A Study on the Fouling Process in Inverted Siphons over Time

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Abstract In Amsterdam, over 200 so called inverted siphons are situated. As these siphons are prone for blockages, it is key that these parts of a sewer system are maintained proactively. This article outlines the basis of a methodology that can be used to estimate the fouling degree of sewers with the use of water level measurements. Even though the measurement period appeared to be of restricted length, the methodology can be considered promising. Furthermore, evidence has been found that the cleaning regime plays a role in the initial accumulation of Fat, Oil and Grease (FOG), which therefore could be the basis of the development of effective measures to prevent blockages.

Keywords inverted siphon; FOG; blockage; measurement technique

Introduction

Over the years, there has been an increased shift from reactive maintenance towards proactive maintenance in sewer asset management (Arthur, Crow, & Pedezert, 2008). Nevertheless, despite regular, proactive maintenance, clogging still occurs in sewer systems. About 50 to 75% of all sewer blockages is thought to be caused by Fat, Oil and Grease (collectively termed FOG) deposits (Keener, Ducoste, & Holt, 2008). The majority of these FOG deposits appear to be metallic salts of fatty acids, which exhibit high sample strengths (Keener, Ducoste, & Holt, 2008). Therefore, blockages can require quite some effort to be removed, and are preferred to be prevented rather than resolved. In order to implement a proactive cleaning strategy to prevent these FOG blockages, more information is needed on the accumulation process of FOG deposits in sewer systems.

Even though there are numerous studies performed on the physical properties of FOG deposits as well as on managing FOG in sewer systems (e.g. Williams et al. (2012), He et al. (2013) and Arthur et al. (2008)), little research has been done on the

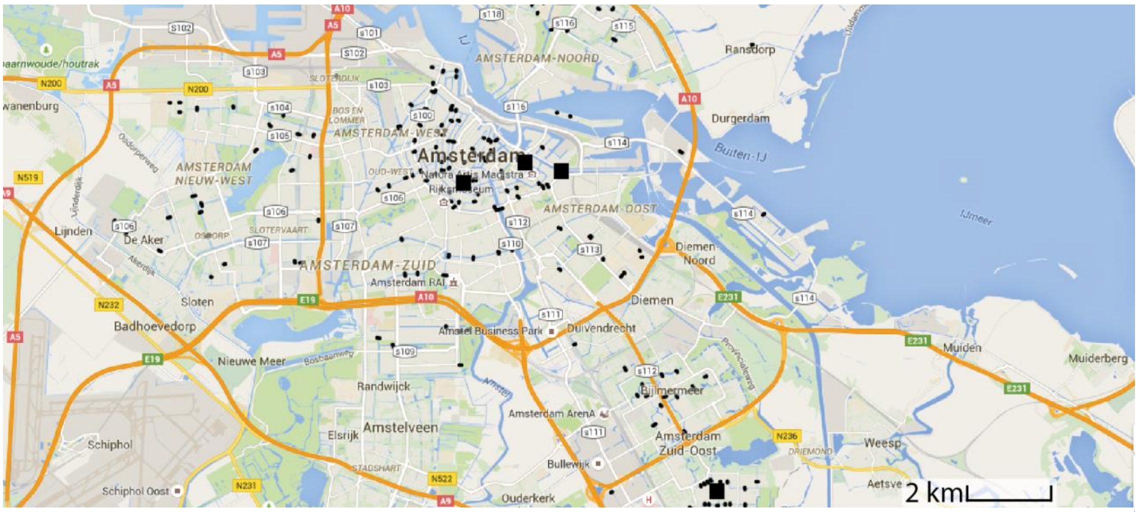

Figure 1. Map of Amsterdam. Small dots: locations of all inverted siphons. Squares: four selected inverted siphons for research

accumulation process of FOG over time. However, it is known that FOG accumulation problems are associated with food establishments, residences or industrial food production. FOG present in effluent can accumulate on sewer pipe walls as a result of a chemical reaction or a physical aggregation process, where these deposits tend to appear at the sewer/water interface (Williams, Clarkson, Mant, Drinkwater, & May, 2012).

The study described in this article was conducted in the city of Amsterdam, the Netherlands. The typical canals of Amsterdam are famous for its beauty but also create difficulties when a canal needs to be crossed by a gravity sewer. In general this problem is solved by using an inverted siphon, of which over 200 can be found throughout Amsterdam (Figure 1). An inverted siphon is a specific part of a sewer system that flows under gravity which makes a declining, followed by an inclining angle to cross an obstacle, of which a schematic overview can be found in Figure 3. They are applied when crossing an obstacle is not possible by having the whole sewer length at a lower level, which is disadvantageous for pumping water up for further process (Butler & Davies, 2000). Unlike stated in Butler & Davies (2000), the inverted siphons in Amsterdam are not conducted in plural form; only one pipeline is used for crossing. Therefore, no backup route is present, which means blockages of siphons will often result in combined sewer overflows (CSO).

After interviewing sewer personnel, it became apparent that these inverted siphons are prone for FOG blockages and are difficult to clean because of its dimensions and its layout. To find effective, proactive measures to prevent blockages in inverted siphons, a study was initiated to elaborate further on the occurrence of FOG deposits by studying the location and appearance of the deposits in siphons. Moreover, a measurement method based on water level differences is presented and discussed, which could be used for the estimation of the fouling degree of a sewer system.

For this study, four inverted siphons were selected on which numerous experiments and measurements were performed. Before measurements began, these inverted siphons were inspected to assess the location and degree of FOG deposits present at that time, after which the siphons were cleaned to obtain the initial situation. Next, sensors were placed to assess the difference between up- and downstream water levels of the inverted siphon, followed by a six-month measurement period. After this period, all inverted siphons were visually inspected once more, verifying the measurement results. An uncertainty analysis revealed the significance of the different sources of error in the measurement results. Based on the measurement results combined with the uncertainty analysis, as well as needed theoretical considerations, conclusions and recommendations are defined.

Materials and Methods

For this study four inverted siphons on various locations in Amsterdam were selected, indicated in Figure 1. All selected siphons discharge by gravity and are known to block frequently. The selected siphons have different specifications (dimension, material, the sewer type) as can be seen in Table 1. The dry weather flow (DWF) is based on a model.

In the following paragraphs all sensors used and measurements carried out for this research are described. In the first paragraph it will be explained how the siphons were cleaned and inspected. Furthermore, to study the fouling process of functioning siphons,

Table 1. Properties of selected inverted siphons

Inverted Siphon ID	**Sewer System type**	**Diameter [m]**	**Material**	**Slope Down-/upwards [^{0}]**	**Maximum DWF [m^3/s]**
Cruquiuskade (1)	Combined	0.4	Steal	30 / 30	0.0338
Entrepotdok (2)	Combined	0.315	PVC	30 / 30	0.0089
Herengracht (3)	Combined	0.8	Cast Iron	30 / 30	0.0136
Puiflijkpad (4)	Separate	0.25	PVC	22.5 / 22.5	0.0238

water level measurements as well as an estimation of the discharge are needed, which will be discussed in the proceeding paragrahs.

Sewer cleaning and inspection

To analyse the location and the amount of fouling in the selected inverted siphons, an inspection was carried out in all four siphons. After this preliminary inspection the siphons were thoroughly cleaned (obtaining the initial situation), and the measurements were started.

The inspection and cleaning process of the siphons consisted of the following steps:

- Installation of pigs to temporarily block the flow
- removal of water from the siphon
- assessment of the fouling by CCTV camera inspection
- thorough cleaning of the siphon followed by a CCTV inspection to verify if all fouling was removed
- measurement of the sewer invert’s vertical profile using the integrated tilt measurement of the camera tractor (Dirksen, Pothof, Langeveld, & Clemens, 2014)

For the inspection an IBAK KRA85 camera tractor was used. The cleaning was done using two different techniques; for the smaller diameters (up to 0.6m) a nozzle was used, which cleans by means of multiple rotating water jets operating under high pressure. For the larger diameters, as well as the more precise work, a camera tractor with a camera and integrated water jet is used. This tractor has a free operable water jet which performs under water pressure of up to a 1000 bar in combination with live images of the cleaning activities.

