sewer FOG deposits

This study shows that FOG deposits collected from building drainage systems are metallic salts of fatty acids. This is similar to FOG deposits collected from main sewer systems. The appearance and chemical composition of the collected FOG deposits, together with the FTIR analysis performed for this study, demonstrate that such metallic salts result from the saponification reaction between calcium and FFAs. Despite this similarity, the deposits collected from different locations within the sewer network overall display a great variation. This suggests that they result from different formation mechanisms.

The deposits from kitchen drains tended to be grainy, which might be related to their high calcium levels and low total fat contents. It is thought that also debris is accumulated in the kitchen drain deposits.

The FOG deposits collected from lateral house connections had a predominantly soft, waxy consistency. Compared with the deposits from main sewers, the lateral house connection samples showed higher overall calcium levels. In addition to different environmental circumstances, such as water hardness, measurement methods might account for the differences. Besides, it is suggested that both the high calcium levels and the waxy appearance could have resulted from different calcium sources and their corresponding formation mechanisms (Iasmin et al., 2014).

Despite the relatively high calcium levels, six out of seven lateral house connection samples had a total fat to calcium ratio that was higher than the stoichiometric saponification ratio (2:1). It is suggested that the majority of lateral house connection FOG deposits contained excess FFAs due to compression of the electrical double layer (DLVO theory) that draws counter-charged particles within the FOG deposit matrix (He et al., 2011, 2013).

Furthermore, the FTIR analysis showed that glycerol accumulated in the lateral house connection deposits, suggesting that saponification was ongoing. These glycerol bands have not been observed in main sewer spectra before. It is thought that oil hydrolysis has taken place close to or within the FOG deposit matrix, potentially related to the cooling of fats within lateral house connections. In addition, it is thought that intermittent flow patterns in building drainage systems could have enhanced this accumulation of FOG.

For all FOG deposits, palmitic acid (C16:0) was the most common saturated acid, oleic (C18:1) the most common monounsaturated acid and linoleic (C18:2) the most common polyunsaturated acid. All deposits had fatty acid profiles with higher saturated fat content and shorter aliphatic chains compared to the profiles of the cooking oils used, suggesting that aliphatic chains have shortened over time due to the possible chemical and/or biological in sewer systems (Dereli, 2015; Lalman and Bagley, 2000; Matsui et al., 2005; Pereira et al., 2001). Hence, this suggests that such in-sewer transformations from unsaturated to saturated acid may already take place in building drainage systems.

Compared with the deposits from main sewers, the samples from building drainage systems overall showed higher calcium levels. In contrast to many public sewers, such systems are not made of concrete. Therefore, the results show that concrete is not essential for the FOG deposit formation process in sewer systems. It is thought that background levels of calcium in drinking water and calcium present in food accounted for the calcium in FOG deposits.

As calcium levels in food were not studied and all households were located in the same drinking water district with similar sewer system types, this study could not provide any quantitative information on the particular relationship between calcium disposal and the calcium content in FOG deposits.

The implications of the study findings

Although the results mainly provide information about the qualitative effect of the cooking oil disposal, this study provides valuable insights into the impact of FOG disposal patterns on FOG deposits in building drainage systems and reveals new information on characteristics of such FOG deposits. Since blocked building drainage systems have a large impact on the sewer serviceability and bring along high costs that are often born by individual property owners (Post, 2016b) this study may contribute to the development of more effective maintenance or measures to prevent FOG blockages in building drainage systems, thereby decreasing clearing costs for property owners. Nevertheless, further research is needed to obtain more information on the full impact of specific domestic disposal patterns on FOG deposits and consequential blockages.

5.2 Pumping Stations

The second part of this thesis used the scale of catchment areas and provides insights into important aspects of catchment demographics and pumping station characteristics that are related to the accumulation of FOG in pumping station. It thereby provides an answer to the fourth and fifth sub questions of the research question. Generalized linear mixed model (GLMM) procedures were used to analyse the data, consisting of 126 observations of catchments and corresponding pumping stations, located in five different cities. This study presents a procedure to model the probability of the presence or absence of FOG in pump sumps, as a function of demographic and general system characteristics of catchment areas.

The influence of population FOG disposal patterns on the accumulation of FOG in pumping stations

The final model contains three variables, representing the average income, FSE density, and kinetic energy of wastewater. The high significance of the variable income demonstrates that it is possible to identify a relationship between domestic disposal patterns and the accumulation of FOG in sewer systems on a catchment scale. This suggests that some aspects of lifestyle, i.e. FOG disposal patterns, are shared by particular demographic groups, thereby resulting in significant variation in the probability of FOG accumulation in pumping stations between catchment areas. Additionally, the analysis shows that structural configurations of pumping stations could play an essential role in the prevention of severe FOG accumulation.

The model reveals that severe accumulation of FOG in pump sumps is negatively related to the average income earned per person in the catchments. It is expected that particular FOG disposal patterns are shared by individuals of one income-group, as income cannot influence the accumulation of FOG in itself. Particular diets, cleaning habits and typical moments of FOG disposal might be aspects comprising such disposal patterns, and further research is required to obtain insights into how these aspects may influence the accumulation of FOG. As the dropped variable 'percentage of non-western immigrants' was highly correlated with income, these particular disposal patterns might be culture-bound.

Furthermore, the model revealed that FSE density is positively correlated with the presence of FOG deposits in pump sumps. As accumulation of FOG is generally known to be severe in restaurant and bar areas, it is thought that the presence of FSEs directly contributes to the accumulation of FOG.

The impact of sewer system characteristics on FOG accumulation in pumping stations

In addition to income and the presence of FSEs, the model finds a relationship between total kinetic energy of DWF per storage capacity and presence or absence of FOG in pump sumps. As previous studies mentioned the possible influence of low flow velocities on the FOG deposit formation process (Dirksen et al., 2012; Dominic et al., 2013) and since the flow velocity is directly proportional to the square root of kinetic energy, it is thought that there is a causal link between kinetic energy and the accumulation of FOG.

Since the dropped variable ‘daily operation time’ was correlated with the variable kinetic energy, and since this variable also affects the movement of water in pump sumps, it is thought that this variable might also have been driving the system.

The implications of the study findings

The results of this study can provide useful information for municipalities to prevent the accumulation of FOG or make maintenance strategies more effective. In particular for catchments receiving wastewater from areas where the average income is low and/or the FSE density is high, higher construction or remodelling costs to increase the kinetic energy might be justified. Adapting the switch-on and switch-off levels such that the invert level is above the representative water level might be an effective measure to prevent the accumulation of FOG; however one has to keep in mind the adverse effect of air entrainment that this measure could bring along. Further research is needed to find the most appropriate balance between the different design aspects of pumping stations. The benefits of the policy should outweigh its costs; hence, more profound insights into the effects of such measures, e.g. the consequences of discharging the FOG to wastewater treatment plants, are required.

The predictive performance of this model is inferior to describing relationships, as the study has used a descriptive modelling approach. It primarily provides new insights, and reveals important aspects of catchment demographics and pumping station characteristics that are related to FOG deposits in pump sumps. As the assumptions of both independence and homogeneity, however, were violated, the outcomes of the model should be interpreted with care.

