Evaluation of two stormwater infiltration trenches in central Copenhagen after 15 years of operation

Etude de deux tranchées d'infiltration après 15 ans de fonctionnement dans le centre de Copenhague

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RÉSUMÉ

En 1993, deux tranchées d'infiltration ont été installées dans le centre de Copenhague. Après leur mise en place, le système a été contrôlé en continu pendant près de trois ans. Durant cette période, une légère diminution des performances, probablement causée par le colmatage des tranchées, a été notée. En 2009, une nouvelle étude a été réalisée pour voir si la diminution de rendement se poursuivait et pour déterminer le fonctionnement du système. Les niveaux d'eau dans les tranchées ont été contrôlés pendant près de 4 mois, et sur cette période sept événements ont été retenus pour analyser le taux d'infiltration dans le sol environnant. Une analyse similaire a été menée sur des séquences de tempête, en 1993, peu de temps avant que les tranchées n'aient été installées. Une comparaison de ces données montre que l'infiltration a diminué depuis la mise en place du système il y a 15 ans et que la baisse est statistiquement significative ($p < 0{,}01$). Un modèle de colmatage a été ajusté aux données et des prévisions ont été faites pour les performances futures du système. Les résultats montrent que, si l'obstruction continue au rythme actuel, après 100 années d'exploitation, le système va décharger environ 10 fois plus d'eau dans les égouts par rapport au volume initial. Cela correspond à environ 60% du ruissellement total de la région. Les résultats montrent qu'il est important de prendre en compte des facteurs comme le colmatage et l'entretien du système lors de la mise en place de tranchées d'infiltration.

ABSTRACT

Two stormwater infiltration trenches were installed in 1993 in an area in central Copenhagen. The system was monitored continuously for almost three years after establishment, and a small reduction in performance over that time, possibly due to clogging, was noted. A new study was conducted in 2009 to see whether the reduction in performance has continued and to determine how the system performs today. Water levels in the trenches were monitored for almost 4 months, and from this period 7 events were selected to analyze the infiltration rate. A comparison with similar analyses on storm sequences from the first 3 years of operation shows that the infiltration has decreased since the establishment of the system 15 years ago. The decrease is statistically significant ($p<0.01$). A clogging model was fitted to the data and predictions were made for future performance. The results show that the system will discharge around 10 times more annual overflow to the sewers after 100 years of operation compared to the initial volumes, if clogging continues at current rates. This corresponds to 60% of the total runoff from the area. The results show that clogging and proper maintenance are important factors to consider when implementing stormwater infiltration trenches.

KEYWORDS

Clogging; Copenhagen; Stormwater infiltration trenches; Sustainable Urban Drainage Systems

1 INTRODUCTION

Small scale stormwater infiltration systems, such as soakaways and infiltration trenches, are often used as a means of reducing runoff and managing water resources in urban areas. Soakaways allow runoff from roofs, roads or other impermeable areas to be temporarily stored underground while slowly percolating into surrounding soils (CIRIA, 2007). They generally lead to significant decrease of stormwater discharge to sewer systems and may therefore contribute to the mitigation of flooding problems due to surcharge of sewer networks, reduction of combined sewer overflows, and enhanced groundwater recharge. The use of soakaways and infiltration trenches has a potential of becoming even more widespread in the future as a means of adaptation to changing rainfall patterns caused by climate change (Semadeni-Davies et al., 2008).

A number of studies indicate that the performance of these systems will decrease with time due to clogging effects from fine particles that enter the system via the stormwater inflow (see for instance Revitt et al., 2003). Field investigations have been carried out in several locations to estimate the decrease in performance (e.g. Lindsey et al., 1992, Dechesne et al., 2005). Existing clogging models are empirical time-dependent relationships (Dechesne et al., 2004; Endo et al., 2009) or based on cumulative mass of sediment particles entering the system (Siriwardene et al., 2007). However, very few long term field studies (>10 years) exist, and there are no general methods for predicting future performance, lifetime or maintenance requirements for such structures. More long term studies of soakaways and infiltration trenches are needed to draw conclusions on the above issues.

In the early 1990’s, two infiltration trenches were established to manage roof runoff from a housing area in Nørrebro in central Copenhagen. The system was monitored for almost 3 years after the installation, and already during this short period some indications of reduced performance were seen (Warnaars et al., 1999). This paper describes a new study that has been conducted during 2009 to verify whether the tendencies seen in the first years of operation have continued and to determine the extent of system clogging. A new, physically based, time-dependent clogging model is presented, which can be used to predict the future performance of the system and estimate the expected lifetime. The aim is to contribute to a better understanding of how the performance of sokaways develops over longer time periods and to determine how long their expected lifetime may be.

2 METHOD

2.1 Field study

This section describes the field site and methods used during the two field studies in 1994-1997 and 2009.

2.1.1 The field site

The infiltration system was constructed in 1993, in connection with a project initiated by Copenhagen Municipality with the aim of evaluating the possibilities of stormwater infiltration in the inner city areas. The field site is located on an inner yard at Lundtoftegade in the area Nørrebro in central Copenhagen (see figure 1).