Water level measurements

As mentioned previously, the difference in water level up- and downstream of the inverted siphons is used to analyse the increase of fouling over time. For the water level measurements a Keller data collector (DCX-22 AA) was used, which comprises two pressure sensors: one for the water pressure, and the other for the barometric pressure. The actual water level is the result of the water pressure compensated for the atmospheric pressure. Before the sensors were installed, all sensors were checked for their precision using a 1m water column; all sensors had a maximum deviation of 0.001m, which is well within specification boundaries.

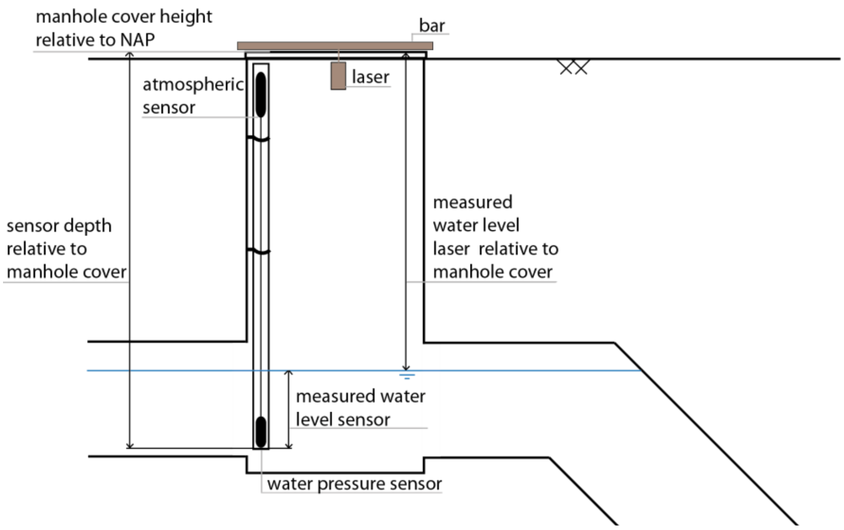

Figure 2. Measurement set-up in manhole using atmospheric a compensated sensor for water level measurements. A laser sensor is used to verify water levels relative to manhole cover

For each of the inverted siphons the measurement set-up consisted of two measurement devices which were installed in the nearest manhole upstream and downstream of the siphon. All sensors were placed in plastic tubes with a diameter of 0.03m to prevent fouling of the sensor as well as to assure its location (Figure 2). The lower half of the tube was perforated to ensure that the water pressure sensor was in contact with the water.

The loggers of the sensor were set at a measurement frequency of once per two minutes. Every two weeks the measurement locations were visited to check for abnormalities that could influence the measurements (e.g. objects getting caught behind the tube) and to collect the data. In order to collect the data, the pressure sensor was removed from the water. As a result both sensors measured atmospheric pressure. In the section Results and Discussion it will be explained how these measurements were used for data validation.

In order to compare the water level upstream and downstream of the siphon, the measured water levels needed to be converted into water levels relative to a known benchmark. In the Netherlands the NAP (Normaal Amsterdams Peil) is used. For the conversion, two properties needed to be determined:

- the vertical position of the manhole covers up- and downstream of the inverted siphon, for which a levelling instrument is used

- the distance between the sensor and the manhole cover, for this measurement a Fluke 4141D laser distance meter is used. To allow automatic data acquisition of time series a LR4 interface board was added to the laser meter. The laser sensor has an accuracy of 0.5 mm (Stanic, Langeveld, & Clemens, 2014)

In Figure 2 a schematic overview of the measurement set-up is presented. The laser meter was attached to a bar with a known distance between the bottom of the laser sensor and the bottom of the bar. This bar was placed up onto the manhole rim. The suspension of the laser by a chain assures that laser beam is always perpendicular to the water surface, independent of the position of the bar. Laser meters are usually used on solid surfaces; water however may reflect the laser beam in various directions or the beam may even pass through. Therefore, ordinary coffee creamer (in powder form) was used to create a thin reflecting layer on top of the water. These laser measurements have been executed four times during the research period at all the different siphon locations.

In the section Data preparation it will be explained how the data of the levelling device and the laser meter will be used for data validation and to convert the measured water levels in order to obtain the water level difference up- and downstream of the siphon.

Discharge measurements

The difference in water level is not only dependent on the fouling degree but on the discharge as well, which will be explained in more detail in the section Theory. As stated previously, the maximum discharges listed in Table 1 are estimated by a model. To assess if the order of magnitude of these estimations is plausible, the discharge in one of the inverted siphons was measured.

In order to have a non-intrusive, simple and inexpensive measurement, it was decided to quantify the discharge using a tracer. When choosing a tracer it has to be made sure that the material used is conservative in the applied environment. Amongst others Schilperoort et al. (2007) showed that natural isotopes such as heavy water are suitable for wastewater applications.

Tracer experiments were carried out with the following equipment: 220 V-AC dosage pump, Deuterium Oxide (99.8 atom % D), adjustable laboratory pipettes, disposable syringes, disposable filters (1µm), sample bottles, isotope analyser.

The discharge measurements consisted of the following steps:

- *Pump calibration:* in the laboratory, a calibration of the pump is recommended. During the experiment on site it is key that the discharge of the pump is known, as this will determine how much Deuterium is dosed.
- *Tracer solution*: in the laboratory, the operational tracer solution is prepared by dilution of the commercial solution. For this preparation, 3.1e-5 m^3 of Deuterium is diluted with 0.002 m^3 of local canal water.
- *Injection and sampling on site*: before the experiment begins, a sample is taken to establish the background concentration. At the upstream manhole of the inverted siphon, the diluted tracer solution is injected with a constant rate of $\Delta Q =$ 0.0083e-3 m^3/s for the duration of 6 minutes. After the start of the injection in the upstream manhole, samples are taken at the downstream manhole with a time step of $dt =$ 30s, up to 25 minutes after the injection was initiated.
- *Analysis*: all samples are filtered by using disposable syringes in combination with the 1µm filters, before analysis by the isotope analyser can start. The analysis in this experiment was performed by UNESCO IHE.
- *Data processing:* when plotting the concentration deuterium in the sewer water present against time, a clear pulse must be observed, which after an ascending gradient shows a constant concentration for a number of minutes, afterwards followed by a descending gradient.
- *Computation of discharge:* the discharge for each experiment is computed by means of the mass balance:

$$Q_{deuterium} = \Delta Q \frac{C_{inj}}{C_{Measured}} \tag{1}$$

Where $Q_{deuterium}$ is the discharge in the inverted siphon [m^3/s], ΔQ is the injected discharge [m^3/s], C_{inj} is the injected deuterium concentration [g/m^3] and $C_{Measured}$ is the stable concentration in the sewer water, following from the data processing [g/m^3].

To verify the results of the constant rate injection, calculations can be made by the use of assuming a sudden injection:

$$Q_{deuterium} = \frac{C_{inj} \cdot V_{inj}}{\int_{t_0}^{t} C_{corr}(t) \cdot dt} \quad (2)$$

where V_{inj} is the injected deuterium volume [m^3] and C_{corr} is the measured concentration deuterium, corrected for background concentration [g/m^3].

The discharge measurements were performed at two different moments in time in one of the four inverted siphons. In the section Results and Discussion the measurements results discussed.

Theory

In this section the relation between the increase in water level difference and the amount of fouling is described. Over time it is expected that due to fouling, the wetted cross sectional area reduces resulting in an increase in water level difference. Here, a constant discharge is assumed. Eq. (3) describes this relation based on Bernoulli's Principle:

$$\Delta h = \xi_{total} \frac{Q^2}{2g \cdot A^2} \quad (3)$$

where Δh is the water level difference [m], A is the wetted cross sectional area [m], Q is the discharge [m^3/s], ξ_{total} is a combined friction coefficient and g is the gravitational acceleration [m/s^2].