This study demonstrates a procedure to reveal important user-based and system-based aspects that are related to the accumulation of FOG in pump sumps on a catchment-scale. As the model focused on the accumulation of FOG solely in pump sumps, it remains unknown to what extent this accumulation is representative for the accumulation of FOG throughout the entire sewer network of the catchment upstream.

5.3 Overall Sewer Network

This thesis qualitatively demonstrated that FOG disposal patterns influence the accumulation of FOG. It primarily provided new insights into the characteristics of FOG deposits in building drainage systems, and into important aspects of catchment demographics and pumping station characteristics that are related to the accumulation of FOG in pumping stations. Following from the answers to the sub questions that were given in the previous sections of this chapter, this thesis provides, to some extent, an answer to the main research question: *“What is the relationship between FOG deposits in sewer systems and FOG disposal pattern?”*

Further research is, however, required to understand how domestic FOG disposal patterns, sewer system characteristics, and geometrical configurations and operational settings of pumping stations influence the severity of FOG accumulation throughout the entire sewer network.

To be able to combine the outcomes of the study on both the scale of households and the scale of catchments, more detailed information on FOG usage and FOG disposal patterns on a geographical scale are essential.

6 Recommendations

6.1 Building Drainage Systems

6.1.1 Sampling method

Due to practical difficulties, only eleven FOG deposit samples were collected and seven questionnaires were conducted for this study. Because of this low number of observations, no statistical analysis was performed and, therefore, also no questionnaires were conducted with people without frequent FOG problems. Hence, only qualitative information about cooking oils and fats used could be studied. The relation between FOG blockage frequencies and FOG disposal patterns, for instance, was not investigated, and only suggestions on probable relations could be made.

For future research it is recommended to have a larger dataset; over thirty samples should be collected, both from kitchen drains and from lateral house connections. This enables performing a statistical analysis of FOG deposits in relation to FOG disposal patterns.

In addition, it is recommended to conduct questionnaires with two strata; both people with, and people without frequent FOG problems. Preferably, the second stratum, households without FOG problems, should be based on the first stratum, people with FOG problems. For instance, the direct neighbours of the households with blocked house connections could be approached, resulting in two strata with comparable conditions of lateral house connections and demographic characteristics.

6.1.2 FOG disposal patterns

The manner of collecting information on disposal patterns could have been suspicious to response biases. Regarding FOG disposal, only information on cooking oils was collected, while fat, oil and savoury sauces make up only 26% of the 88 g total fat consumption (Voedingscentrum, 1998). In addition, socially desirable answers might have been given. In an ideal situation, more precise information on disposal patterns, both qualitative and quantitative information, should be collected. Collecting samples or using sensors to analyse wastewater composition might give more precise information. In addition, data on water consumption and soap usage should be collected.

6.1.3 Site selection and analysis methods

For this study, all samples were collected from the same part of the city, as these were the service areas of the service engineers that collected the samples. To be able to study the influence of, for instance, drinking water hardness, pipe material, the (location of) connected downspouts and soil-settling rates, samples should be collected under varying conditions.

In addition, also other minerals apart from calcium should be measured, since this would provide information about the different metal ion sources, i.e., concrete sewers, drinking water or rainwater. Furthermore, Iasmin et al. (2014) showed the possible influence of pH and temperature on the formation process, which could be taken into account as well.

6.1.4 FOG within building drainage systems

The deposits collected from different locations within the sewer network displayed a great variation. For instance, the lateral house connection deposits that were collected for this study had a waxy appearance and predominantly consisted of saturated fat, while the deposits collected from main sewers in previous studies had a more grainy appearance and had higher unsaturated fat levels. It is unknown what has caused these differences.

In an ideal situation, FOG deposits from different locations within the same building drainage system and its connected main sewer should be analysed. By considering the FOG deposits at different locations within the same network, the differences in composition and formations mechanisms could be studied. Although clogging often occurs at particular locations within sewer systems, FOG is thought to accumulate in smaller quantities throughout the rest of the sewer system.

6.1.5 Biological activity

While lab-based calcium soaps that were produced under alkali-driven hydrolysis conditions displayed the same FFA profile as its fat source, for the FOG deposits collected from sewer systems this was not the case. It is thought that beta-oxidation caused by microorganisms may account for these in-sewer transformations (Ducoste et al., 2008; Matsui et al., 2005).

For future research it is recommended to study the influence of such biofilms in sewer systems, as this could provide useful information on the probable in-sewer transformations.

6.2 Pumping stations

6.2.1 Systematically recording of FOG accumulation

Recording the accumulation of FOG systematically would make the dataset more feasible for statistical analysis and would increase the reliability of the data.

As the responsible employees selected the pumping stations themselves, the dataset was sensitive to perception and only contained information about the 'presence' or 'absence' of FOG. There is no absolute boundary between the two levels, and the severity of accumulation was based on personal judgement. In addition, the dataset might have been subject to a selection bias, as the pumping stations that were selected were possibly not representative for the entire population.

This would be resolved when the presence and removal of FOG deposits would be systematically recorded. Quantitative information on FOG accumulation and the removal of such accumulation allows for improved data analysis. Hence, this information can be used to improve and enhance system performance, thereby preventing the accumulation of FOG, or to make municipal maintenance strategies more effective.

6.2.2 Sampling method

For this study, the GLLM assumptions of homogeneity and independence were violated. This is thought to be partly the result of an inappropriate sampling method. An underlying reason for the observed patterns could be the small number of observations with higher values for the explanatory variables. Systematically recording the accumulation of FOG was thought to resolve such patterns. Another solution, which might be less comprehensive, would be to alter the sampling method.

For future research, it is recommended to have a larger dataset, as this could resolve the observed dependency between observations and would enable to verify the significance of the model variables. The dataset should preferably be composed using a stratified sampling method (Buglear, 2010), as this would resolve the low number of observations for larger values (Zuur et al., 2009). It is proposed to base the strata, in addition to the two strata of clean and foggy pumping stations, on the significant variables from this study.

6.2.3 Information on system characteristics

This study solely focused on the accumulation of FOG in pumping stations and did not take into account the sewer system upstream. However, based on previous studies (de Groot et al., 2015; Dirksen et al., 2012; Dominic et al., 2013), it is thought that the presence of particular configurations, such as inverted siphons and sagging sewers, may prevents the pump sump to become filthy, since they cause the FOG to accumulate upstream of the pumping station. Hence, such configurations have to be considered if one is interested in the accumulation of FOG in pumping stations.

Additionally, environmental characteristics, such as soil inclination, and other system characteristics, such as pipe material, should be taken into account.

6.2.4 Information on demographics and FOG disposal

This study only took into account the demographic variables that were readily available from the database of Statistics Netherlands (2015). Little is known, however, about which demographic factors could possibly influence the accumulation of FOG, and the dataset did not contain any information on particular disposal patterns. Data on oil usage, e.g. from supermarkets, are essential to study such FOG disposal patterns on a geographical scale. This would also enable to link the result of studies that were performed on the larger scale of catchment areas and the smaller scale of building drainage systems.

6.2.5 Modeling approach

This study used a descriptive modeling approach, and investigated the relationship between the accumulation of FOG in pump sumps and demographics FOG disposal patterns. The dataset was therefore not split in a test and training set, resulting in overestimated values for model performance (Zuur et al., 2009). Hence, for future research, it is recommended to perform (simulation-based) cross-validation to compare model predictions against data. Then, representative data on model performance could be obtained. This enables to use to model for predictions, provided that the model assumptions are met by the data.

6.2.6 Physical processes of FOG accumulation

As this study used a statistical modelling approach, various simplifications on the pump sump geometry had to be made, and many parameters that influence such velocity patterns, e.g. the shape of the pump sump, the inlet position and the location of the suction inlet, were therefore not considered. Hence, to reveal information on the actual impact of kinetic energy and other parameters that are related to the motion of water in the pump sump, one should consider the physical processes occurring in the pumping stations.

This study showed that higher values for kinetic energy per unit of volume decrease the probability of FOG accumulation in pumping stations; however, higher values for kinetic energy could increase the risk of air entrainment. This could lead to pump failures. Hence, future research should focus on finding the most appropriate balance between the prevention of FOG accumulation and the prevention of air entrainment.

In addition, FOG is known to accumulate at different places within the pump sump and these FOG deposits show different characteristics and appearances. Also following from the results of the study on the scale of building drainage systems, it is thought that the appearance depends on, among other things, particular FOG disposal patterns and FOG formation processes. This suggests that the binary character of the response variable might have oversimplified the situation, which could have affected the values of the estimated parameter coefficients. Hence, for future studies, one may want to differentiate between such different appearances.

6.2.7 Cost effective FOG removal

FOG is known to accumulate at various locations within the sewer network; this implies that if its accumulation will be prevented at one place, it is likely to accumulate at another place. Thus, if pumping stations will be designed such that FOG will be discharged by pumps, it may accumulate in pressurized pipes or it

ends up at wastewater treatment plants, where it could inhibit treatment processes (Cammarota and Freire, 2006).

As there is currently limited knowledge available on the formation of FOG deposits, the associated costs for its removal from different locations within the sewer network and possible solutions to prevent the accumulation of FOG, i.e. biodegradation (He et al., 2015) and the ‘flushing regimes’ that Waternet is currently experimenting with (see Section 4.2.7), further research is required that focuses on cost effective FOG removal.

Appendix A: FTIR spectrometry

Fourier transform infrared (FTIR) spectroscopy, the first application of which was presented by Fahrenport (1961), uses infrared radiation that is passed through a sample. The resulting spectrum depends on the sample's molecular structure with absorption peaks corresponding to frequencies of the stretching and bending vibrations of specific intermolecular bonds. Figure 33 shows the different molecular vibrations that are able to absorb infrared light. For FOG deposits, this could provide information on the presence of calcium-oxygen bonds for instance, hence making FOG deposits the result of saponification reactions.

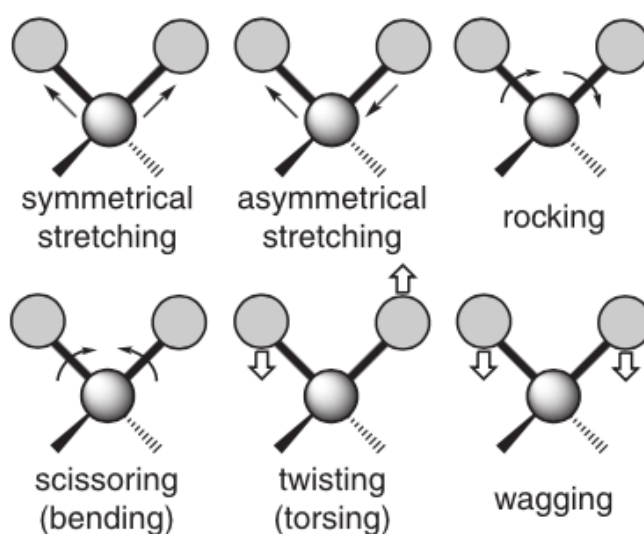


Figure 33 - Molecular vibrations that are able to absorb infrared light, resulting in FTIR spectra corresponding to specific molecular structures. The black arrows indicate motions in the paper plane and the white arrows indicate movement out of the paper plane. (Blum and John, 2012)

Appendix B: Questionnaire (in Dutch)

Beste,

Graag nodig ik u uit om deel te nemen aan mijn afstudeeronderzoek over verstopping van riolering door vet. Vet kan, in combinatie met zeep, leiden tot harde afzettingen in het riool en zo leiden tot verstoppingen. Onduidelijk is hoe verstopping door vet kan worden voorkomen. Ik ben een student Water Management van de Technische Universiteit in Delft. Voor mijn onderzoek neem ik deze enquête af en neem ik een monster van het vet uit het riool. Vervolgens onderzoek ik wat de relatie is tussen deze twee.

Ik gebruik de resultaten alleen voor mijn onderzoek. Ik geef in geen geval informatie van dit onderzoek door aan derden.

Het beantwoorden van de vragen duurt ongeveer 10 minuten.

Bij voorbaat dank,

Eva Nieuwenhuis
Student Water Management
Technische Universiteit Delft

Inleiding onderzoek

Wie ben ik?

Ik ben een student Water Management van de Technische Universiteit in Delft. Voor de laatste opdracht van mijn studie doe ik onderzoek naar verstopte rioleringen door vet. Hiervoor neem ik deze enquêtes af en neem ik een monster van het vet uit het riool.

Wat is het onderzoek?

Vet veroorzaakt vaak verstoppingen in rioleringen en dit kan leiden tot stank, lekkages of zelfs overstromingen. Vet kan in het riool terecht komen door bijvoorbeeld het schoonmaken van pannen. Het verzamelt zich op bepaalde plekken in het riool en kan zo het riool verstoppen. Het is onbekend waarom vet op de ene plek wel tot problemen leidt en op andere plekken niet. Ligt het aan de leiding, komt dit door het soort vet of misschien het moment van afwassen? Het doel van mijn onderzoek is om te kijken wat de verstoppingen door vet veroorzaakt.

Hoe wil ik dat onderzoeken?

Ik neem een monster (een stukje) van het vet in uw riool. Ook wil ik u vragen stellen om te kijken wat voor vet u vooral gebruikt en hoe dit uiteindelijk in het riool terecht komt. De vragen gaan over de leiding en uw huis, over het vet waarmee u kookt en over het afwassen en wassen. Vet en zeep samen kan namelijk ook leiden tot verstopping. Het vragenstellen duurt maximaal 10 minuten. Alle gegevens zullen vertrouwelijk behandeld worden en ik ben de enige die de enquêtes inkijkt.

Wat gebeurt er met de resultaten?

De resultaten zijn alleen bedoeld voor mijn onderzoek. Als bijvoorbeeld uit dit onderzoek blijkt dat uw gedrag rioolverstoppingen bevordert, zult u niet ineens meer hoeven te betalen.

Als u geïnteresseerd bent in de resultaten, houd ik u op de hoogte.

Algemene informatie

Codering monster:

Informatie over systeem/aansluiting (invullen, samen met RRS)

Woningtype: aantal bouwlagen

Huisaansluiting: aantal aangesloten huizen op 1 leiding

Leidingwerk: materiaal

Gietijzer

Gres

PVC

PE

Beton

Anders:

Leidingwerk: conditie/lengte/leeftijd/etc:

Type systeem benedenstrooms:

Gemengd

Gescheiden

Locatie van verstopping

Hangende leiding

Grondleiding

Na de gootsteen

Anders:

Monstername:

Beschrijving monster:

Bouwjaar huis:

Algemene informatie (vragen aan bewoner)

Wie is de huiseigenaar?