To describe the relation between the increase in water level difference and the amount of fouling, the following assumptions about the accumulation of deposits in the siphon are made:

- only FOG deposits at the top of the pipe invert are considered
- the deposits are assumed to be uniformly distributed over the length of the inverted siphon
- the deposits are considered to accumulate linearly

The assumed process of FOG accumulation is schematized in Figure 3.

The relation between Δh and the reduction of wetted cross sectional area is also dependent on ξ_{total} as can be seen in Eq. (3). ξ_{total} is calculated by:

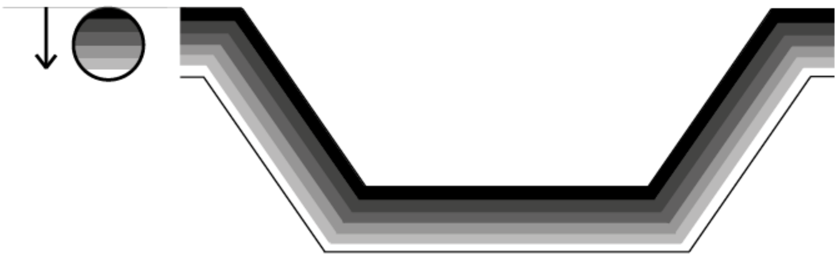

Figure 3. Uniform increase in FOG deposition, starting in the in black, growing downwards indicated by lightening of colour

$$\xi_{total} = \xi_{in} + 4 * \xi_{kink} + \xi_{friction} + \xi_{out} \tag{4}$$

where ξ_{in} is the entrance loss coefficient, ξ_{kink} is the kink loss coefficient due to the angles an inverted siphon makes, $\xi_{friction}$ is the friction loss coefficient and ξ_{out} is the exit loss coefficient.

The entrance loss coefficient, the kink loss coefficient and the exit loss coefficient are considered constant and are determined by using Idel'Chik (1966). The friction loss coefficient is calculated using the Darcy-Weisbach Equation:

$$\xi_{friction} = f_D \cdot \frac{L}{D} \tag{5}$$

where f_D is the Darcy friction factor, L is the length of the inverted siphon [m] and D is the hydraulic diameter of the pipe [m]. The Darcy friction factor can be found in a Moody diagram or can be solved iteratively by using the Colebrook equation:

$$\frac{1}{\sqrt{f_D}} = -2\log\left(\frac{2.51}{Re \cdot \sqrt{f_D}} + \frac{k}{3.71 \cdot D}\right) \tag{6}$$

where Re is Reynolds number and k is the roughness coefficient [m]. The roughness coefficient depends on pipe invert material, which varies for the different inverted siphons. Though, in this study a constant k of 0.003m is used for all four inverted siphons, which corresponds to a roughness coefficient of mature foul sewers (Mulley, 2004). When describing the relation between the water level difference and the fouling degree, it has to be kept in mind that the friction loss is also dependent on the (reduction of) the wetted cross-sectional area, as can be seen in the above stated formulas.

In the section Results and Discussion the resulting formulas will be used to calculate the expected relation between the increase in water level difference and the amount of fouling, where they will be compared to the results from the water level measurements.

Results and Discussion

As described previously, the water level up- and downstream of inverted siphons on four different locations was measured. After the siphons were inspected and cleaned in the last week of September 2014, sensors were installed. For a period of six months water level measurements have been monitored every 2 minutes. Following this measurement period, another visual inspection was performed to verify if the estimated fouling based on the measurement data is consistent with the real build-up of FOG deposits during these six months. In this section the results of both of the visual inspections, the water level measurements and the calculated fouling percentages will be discussed.

Initial situation

The initial situation of the four inverted siphons was assessed by visual inspection before the measurement equipment was installed. As it was unknown when the siphons were last cleaned, the observed situation only gives information on the location and type of deposits that can be expected in the studied siphons.

Analysis of the inspection footage of the inverted siphons showed that there was a notably large amount of FOG deposits present. In Figure 4 a schematic representation of the situation of all four the inverted siphons before cleaning is shown. These drawings are based on visual interpretation of the inspection footage and were made by the author, whom was also present during cleaning activities. Please note that the scales in the figure for all four inverted siphons are different and the flow direction is from left to right.

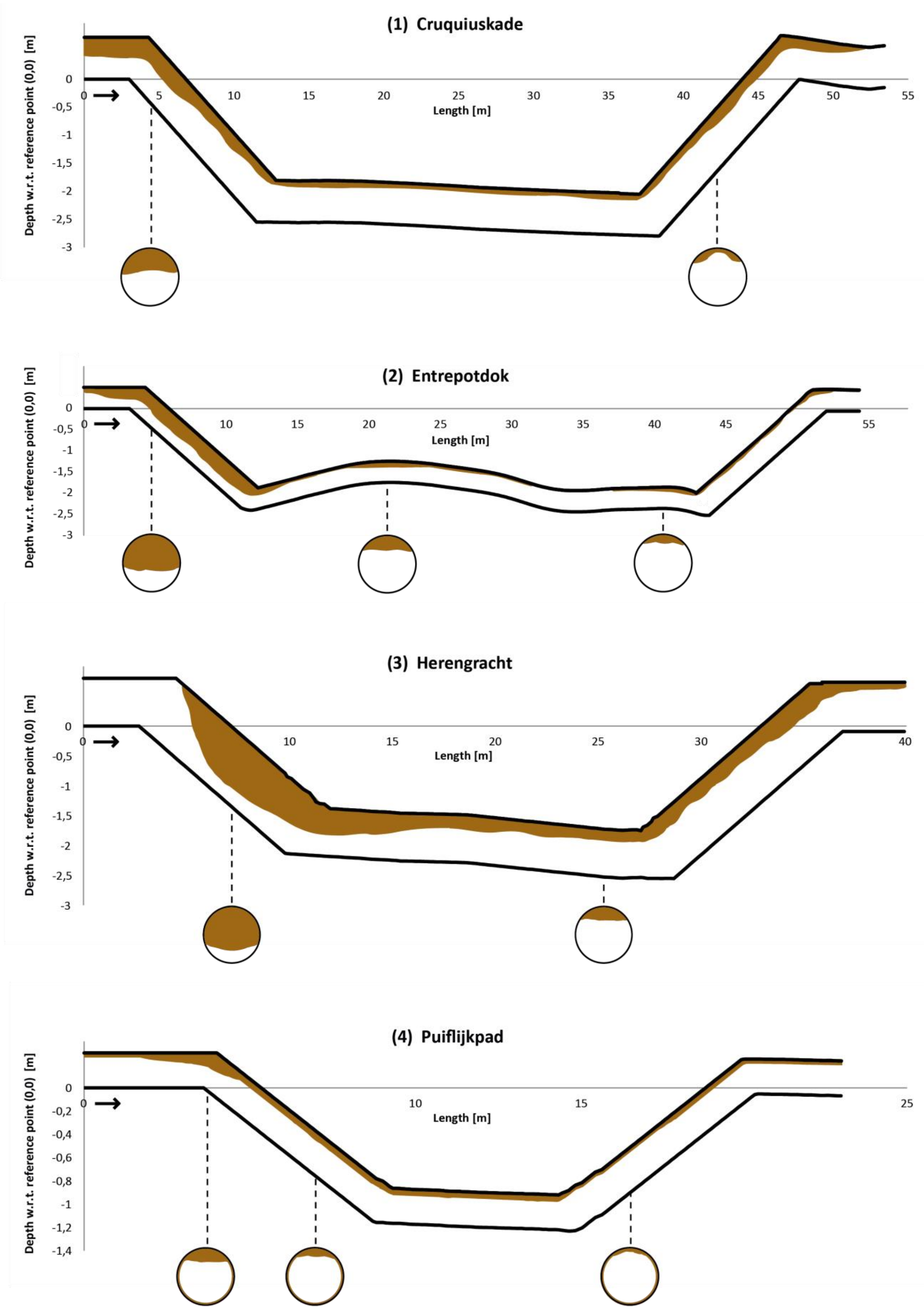

Figure 4. Degree of fouling in all four inverted siphons. Flow direction (DWF) is from left to right. Note that the scales of the axes are different for every inverted siphon.

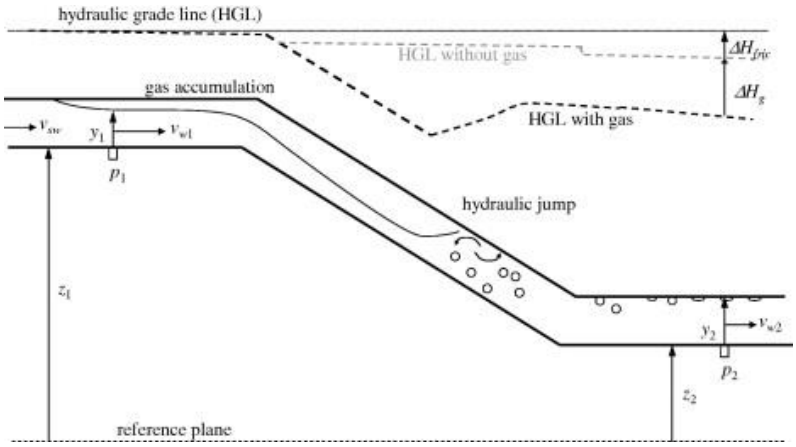

Figure 5. Accumulation of air in an elongated air pocket (Pothof & Clemens, 2010)

In all four inverted siphons large amounts FOG deposits were found in the inclining and especially declining parts of the inverted siphons. In siphon (3) no FOG deposits were found present in the first, horizontal part, of the siphon. A logical explanation for this observation is that the water level in this part of the sewer normally does not reach the soffit, whereas FOG deposits are known to appear at the sewer/water interface (Williams, Clarkson, Mant, Drinkwater, & May, 2012).

Another remarkable aspect that can be seen in Figure 4 is the vertical profile of inverted siphon (2), where the middle section has risen. A possible explanation for this phenomenon is that the soil cover is no longer sufficient. This might allow the inverted siphon to float upwards while it is filled with air, for example during cleaning activities. Another explanation could be that an anchor got caught behind the inverted siphon, or some errors made during the construction phase. Interestingly, an accumulation of FOG deposits was found at the location where the soffit is the highest. Accumulation of air at this location might be an explanation.

Baring in mind that FOG deposits are known to appear at the sewer/water interface, it was not expected to find large amounts of FOG deposits in the part of the siphon that is always completely filled with sewerage. An explanation of this observation might be found in the travelling of air bubbles in pressurized sewers.

In Figure 5 a schematic drawing of the accumulation of air pockets in the downward slope of a pressurized sewer is shown (Pothof & Clemens, 2010). Interestingly, when comparing the location and shape of the FOG deposits in the

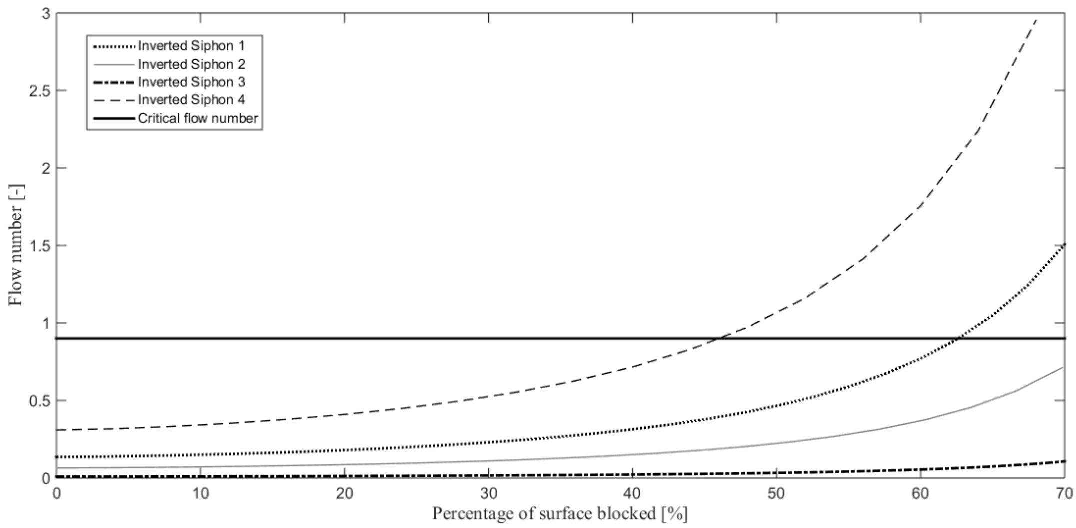

Figure 6. Flow number for all four inverted siphons with different fouling percentages

inverted siphons depicted in Figure 4 with the location and shape of accumulated air pockets shown in Figure 5, an apparent similarity is visible.

As described by Pothof and Clemens (2010), air pockets will be formed if the flow velocity (i.e. flow number) is small enough. To check if air pockets are formed and manifest a similar shape as shown in Figure 5, Eq. (7) is used (Pothof & Clemens, 2010).

$$F = \frac{v}{\sqrt{gD}} \tag{7}$$

where F is the flow number [-].

Figure 6 depicts the relationship between the reduction of the wetted cross sectional area and the flow number. Every value for the flow number above the critical value of 0.9 will result in the formation of an air pocket. When the sewer is clean, the flow numbers of all four inverted siphons during DWF is well beneath 0.9, which leads to the formation of air pockets. As FOG deposits were found on the same location as the expected air pocket, the formation of these air pockets is thought to be the explanation of the accumulation of FOG deposits in the inverted siphons.

As the FOG deposit will accumulate the flow number will increase locally. As a consequence the air pocket will enlarge in a downstream direction resulting in slowly downwards growing FOG deposits as illustrated in Figure 7.

After visual inspection the siphons were cleaned. The consistency of the FOG deposits was very firm; it took several seconds with a water jet under extremely high

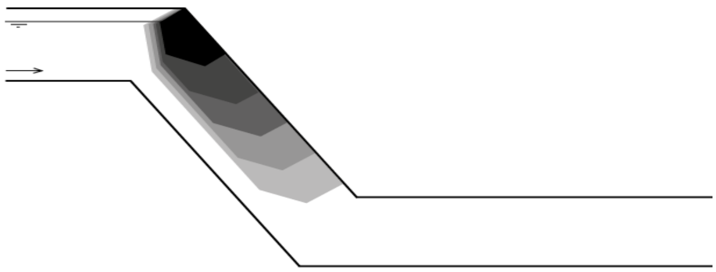

Figure 7. Accumulation of FOG deposits, starting in the in black, growing downwards indicated by lightening of colour. Flow is from left to right

pressure directly targeted on the FOG deposits to detach them from the sewer invert. On average, it took up to a day for the sewer personnel to clean one inverted siphon. After cleaning, visual inspection was used to verify whether the siphons were clean.

Data preparation

To define the relation between the water level difference over time and the fouling degree by using Eq. (3), a constant discharge needed to be assumed. Therefore, only water level measurements with an assumed constant discharge can be compared, leading to the exclusion of measurement data collected during rain events. Furthermore, the resulting diurnal DWF patterns are compared to one another to exclude days with inconsistent diurnal patterns. In addition, the measurements of atmospheric pressure by both pressure sensors during data collection, as stated previously in the section Materials and Methods, are compared to one another, to compensate for step trends in the water level measurements.

Selection of dry weather days

To select the days for water levels not to be influenced by rainfall, radar data is used. When the amount of rainfall in the concerning grid cell (spatial resolution 1km x 1km) during 30 minutes exceeded 0.001m, the concerning day is excluded from the analysis.