Koophuis

Huurhuis (particulier)

Huurhuis (woningbouwcorporatie)

Wat is de grootte van uw huishouden?

Sinds hoeveel jaar woont u hier?

Hoeveel verstoppingen heeft u gehad afgelopen 10 jaar?

Hoeveel verstoppingen hiervan waren hiervan in de keuken (aanname=vet)?

Hoe vaak draait de wasmachine gemiddeld per week?

Op hoeveel graden draait de wasmachine gemiddeld?

30

40

60

90

Anders:

Op welke moment draait de wasmachine vooral?

Ma-vr (doordeweeks)

7-10 (ochtend)

10-17 (middag)

17-21 (avond)

21-7 (nacht)

nvt

Za-zo (weekend)

7-10 (ochtend)

10-17 (middag)

17-21 (avond)

21-7 (nacht)

nvt

Wat voor zeep gebruikt u voor de wasmachine?

Vloeibaar wasmiddel

Poeder wasmiddel

Gel wasmiddel

Tabletten

Anders:

Hoe vaak draait de afwasmachine gemiddeld per week?

Op welk programma draait de afwasmachine gemiddeld?

Licht/eco programma (<50 graden)

Normaal/dagelijks/auto programma (55-65 graden)

Intensief programma (70 graden)

Anders:

Op welke moment draait de afwasmachine vooral

Ma-vr (doordeweeks)

7-10 (ochtend)

10-17 (middag)

17-21 (avond)

21-7 (nacht)

nvt

Za-zo (weekend)

7-10 (ochtend)

10-17 (middag)

17-21 (avond)

21-7 (nacht)

nvt

Wat voor soort afwasmiddel gebruikt u voor de afwasmachine?

Poeder afwasmiddel

Tabletten

Anders:

Wast u vieze pannen/schalen/bakplaten met de hand af of gaan deze in de afwasmachine?

Handafwas

Vaatwasser

Nvt (niet van toepassing)

Anders:

Als er vieze pannen/schalen/bakplaten bij de afwas zijn, wordt hier iets mee gedaan voordat ze af gewassen worden?

Een doekje door de pan/schaal halen

Voorspoelen met water

Laten weken in water

Nvt (niet van toepassing)

Anders:

Als u de afwas met de hand doet, op welke momenten doet u meestal een dergelijke afwas (dit gaat alleen over een grote afwas; die ook pannen/borden bevat)?

's Ochtends (7-10)

's Middags (10-17)

's Avonds (17-21)

's Avonds laat/ 's nachts (21-7)

Nvt (niet van toepassing)

Hoe vaak doet u een dergelijke 'grote' afwas per dag?

Heeft en gebruikt u een kitchen grinder?

Ja

Nee

Kook-/eetgewoonten (vragen aan bewoner)

Hoe vaak wordt er per week warme maaltijd gekookt in uw huishouden?

Wat voor olie/vet wordt er met name gebruikt om in te koken? (meerdere antwoorden mogelijk)

Roomboter

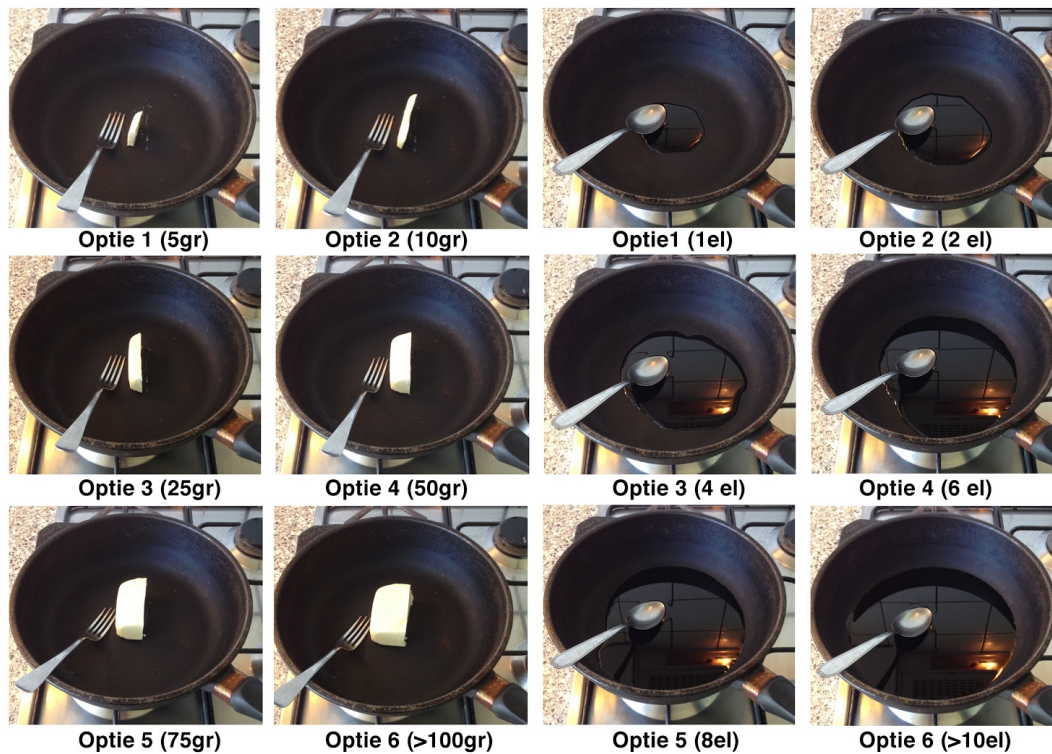
Margarine
Vloeibaar bak- en braadvet
Dierlijk vet
Olijfolie
Zonnebloemolie
Kokosolie
Andere plantaardige olie (mais, soja, rijstolie)
Anders:

Als er wordt gekookt met boter bij u thuis; welke hoeveelheid wordt er dan gemiddeld in de pan gebruikt? (Zie Figuur 1; deze plaatjes zijn per email verstuurd)

Optie 1 (5 gram)
Optie 2 (10 gram)
Optie 3 (25 gram)
Optie 4 (50 gram)
Optie 5 (75 gram)
Optie 6 (>100 gram)
Nvt

Als er wordt gekookt met olie/vloeibaar vet bij u thuis; welke hoeveelheid wordt er dan gemiddeld in de pan gebruikt? (Zie Figuur 1; deze plaatjes zijn per email verstuurd)

Optie 1 (1el)
Optie 2 (2el)
Optie 3 (4el)
Optie 4 (6el)
Optie 5 (8el)
Optie 6 (>10el)
Nvt



Figuur 1 – Gemiddelde gebruikte hoeveelheid vet (links) of olie (rechts) om in te bakken

Hoe vaak wordt er per maand in uw huishouden gefrituurd (in de pan of frituurpan)?

Wat voor vet gebruikt u thuis om te frituren?

Vloeibaar frituurvet

Vast frituurvet

Dierlijk vet

Nvt (niet van toepassing)

Anders:

Wat wordt er met het frituurvet gedaan bij het schoonmaken van de pan?