Selection of representative days

For the selection of days it is assumed that every day has a certain representative diurnal DWF pattern, which is constant throughout the entire measurement period. Every day with an inconsistent curve is excluded from the analysis. Possible explanations for these

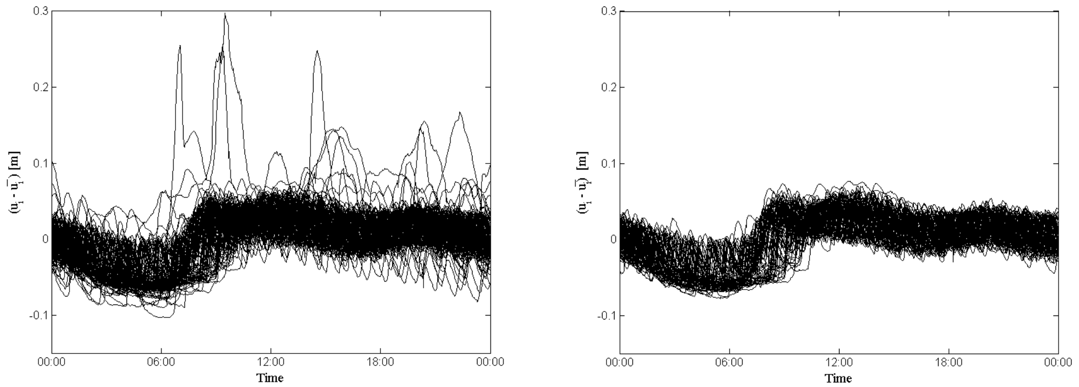

Figure 8. Left figure: daily water level curves, right figure: daily curves, where non-similar days are excluded

inconsistencies could be rain events smaller than the set threshold as stated previously or singular disposals of water by for example the sewer cleaning personnel.

For the selection of representative days, every daily dataset relative to its daily average was plotted, as illustrated in the left graph of Figure 8, in which a clear DWF pattern with a 0.1m band can be seen. The 0.1m fluctuations are induced by a pumping station which is water level regulated. However, there are also multiple days with larger peaks visible. All days with these larger peaks were selected visually and excluded from the dataset, resulting in the right graph of Figure 8.

Compensation for step trend in water level measurements

During the measurement period a step trend was found in the water level measurements of multiple sensors. In the upper graph of Figure 9 the water level measurements of one sensor are shown as an example. In the lower graph of Figure 9 the difference between the water pressure sensor and the atmospheric sensor during data collection is shown. Remarkably, the step trend in water level measurements (0.11m) is of the same magnitude as the change in atmospheric pressure difference as found at the preceding and following data collections. Therefore it is concluded that during data collection either the atmospheric pressure sensor or the water level sensor is deregulated.

As the cause of the step trend in the water level measurements is known, the data can be compensated for it. After visual inspection of the data of all eight sensors, the data of six out of the eight sensors was compensated for step trends.

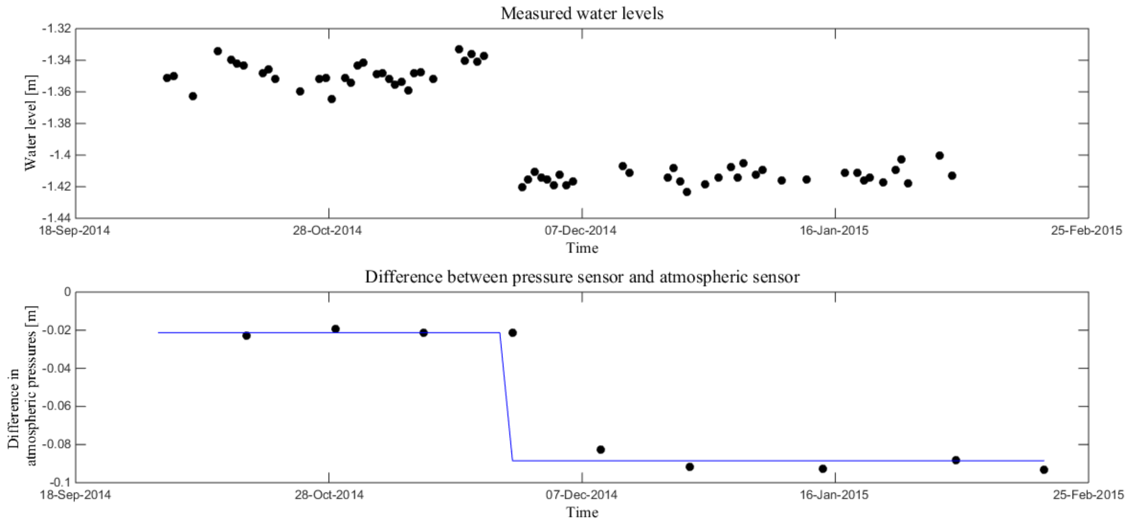

Figure 9. Upper graph: water level measurements of a sensor, lower graph: difference between atmospheric and pressure sensor. Period in both graphs is October 1st, 2014 up to February 5th, 2015; Note the difference between both y-axes

Error analysis

The interest of this research lies in the fouling process of an inverted siphon. As explained previously, the fouling is described by the reduction of the wetted cross sectional area. The difference in the wetted cross sectional area is dependent on the discharge, the water level difference and the friction factor (Eq. (3)). As the friction factor is also a function of the wetted surface area, A is only dependent on Q and Δh:

$$A = f(Q, \Delta h) \tag{8}$$

Therefore the uncertainty in Q and Δh determine the reliability of the estimated increase of fouling (by a reduction of A) during the measurement period. In this chapter the error in the water level measurement and discharge measurement is analysed.

Uncertainty in water level measurements

From previous experience with water level sensors in waste water, it is known that laboratorial specifications are rarely attained. Probable causes for not complying with its specifications are issues with the transducer accuracy, fouling, temperature compensation and drift (Sorensen & Butcher, 2011).

The uncertainty of the water level measurement relative to the manhole cover is composed of the error in the measurement of the manhole cover and a remaining error containing all undefinable or unknown errors.

Error in the measurement of the level of the manhole cover ($\boldsymbol{\sigma^2_{manhole}}$)

Because the difference in water level upstream and downstream of the inverted siphon is studied, only the accuracy of the measured difference in level of the manhole cover upstream and downstream of the siphon is of interest. As this difference is measured by one reading of the levelling instrument, the accuracy is in the order of tenths of millimetres. In comparison to the other errors this error is insignificant.

Random error ($\boldsymbol{\sigma^2_{miscellaneous}}$)

Random errors can be caused by either the measurement equipment or irregularities in the measured object. Probable causes are:

- relocation of the sensor after data collection
- fouling of the sensor
- buoyancy of the sensor during high water levels
- blockage of the tube; no direct contact of the sensor with water
- compensation for step function error in data

For the estimation of the uncertainty in the measured water levels, a comparison was made between the measured water levels and the laser measurements.

The laser measurements have been executed four times during the research period at all locations. The standard deviation is calculated based on the entire population of 32 samples (8 sensors, 4 measurements). The standard deviation is calculated by

$$\sigma^2 = \frac{\sum(x - \bar{x})^2}{(n-1)} \quad (9)$$

where x is the difference between water level measurement and laser measurement [m], $\bar{x}$ is the average difference between the two measurements [m], and n is the number of samples. Using an average difference of 0m and 32 samples, this resulted in a standard deviation of 0.0116m ($\sigma_{miscellaneous}$).

The resulting standard deviation is the combination of the accuracy of the water level measurement and the laser measurement. As the accuracy of the laser meter is 0.0005m (Stanic, Langeveld, & Clemens, 2014), the standard deviation of the random error of the water level measurement is 0.0115m.

As mentioned previously there can be multiple causes for this random error. As explained in the section Materials and Methods, during data collection both the atmospheric and water pressure sensor measured atmospheric pressure. Previously, it was explained that step trends were compensated for. When calculating the average difference between both measurements before and after the step trend (straight lines in Figure 9), it can be seen that even after removal of step trends, there is still a small difference between individual measurements (dots in Figure 9) in comparison to its average. These differences can be used to calculate the uncertainty due to random errors in either the water pressure sensor or the atmospheric pressure. For the calculation first the differences are compensated for the step trend, second the datasets are divided in separate periods: before and after the step trend.

This resulted in 14 data pools with 2 to 7 data points per pool. The size of the pool varies as the step trend initiates at different moments in time. Each pool was checked for normality to the extent possible and were confirmed to be normally distributed. The resulting datasets are used to estimate the standard deviation. As the number of data points in each dataset varies the principle of pooled variance is used:

$$\sigma^2 = \frac{\sum_{j=1}^{n}\left((n_j - 1)\sigma_j^2\right)}{\sum_{j=1}^{n}(n_j - 1)} \tag{10}$$

This resulted in a standard deviation of 0.0037m. With this calculation it is concluded that of the total random error of 0.0115m, 0.0037m can be attributed to random errors in the water level or atmospheric pressure sensor.

Total error in water level difference measurement ($\boldsymbol{\sigma^2_{\Delta h}}$)

Combining both above mentioned errors, the error of the measurement of the water level difference between upstream and downstream location of the inverted siphon can be estimated by:

$$\sigma_{\Delta h}^2 = \sigma_{manhole}^2 + 2\sigma_{miscellaneous}^2 \quad (11)$$

With $\sigma_{manhole}$ assumed to be equal to zero and $\sigma_{miscellaneous}$ = 0.0115m, this results in $\sigma_{\Delta h}$ = 0.0163m. Therefore, over the measurement period a water level difference of at least 0.0325m, which is equal to twice the standard deviation, needs to be measured to ensure the data is significant with a 95% confidence level.

Uncertainty in the estimation of the discharge

As no discharge measurements were available, model-based discharges are used for the estimation of the fouling degree. To verify if these model-based discharge estimations are plausible, for one siphon discharge measurements using tracers were performed at two certain moments in time. In this paragraph first the error in the discharge measurement is discussed, secondly the results of the discharge measurements are compared to the model based discharges. Finally the error in the estimation of the discharges used for to study the fouling process is assessed.

Uncertainty in discharge measurements

Due to a lack of resources and time, not all model-based discharges were verified by discharge measurements, which make quantifying the uncertainty in the discharge used in this research impossible. If however the resources and time would have been available, the discharges in all four inverted siphons would have been measured performing the tracer-experiments. To get an idea on what the order of magnitude of the uncertainty of the discharge could be, the uncertainty of the tracer-based discharge measurements has been calculated.

The uncertainty of the discharge measurement using tracers can be calculated by Eq. (12) (Lepot, Momplot, Lipeme Kouyi, & Bertrand-Krajewski, 2014). Though Lepot et al. used a different tracer, the execution of the tracer-method remains equal, and therefore the equation can be used for the deuterium experiment as well.

$$\sigma^2(Q_{deuterium}) = \frac{(\sigma^2(C_{inj}) \cdot V_{inj}^2 + \sigma^2(V_{inj}) \cdot C_{inj}^2)}{\left(\int_{t_0}^{t} C_{corr}(t) \cdot dt\right)^2} + \sum_{t_0}^{t} \sigma^2(C_{corr}(t)) \cdot \left[\frac{C_{inj} \cdot V_{inj}}{\left(\int_{t_0}^{t} C_{corr}(t) \cdot dt\right)^2}\right]^2 \quad (12)$$

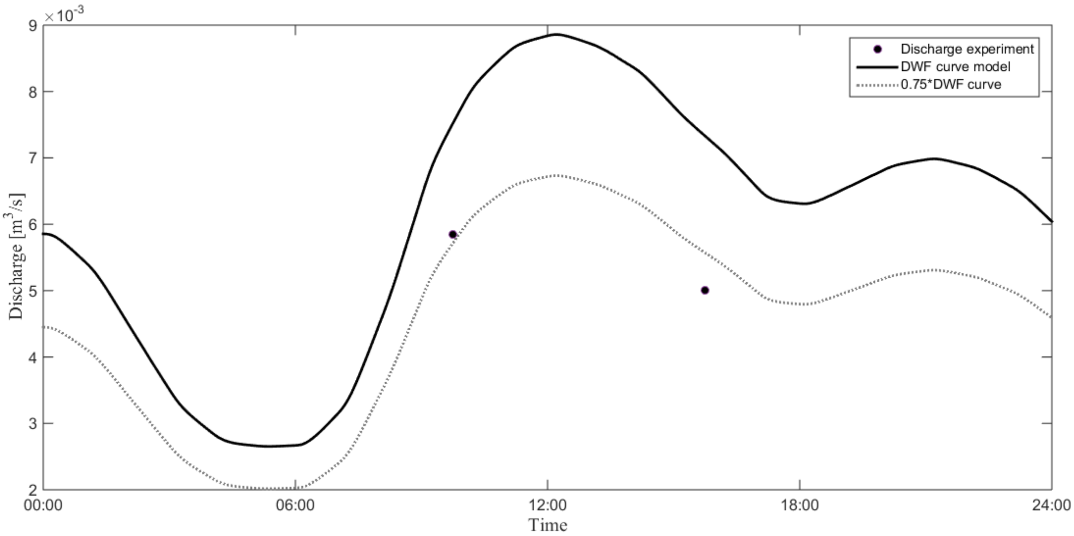

Figure 10. DWF curve in inverted siphon (2), based on a model. Single data point represents discharge measured during deuterium experiment

For the calculations, an accuracy of 0.1% of the amount of injected molecules deuterium is assumed, which is consistent with the maximum total accuracy of the isotope analyser used for the analysis. Furthermore, an uncertainty of 0.0001m^3 is assumed for the injected volume. For the uncertainty of the measured deuterium concentration, it is assumed that the biggest constituent is the error made in sample time. A sample time error of 2 seconds combined with an average difference in concentrations of 3.44e14 molecules/m^3 per second, results in $\sigma(C_{corr}(t))$ = 6.87 molecules/m^3. Calculations of the total uncertainty of the measured discharge resulted in $\sigma(Q_{deuterium})$ = 0,0066m^3/s, which is equal to almost 10% of the measured discharge.

Comparison of the measured discharges and the model-based discharges

In Figure 10 the model's DWF curve as well as the result of the discharge measurement is shown. Although the discharge measurement results match the 75% curve better instead of the model based DWF curve, the model results and the measurement results are in the same order of magnitude. Therefore it is concluded that the model results are plausible.

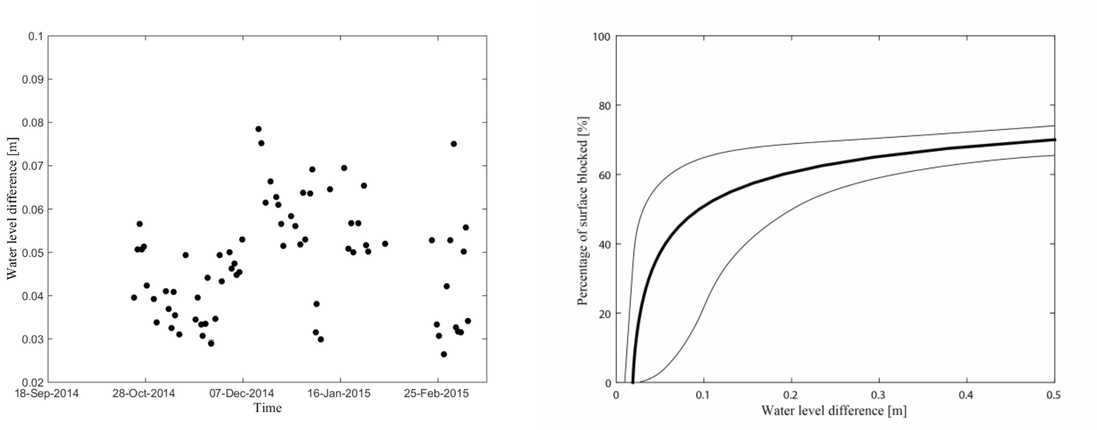

Figure 11. Left: water level difference over time of inverted siphon (1). The dots represent the 15min-average DWF peak of daily data. Right: modelled relationship between water level difference and the fouling degree

The uncertainty of the model-based discharges used for the calculation

As the model-based discharges were found to be plausible, these will be used for the calculation of the fouling degree of the siphons. As no real-time measurements of the discharge are available the diurnal discharge pattern is assumed to be equal throughout the entire measurement period. As no measurements are available the total uncertainty (model and assumption) can only be estimated. For the calculation of the fouling degree the uncertainty in the discharge is estimated at 10%.