Afgieten in de gootsteen

Afgieten in de wc

Overschenken en weggooien in de prullenbak/inzamelpunt

Nvt (niet van toepassing)

Anders:

Wat wordt er met olie uit tonijn/gedroogde tomaat/tapas gedaan na gebruik?

Afgieten in de gootsteen

Afgieten in de wc

Weggoeien in de prullenbak (eventueel na overschenken)

Nvt (niet van toepassing)

Anders:

Hoeveel van dit soort potten op olie worden er gemiddeld per week gebruikt?

Wat wordt er met restjes room, yoghurt of melk gedaan?

Leeggooien in de gootsteen
Leeggooien in de wc
Weggooien met verpakking en al
Nvt (niet van toepassing)
Anders:

Hoeveel kopjes (100ml) van deze melkproducten worden er gemiddeld per week weggegooid?

Wat wordt er gemiddeld met restjes soep en saus gedaan?
Leeggooien in de gootsteen
Leeggooien in de wc
Weggooien in de prullenbak
Nvt (niet van toepassing)
Anders:

Hoe vaak per week komt dit voor?

Bedankt voor uw medewerking! Bent u eventueel beschikbaar voor verdere vragen mocht ik iets over het hoofd hebben gezien met het afnemen van de vragen?

Appendix C: Letter to the municipalities (in Dutch)

Geachte Gemeente, Afdeling Watermanagement,

Mijn naam is Eva Nieuwenhuis en ik ben bezig met mijn afstudeeropdracht met als onderwerp 'relatie tussen lozingsgedrag en vetophoping in riolen'. Deze afstudeeropdracht is onderdeel van het kennisprogramma Urban Drainage en wordt begeleid door prof.dr.ir. Francois Clemens en dr.ir. Jeroen Langeveld.

Vetaanslag is een belangrijke oorzaak van verstoppingen van gemalen, zinkers persleidingen, riolen en huisaansluitingen en vormt een grote kostenpost voor gemeentes en burgers. Voor bijvoorbeeld huisaansluitingen is bekend dat 40% van de verstoppingen samenhangt met vetophoping.

Opvallend is dat in sommige bemalingsgebieden de vetproblematiek ernstiger is/likt dan in andere bemalingsgebieden. Het is aannemelijk dat dit (deels) komt door verschillen in lozingspatronen van (individuele) gebruikers en dat het lozen van meer vet, leidt tot hogere verstoppingsfrequenties en versnelde drijf laagvorming bij gemalen.

In mijn afstudeeropdracht wil ik in beeld brengen op welke wijze vetophoping zich manifesteert in de riolering en of het mogelijk is een relatie te leggen met stelsel- dan wel populatiekenmerken. Op het niveau van huisaansluitingen ga ik dit onderzoeken door voor een aantal verstopte huisaansluitingen de aard van de vetverstopping na te gaan en bij de bewoners te informeren naar hun eet- en kookgedrag.

Op het niveau van bemalingsgebieden wil ik graag in beeld brengen welk deel van de bemalingsgebieden op basis van vetophoping in het gemaal is te karakteriseren als 'vies' en in hoeverre dit te linken is aan stelselkenmerken, inspectiebeelden en populatiekenmerken.

Voor het onderzoek op het niveau van bemalingsgebieden wil ik u hierbij vragen om uw medewerking. Deze medewerking bestaat uit het verstrekken van de volgende gegevens:

- Vetophoping: welke gemalen in uw gemeente staan specifiek bekend om:
 - o Het optreden van vet problemen en zo ja, is het mogelijk een indicatie te geven van benodigde reinigingsfrequentie en verwijderde hoeveelheden?
- Algemene stelselkenmerken voor alle bemalingsgebieden:
 - o pompcapaciteit
 - o type systeem (gescheiden of gecombineerd)
 - o begrenzing van het bemalingsgebied
- Specifieke gegevens voor aantal (nog te selecteren) bemalingsgebieden:
 - o kenmerken leidingen: materiaal, diameter, leeftijd
 - o geclassificeerde inspectiebeelden, met name de aspecten vetafzetting en waterdiepte

U wordt vriendelijke verzocht de informatie per email te versturen naar e.m.nieuwenhuis@student.tudelft.nl. Wanneer u vragen heeft, schroom dan niet contact op te nemen met ondertekende.

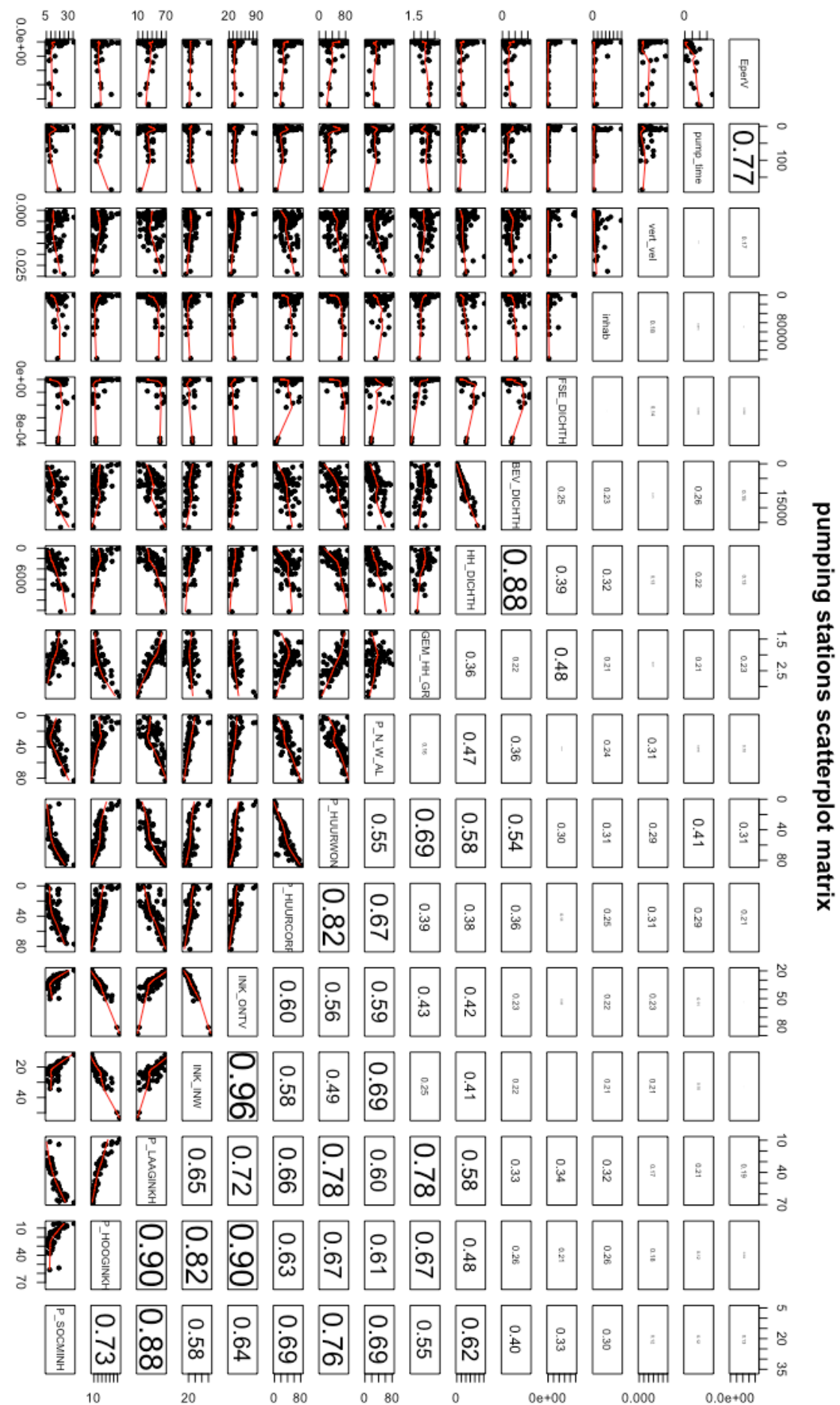
In afwachting van uw antwoord,

Eva Nieuwenhuis
Student Watermanagement

e-mail: e.m.nieuwenhuis@student.tudelft.nl
telefoon: 06-42897409

Appendix D: Pairplot for all continuous explanatory variables

The pairplot contains scatterplots with smoothers in the lower panels, and Pearson's correlations in the upper panels.