Data analysis

In this paragraph the data of all four inverted siphons will be presented and discussed separately. For every inverted siphon, every daily maximum water level difference is plotted over time. As explained previously, the measurements were compensated for step trends and measurements collected during storm events as well as days with inexplicable peaks were excluded, explaining the gaps in the plotted dataset.

In addition, the relation between the difference in water level and the reduction of wetted cross-sectional area is calculated based on the formulas as described previously. As the uncertainty of the input parameters have been analysed, an estimation of the confidence interval is presented as well.

For the calculation of the confidence interval Monte Carlo simulations were performed concerning both Δh and Q. For every parameter 1000 simulations were run, with fluctuating averages of Δh with σ = 0.0325m, and for an average equal to the modelled discharge per inverted siphon with σ = 10% of the Q.

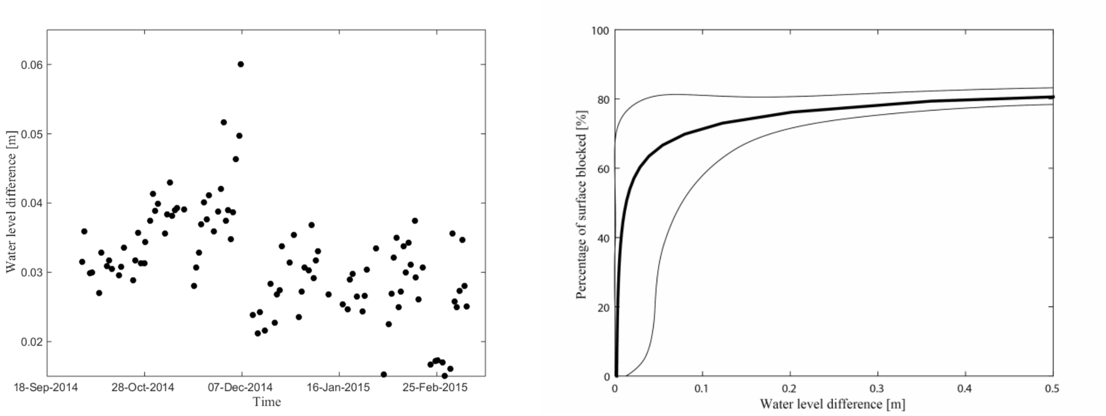

Figure 12. Left: Compensated water level difference over a six-month period for inverted siphon (2). Right: modelled relationship between water level difference and the fouling degree

Inverted siphon (1)

Figure 11 shows the entire dataset of inverted siphon (1). As can be seen the water level difference fluctuates quite strongly even between following days. Taking the measurement uncertainty of 0.0325m into account, no significant increase in water level difference during the measurement period was observed. Nevertheless, when considering the theoretical fouling degree consistent with the measured water level difference as depicted in right picture of Figure 11, a fouling degree of up to 60% might have been present. However, after evaluating the second inspection images, it became apparent that little to no FOG deposits had accumulated.

Inverted Siphon (2)

In Figure 12 the results of the measurements in inverted siphon (2) are shown. Most remarkable is the sudden shift in the beginning of December. For this shift no explanation was found.

Looking at the whole period, no increase in water level difference could be observed. Though, when dividing the graph into smaller periods, increases in water level differences of around 0.02m are visible, followed by a sudden drop. An explanation of these drops might be the positive influence of rain events on the water level difference.

When plotting the water level difference in combination with rainfall, a pattern can be found between heavy storm events and the sudden drops, as shown in Figure 13. As discussed previously, the middle section of this siphon has risen. It is thought that air

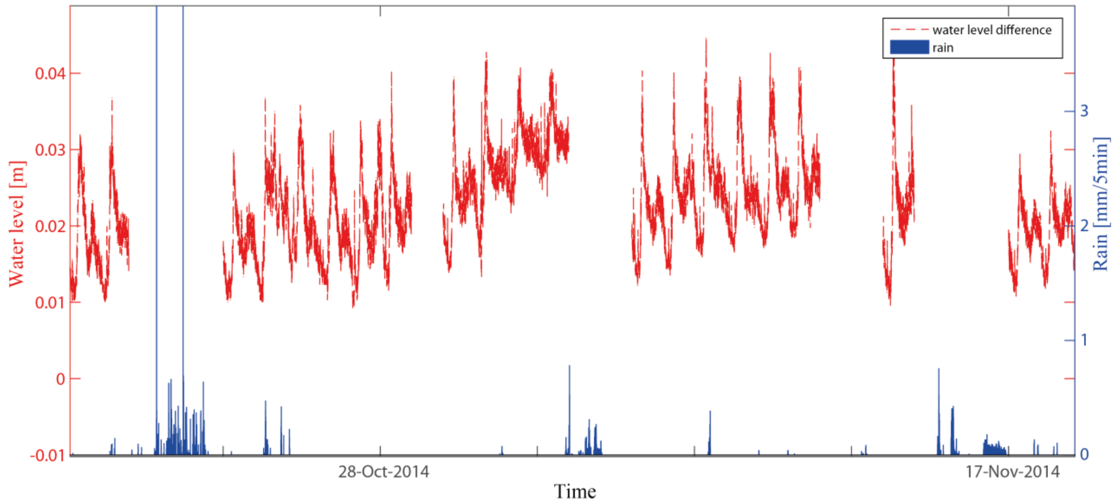

Figure 13. The relation between water level difference and rain. With every heavy rain event, a drop in water level difference can be seen.

accumulates at this part of the siphon, resulting in a local reduction of the cross sectional area, which leads to higher water level differences. An explanation for the sudden drop in water level difference after rain events could be that, during storm events, high flow velocities transport the accumulated air.

Unlike inverted siphon (1), inverted siphon (2) contained a considerable amount of FOG deposits during the second inspection. In Figure 14 the two photos illustrate the status of the fouling at that moment in time. Because the FOG deposits obstructed the inspection camera, only the upstream part of the siphon was inspected.

As can be seen, in the downwards sloping section of the inverted siphon, around 30-40% of the diameter is blocked. Using the right picture of Figure 12, a reduction in

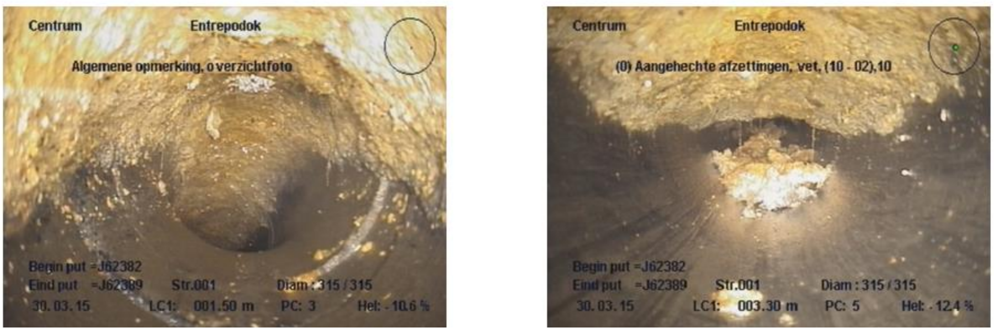

Figure 14. Overview of fouling in inverted siphon (2), 6 months after cleaning. Left: upstream horizontal part, looking towards downwards sloping section. Right: 1m into the downwards sloping part of the inverted siphon

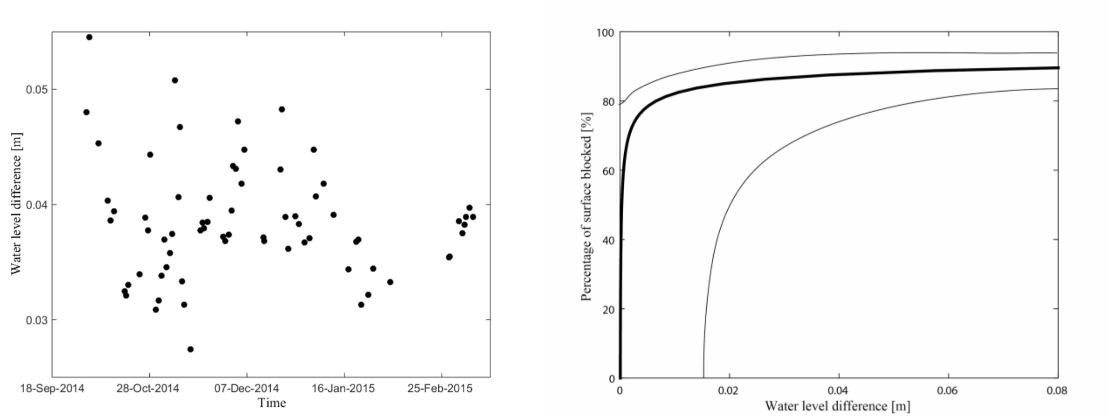

Figure 15. Left: Compensated water level difference over a six-month period for inverted siphon (3). Right: modelled relationship between water level difference and the fouling degree

wetted cross sectional area of 30-40% would result in water level difference of up to 0.05m. Though, no significant water level difference was detected.