Appendix E: Statistical tools for data exploration

Statistical tools were used to enhance data exploration. The background of such tools is briefly discussed in this section.

Variance inflation factor

Variance inflation factors (VIFs) are used for investigating (multi)collinearity. Collinearity is the situation in which there are high correlations among explanatory variables, meaning that one predictor is linearly predicted from the other. Compared with the situation without collinearity, estimated coefficients have higher standard errors and they can also become unreliable and unstable, thus resulting in coefficient estimates that are difficult to interpret as independent effects (Neter et al., 1996).

Pairwise correlations among explanatory variables can be examined with visual inspection tools. Such tools, however cannot examine linear dependence among three or more explanatory variables, while variance inflation factors (VIFs) can. The terminology of VIF is due to Marquardt (1970). VIFs measure for each explanatory variable the combined effect of dependences among the explanatory variables on the variance of the particular explanatory variable. The originally response variable is left out and one of the explanatory variables is selected as response variable, while all others are set as explanatory variables within a linear regression model (Montgomery et al., 1992). The value for VIF for the selected variable β is:

$$VIF_{\beta} = \frac{1}{1 - R^2} \quad (23)$$

In which R^2 is the R-squared from the linear regression model, so giving the amount of variation explained by the explanatory variables in the linear regression model. This process is repeated to calculate the VIF values for each explanatory variable of the original model.

Since VIFs calculate how much the variances of regression coefficient parameters are inflated compared with the situation in which the variable would not have been related to others in the model, VIFs are related to the variance of the model parameters: the standard errors of the parameters are augmented with the square root of the VIFs. This implies that a high VIF value is an indication of collinearity, as it means that the variation in the response variable could be explained by the other variables.

One suggests sequentially dropping one variable and repeating the VIF calculation process, until all VIFs are smaller than a preselected threshold (Montgomery et al., 1992). There is, however, no absolute cut off level for the VIF. Previous statistical studies used values ranging from 2 (Zuur et al., 2010) up to 10 (Montgomery et al., 1992).

Cooks Distance

Cooks Distance statistics enable to detect outliers in the explanatory variables and provide information on the change in the regression coefficients for each

observation if the observation would be omitted (Cook, 1977). It is a measure that combines the information of leverage and residual of an observation, in which leverage is a measure for the deviation from the mean of a particular explanatory variable. The greater an observation's leverage, the greater is its potential impact on the estimated regression coefficients. For the underlying mathematics one can read Cook et al. (1977).

Cook Distance cut off values are not absolute and vary between $\frac{4}{n-k-1}$ where n is the number of observations and k is the number of regression coefficients (Fox and Weisberg, 2010), and the often mentioned operational guideline of 1 (Zuur et al. 2009). Visualization of the Cooks Distance is often used to identify the remarkable observations that should be examined in more detail.

Akaike information criterion

The Akaike information criterion (AIC) provides means for model selection, as it is a measure for relative model quality. AIC is an information theory, and provides a framework that allows model comparisons for one given dataset. AIC combines goodness of fit and model complexity in one value and is defined as:

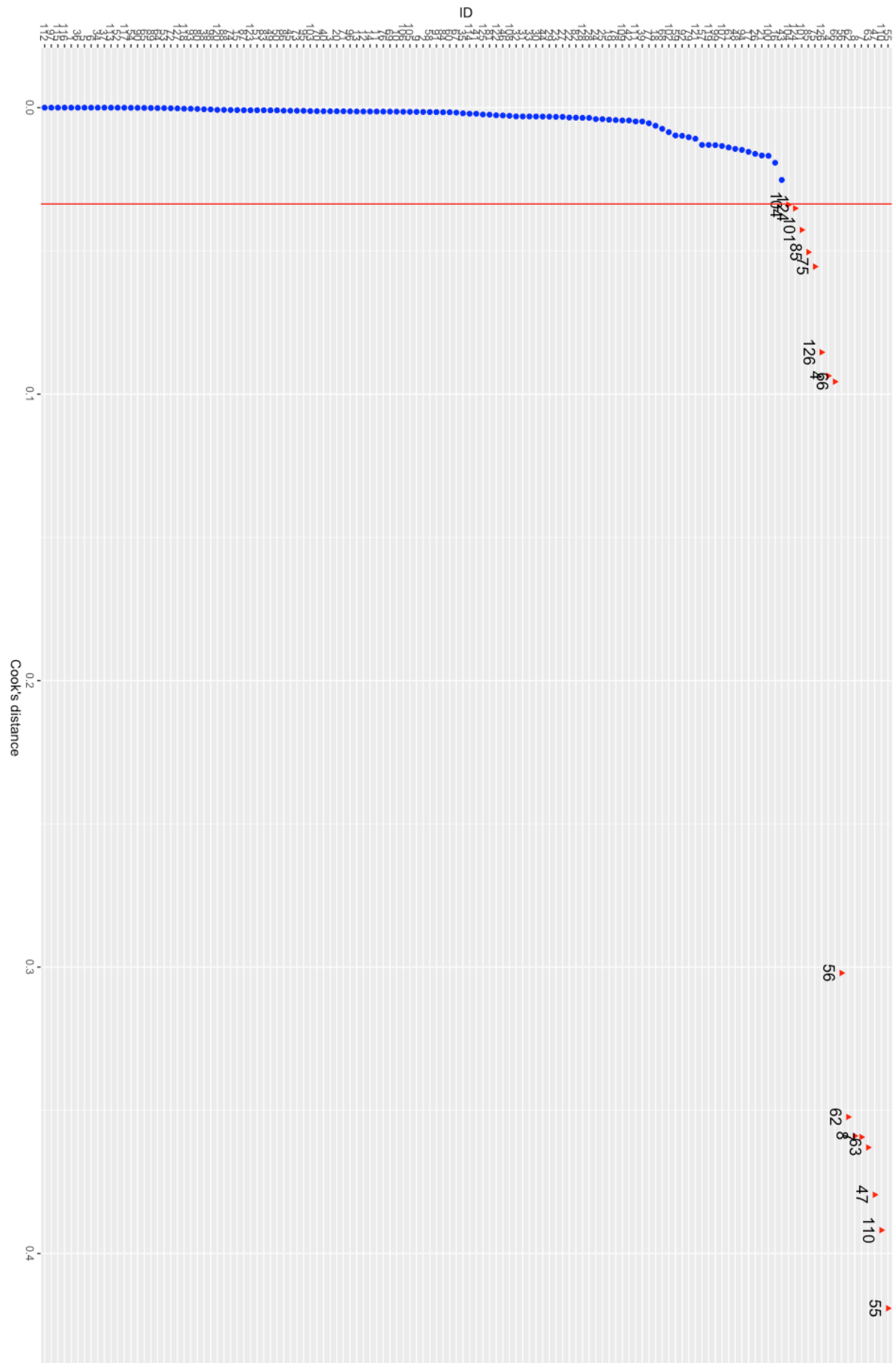
$$AIC = -2L + 2K \quad (24)$$

where L is the maximum log-likelihood of the particular model and K the number of model parameters (Akaike, 1992). The AIC value is a trade off between model biases and model precession, which entails that the lower a model's AIC, the higher the quality of this model.