Inverted siphon (3)

In Figure 15 the water level differences over time in inverted siphon (3) are depicted. Even though the daily averages fluctuate with a difference of around 0.02m from one another, no apparent trend is visible. Considering the expected results as depicted in the right picture of Figure 15 the detection of an increase in water level difference would also be nearly impossible with the used measurement set-up within the first 80% of the reduction in cross sectional area.

During the second visual inspection, large amounts of FOG deposits were found. As can be seen in the left photo of Figure 16, around 10-20% of the inverted siphon

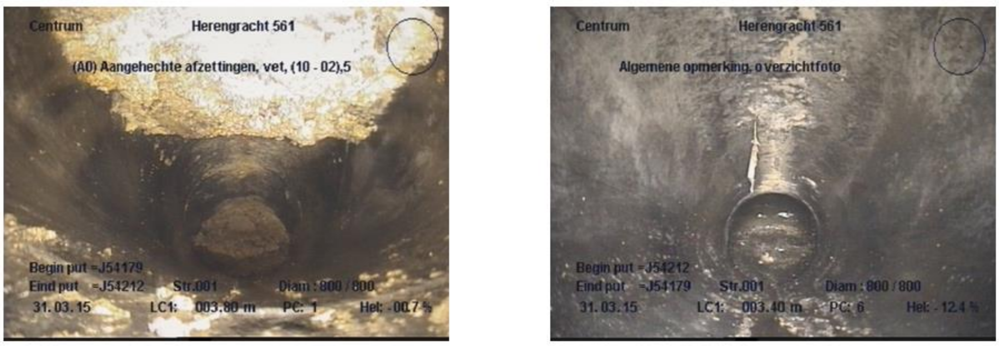

Figure 16. overview of fouling inverted siphon (3), 6 months after cleaning. Left: 1m into the downwards sloping part of the inverted siphon. Right: Upwards sloping part (e.g. downstream)

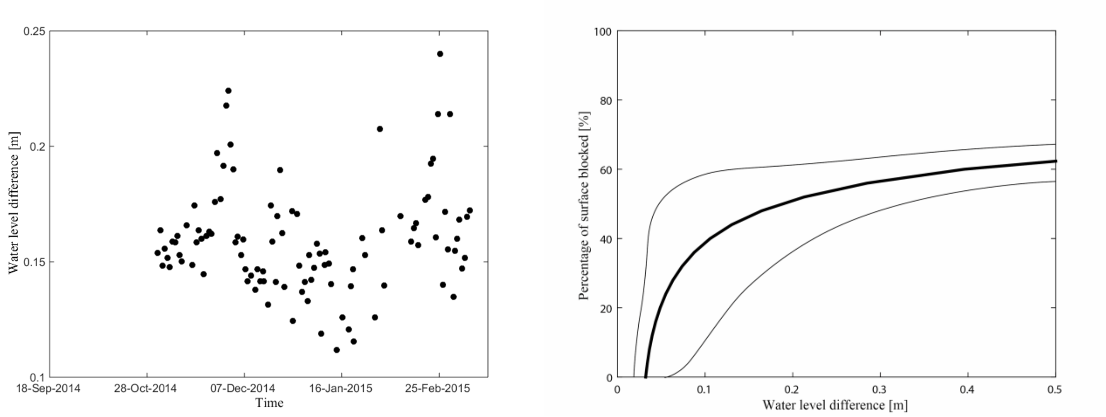

Figure 17. Left: compensated water level difference over a six-month period for inverted siphon (4). Right: modelled relationship between water level difference and the fouling degree

with a diameter of 0.8m is clogged. Remarkably, it can be seen in the left photo that not the entire downwards sloping part of the inverted siphon is covered with deposits. This is the result of the detachment of the FOG deposits due to the drainage of the siphon before inspection could start. For this to happen, the FOG deposits needs to be less firmly attached to the pipe wall and for it to be of a much lower strength than the FOG deposits that were present during the first visual inspection.

Furthermore, as can be seen in the right picture of Figure 16, there are hardly any FOG deposits present in the upwards sloping part of the inverted siphon, which is also representative for the middle part of the inverted siphon. As concluded from the images created by the first visual inspection, in combination with the theory of the Flow number stated by Pothof & Clemens (2010), FOG deposits will start accumulating at the air/water interface, slowly growing in the downwards sloping direction.

Inverted siphon (4)

For inverted siphon (4), the results of the measurements are depicted in Figure 17. Even though the measurement data fluctuates with differences of up to 0.05m from one another, the plot shows no apparent increase in water level difference. This is consistent with the results of the second inspection, where little to no FOG deposits was present over the whole length of the inverted siphon.

Conclusions & recommendations

This study was initiated to elaborate further on the accumulation process of FOG deposits by studying the location and appearance of the deposits in real sewer systems. The choice was made to conduct the study in inverted siphons, as these are known for the frequent blockages by FOG deposits. By monitoring the water level differences over time in an inverted siphon, the fouling degree was estimated.

Even though the four selected inverted siphons were known for their blocking, not all siphons contained a build-up of FOG deposits during the measurement period. An explanation might be that, before starting the measurements, the inverted siphons were cleaned more thoroughly in comparison to normal practice. Therefore, in order to study the accumulation process until blockages occur, it is recommended to continue the monitoring up until the siphons are completely blocked. Ultimately, this will give better insight in the FOG deposit build-up as well as in using the water level measurement technique to predict the fouling degree of a sewer.

Analysis of the inspection footage of the initial situation in the inverted siphons showed that there is an apparent similarity between the accumulation of FOG deposits in siphons and the accumulation of air pockets in pressurised sewer pipes. Here the discharge is key; when the discharge is under a certain threshold, an air bubble is created in the downward slope of the inverted siphon, enabling FOG deposits to accumulate at the water/air interface.

As the studied inverted siphons did not block for at least six months, it appears that thorough cleaning followed by an inspection (to verify if the FOG deposits were truly removed) have had a positive effect on the initial accumulation time. Furthermore, comparison between the consistencies of the FOG deposits observed during the first and second inspection, revealed that FOG deposits found during the second inspection, which accumulated over a period of six months, showed lower strengths. As these FOG deposits were still relatively fresh, it is therefore recommended to clean sewers more frequently, as these FOG deposits require less water pressure, hence being less time consuming. Additionally, it is recommended to keep good records of the pro- as well as reactive maintenance activities, and use these to improve current, mainly reactive management practices.

By performing an error analysis, it became apparent that the measurement technique used for the water level measurements had an uncertainty of 0.0325m to obtain the 95% confidence interval, which is quite large in comparison with the measurement results. Therefore, it is recommended to use water level difference sensors, which eliminates the importance of the location of the sensor, resulting in a smaller random error.

Ultimately, for the water level measurements and therefore the estimation of the fouling degree to be significant, it is preferred that the proportion between the discharge and the diameter of the sewer invert is not too big.

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