As there are different log-likelihood functions, i.e. the REML and the ML, and as the number of parameters depends on the particular dataset, the AIC only allows model comparison of models that are applied on the same dataset (Zuur et al., 2009).

Appendix F: Cooks Distance Plot

Visualization of the Cooks Distance statistics



Appendix G: Theory on statistics

In this appendix, first the general concept behind linear models is explained; thereafter, the theory behind GLMs and GLMMs is discussed and additionally, some statistical tools to enhance data exploration and model selection are reviewed.

GLMMs are extensions to generalized linear models (GLMs). In statistical theory, GLMs were first proposed by Nelder and Wedderburn (1972). They contain a *link* function that links the response variable to the linear regression model, which makes GLMs a generalisation of linear regression. As GLMMs allow for correlations between the observations of the same group, they are extensions of GLMs. GLMMs contain both a *fixed* and a *random* component that explain the response variable; and therefore, they are called *mixed* effects models. The structure of GLMMs follows logically from the structure of Linear Mixed Effects Models, that was first proposed by Laird & Ware (1982).

Linear regression models

The underlying model of (multiple) linear regression takes the form:

$$Y_i = \alpha + \beta_1 \times X_{1i} + \beta_2 \times X_{2i} + \dots + \beta_M \times X_{Mi} + \varepsilon_i \quad (25)$$

$$\varepsilon_i \sim N(0, \sigma^2)$$

The measurement value Y_i is the response (or dependent) variable and is related to M explanatory (or independent) variables X_i . The regression coefficients α and β_i represent the intercept and the slope of the response variables X_i , respectively. The error term ε_i captures all information that remains unaccounted for by the model; e.g., measurement errors or other factors, in addition to the identified variables, that influence the response variable. In a linear regression model, the error term should be normally distributed with mean 0 and variance σ^2 . The model is often fitted using least squares estimates. Based on a random sample with N observations, the regression coefficients $b_0, b_1, b_2, \dots, b_m$ are estimated so that the sum of squared residuals is minimal. Based on such estimators and a set of assumptions, the response variable should follow a normal distribution for example, a statement on the population is made, resulting in the regression coefficients, $\beta_0, \beta_1, \beta_2, \dots, \beta_m$. Other essential assumptions that are made when using a linear model to describe a dataset are: homogeneity, or constant variance in the errors of the data values for all variables, and independence of the explanatory variables. Theoretically, all these assumptions must hold for a dataset to justify the use of linear regression. This limits the applicability of linear regression, since for most datasets, i.e. ecological datasets, this is often not the case (Zuur et al., 2009). To overcome violation of homogeneity, generalized linear regression can be applied.

Generalized linear models

GLMs are based on the theoretical framework of linear regression models and use a unified procedure for fitting the relationship between the response variable and the explanatory variables (McCullagh and Nelder, 1989; Nelder and Wedderburn,

1972). GLMs include a wide variety of statistical models, for example: classical linear regression, logistic regression and Poisson regression. Nelder and Wedderburn (1972) first introduced the class of GLMs, although they did not establish the most important models in the class. McCullagh and Nelder (1989) thoroughly discussed the theory of GLMs and its application on different distributions.

GLMs are characterized by the following aspects: (i) the response variable that follows an arbitrary distribution, rather than a Gaussian distribution as is the case with linear models; (ii) a *linear predictor*, which is a linear combination of the explanatory variables; and (iii) a *link function* that connects the mean of the distribution function of the response variable with the function of the explanatory variables (Nelder and Wedderburn, 1972).

McCullagh and Nelder (1989) specified these characteristics as the three *components* of GLMs: (i) a *random component* that identifies the response variable and its probability distribution; (ii) a *systematic component* that specifies the explanatory variables used in a linear predictor function, and (iii) an *identity link* that specifies the function of the expected value of the response variable and that links the systematic component to the random component. These common properties of GLMs enable to study GLMs as a single class, rather than an unrelated collection of models (McCullagh and Nelder, 1989).

The exact relationship between the response variable and the explanatory variables depends on the particular distribution of the response variable. The model parameters are often estimated by maximum likelihood-based methods, as was also proposed by Nelder and Wedderburn (1972), and McCullagh and Nelder (1989). This results in parameters that maximize the likelihood of making the observations given the parameters. The structure of GLM models allows the magnitude of the variance, which is the expected squared deviation, of each measurement to be a function of its predicted value.

Here, the application of GLMs to describe a dataset that follows a Bernoulli distribution is discussed.

Bernoulli GLMs

The modification of the three characteristic elements of GLMs, the probability distribution, the linear predictor and the link function, for application on data following a Bernoulli distribution are briefly discussed. This GLM uses a logistic *link* function, and is therefore also referred to as a logistic regression model. A comprehensive explanation can be found in McCullagh & Nelder (1989) or Agresti (2002).

Distribution of the response variable

Bernoulli distributions are a special form of binomial distributions. Binomial distributions describe the behaviour of a discrete variable Y_i , in N independent and identical experiments with fixed probability of the possible outcomes. The probabilities are often described as ‘success’ ($Y_i = 1$) with probability $P(Y_i = 1) = \pi$ and ‘failure’ ($Y_i = 0$) with $P(Y_i = 0) = 1 - \pi$. The density function of binomial distributions is:

$$f(y; \pi, N) = \binom{N}{y} \times \pi^y \times (1 - \pi)^{N-y} \quad (26)$$

The function $f(y; \pi)$ gives the probability of success for every value between 0 and N. For Bernoulli distributions $N = 1$, which leads to the following function describing the Bernoulli distribution:

$$f(y; \pi) = \pi^y \times (1 - \pi)^{1-y} \quad (27)$$

This can also be written as $Y_{ij} \sim B(1, \pi_{ij})$, where mean is given by $E(Y_{ij}) = \pi_{ij}$ and the variance by $\text{var}(Y_{ij}) = \pi_{ij} \times (1 - \pi_{ij})$.

Linear predictor

The linear predictor η incorporates the information of the explanatory variables into one quantity and follows the form of the linear regression model:

$$\eta(\beta_i, X_{ij}) = \boldsymbol{\beta} \times \mathbf{X} \quad (28)$$

Where $\boldsymbol{\beta}$ is the regression coefficient matrix and $\mathbf{X}$ the design matrix, or the matrix of explanatory variables.

Link function

GLMs measure the relationship between the discrete response variable and one or more explanatory variables by estimating probabilities using a logistic function, thus modelling π as a function of explanatory variables. The link function should transform the linear predictor η into probabilities between 0 and 1, rather than the continuous outcome of linear regression models.

This is done by the *logistic* link function (or the *logit* function) for example. Other link functions, such as the *probit* link and the *cloglog* link, are available for binomial GLMs as well, but in literature on binomial GLMs, the *logit* link is most frequently used (Agresti, 2002; Zuur et al., 2009). The *logit* of the probability is the logarithm of the odds. The odds (O_{ij}) do not have an upper bound, and thus represent probability on a different scale than π_{ij} :

$$O_{ij} = \frac{\pi_{ij}}{1 - \pi_{ij}} \quad (29)$$

By taking the natural logarithm of the odds, the probabilities are released from their lower limit and can become negative:

$$\log(O_{ij}) = \text{logit}(\pi_{ij}) \quad (30)$$

Hence, the *logit* of the odds enable mapping of the values of η between 0 and 1, as is shown in Figure 34

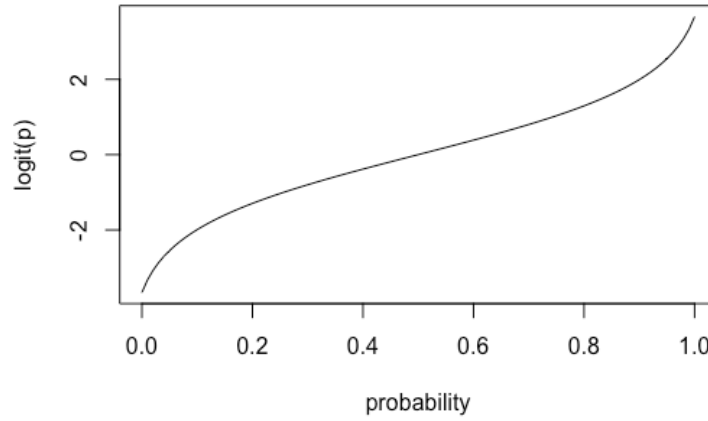


Figure 34 - Plot of the logit p

The GLM for the Bernoulli distribution is now given by:

$$\begin{aligned} \text{logit}(\pi_{ij}) &= \eta(\beta_i, X_{ij}) \Leftrightarrow \\ \pi_{ij} &= \frac{e^\eta}{1 + e^\eta} = \frac{e^{\beta_0 + \beta_1 \times X_{1i} + \beta_2 \times X_{2i} + \dots + \beta_M \times X_{Mi}}}{1 + e^{\beta_0 + \beta_1 \times X_{1i} + \beta_2 \times X_{2i} + \dots + \beta_M \times X_{Mi}}} \end{aligned} \quad (31)$$

Generalized linear mixed models

Generalized linear mixed models (GLMMs) are extensions to GLMs; they enable the incorporation of a temporal or spatial dependence structure between the observations in the model. The random intercept model is an example of such a GLMM.

By assuming a different intercept term for all pairs of observations that belong to the same subject or group, GLMMs solve the non-independence that stems from such pairs of observations. In addition, the allowance for the correlations of the observations, implicitly imposes the compound symmetrical correlation structure (Jiang, 2007). Mistakenly ignoring such dependence structures and applying a common GLM could lead to a different set of significant explanatory variables (Zuur et al., 2009).

GLMMs contain both a fixed and a random component that explain the response variable; and therefore, they are called *mixed* effects models. Compared with the specifications of GLMs and its characteristic components, the distribution of GLMMs is specified as a conditional distribution, and the linear predictor contains an additional component that specifies the random term of the model.

Bernoulli GLMMs

In this literature review, only the inclusion of a random intercept in binomial GLMs is discussed, in extension to the theory on Binomial GLMs. The underlying mathematics can be found in Jiang (2007).

For Bernoulli GLMMs, the random term covers the random intercept. The fixed component of the GLMM describes the average curve of the predicted probabilities, while the random component describes the shift up- or downward of it.

The random term is assumed to be normally distributed with a mean of zero and a certain variance; the smaller this variance, the smaller the contribution of the random intercept and the smaller the variation between the predicted values per group of subject that contain the pairs of observations. As the variance within groups is σ^2_{within} and the variance between groups $\sigma^2_{between}$, the total variance is given by $\sigma^2_{total} = \sigma^2_{within} + \sigma^2_{between}$. While the observations from different groups are considered to be independent, and thus uncorrelated, the correlation between any two observations in the same group equals:

$$\rho = \sqrt{\sigma^2_{within} / \sigma^2_{total}} \quad (32)$$

which explains the compound symmetrical correlation structure of GLMMs.

Distribution of the response variable

Conditional on the random effects b_i , the observations Y_{ij} are binomial distributed with probability $\pi_{ij}|b_i$, in which i stands for the identity of the particular subject that the pairs of observations belong to.

From here, the relationship between the conditional mean of Y_{ij} , in other words the mean value of Y_{ij} for given b_i , and the conditional variation of Y_{ij} can be given by:

$$E(Y_{ij}|b_i) = \pi_{ij}|b_i \quad (33)$$

$$\text{var}(Y_{ij}|b_i) = \pi_{ij}|b_i \times (1 - \pi_{ij}|b_i) \quad (34)$$

Linear predictor

The linear predictor η incorporates the information of the explanatory variables and the random term into one quantity and follows the form of the linear regression model:

$$\eta(X_{ij}, Z_{ij}) = \boldsymbol{\beta} \times \mathbf{X} + \mathbf{b} \times \mathbf{Z} \quad (35)$$

where $\boldsymbol{\beta}$ is the regression coefficient matrix, $\mathbf{X}$ the design matrix of the explanatory variables, $\mathbf{b}$ the random intercept matrix, and $\mathbf{Z}$ the design matrix of the random effects; hence, where $\boldsymbol{\beta} \times \mathbf{X}$ is the fixed effect and $\mathbf{b} \times \mathbf{Z}$ is the random effect.

Link function

The relationship between the conditional mean and the explanatory variables is determined by the logistic link:

$$\text{logit}(\pi_{ij}|b_i) = \eta(\beta_i, X_{ij}) = \alpha + X_i \times \beta + Z_i \times b_i \quad (36)$$

where the random effects b_i are assumed to be normally distributed with a mean of zero and covariance matrix D .

GLMM likelihood functions

Similar to GLMs, the model parameters of GLMMs are often estimated by maximum likelihood-based methods. The form of such likelihood functions for GLMM, however, is much more complicated, as multidimensional integrals are involved (Jiang, 2007). Obtaining parameter estimates in GLMM is therefore difficult, and their actual fitting algorithms depend on the computational method used.

To improve convergence, and thus enable model fitting of GLMMs, explanatory variables should be on comparable scales. The continuous explanatory variables are therefore often standardized prior to fitting, which particularly prevents numerical solver issues for calculating the standard deviations of the fixed effects. Additionally, this standardizing enhances the comparison of effect sizes of the different parameters. (Zuur et al., 2009)

To obtain standardized variables, the mean μ_i is subtracted from the value for each observation X_{ij} , and divided by the standard deviation σ_i , resulting in a mean of zero and a standard deviation of one:

$$X_{ij,standardized} = \frac{X_{ij} - \mu_i}{\sigma_i} \quad (37)$$

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