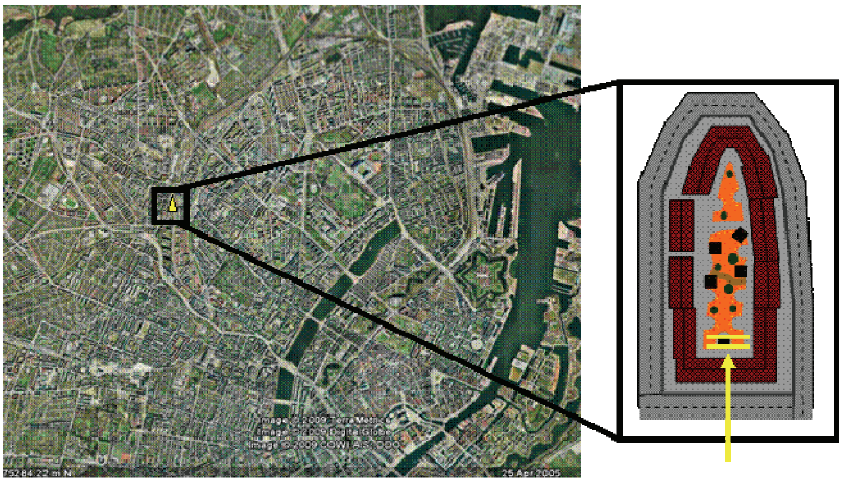

Figure 1. Location of the infiltration trench system in Copenhagen. The arrow shows the placement of trenches.

The system consists of two infiltration trenches connected to one inlet as shown in figure 2. Each trench is equipped with overflow pipes to the sewer network (not shown). The dimension of the trenches is 16 m x 0.8 m x 0.8 m, and the porosity of the filling material is estimated to 0.39. The total effective storage volume of both trenches is thus approximately 8 m^3. The inlet receives water from the surrounding roofs, which cover an area of approximately 600 m^2.

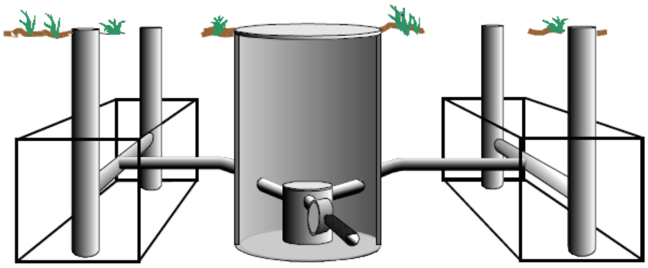

Figure 2. Setup of the infiltration system in Copenhagen

2.1.2 Previous study of the site

The performance of the infiltration system was studied during almost 3 years from 1994-1997 by Warnaars et al. (1999). Water levels in the two trenches, precipitation and inflow were recorded during this period, and the data was used to evaluate infiltration rates and estimated number of overflows per year from the trenches. In addition, a number of soil core samples were taken from the site and analyzed to find the saturated hydraulic conductivity (Warnaars et al., 1999).

This initial study showed that the two infiltration trenches (hereafter named “North” and “South”), although only about 7 m apart from each other, differed significantly in infiltration rate. The field-saturated hydraulic conductivity for the southern trench was estimated to be about 10 times lower than the corresponding value for the northern trench.

2.1.3 Current study

Between the previous study in 1997 and 2008, no investigations were conducted on the ongoing performance of the system. Because of the indications of clogging and reduced performance in other studies, a new study to evaluate current performance was considered to be highly relevant.

In February 2009, four pressure transducers were installed; two in each trench, and water levels were logged once a minute for a period of approximately 4 months.

2.2 Models

2.2.1 Infiltration trench system

A mass balance model of the infiltration trench system was set up in Matlab. The principle is shown in figure 3 and equation 1 (for one trench only).

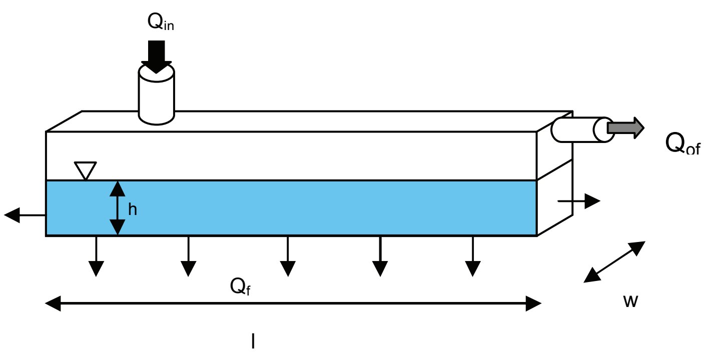

Figure 3. Schematic of the infiltration trench model with notation

$$\frac{dh}{dt} = \frac{1}{l \cdot w \cdot \varphi} \cdot \left(Q_{in}(t) - Q_f(h,t) - Q_{of}(h,t) \right) \qquad \text{Equation 1}$$

where φ is the porosity of the filling material.

The model is complicated by the fact that the trenches function as one when the water level is above the connection point (0.44 m) (see figure 2). This is handled as follows: When the water level in one of the trenches reaches above the connection point, all water above this point will flow to the other trench, and any potential inflow to the system will be directed to the other trench. If the water level is above the connection point in both trenches, they will function as one system with one infiltration rate, equally distributed between the two trenches.

The infiltration model used by Warnaars et al. (1999) was a semi-conceptual model, introduced by Mikkelsen (1995), which assumes unit gradient flow through the sides and the bottom of the soakaway, proportional to the wetted area and the field-saturated hydraulic conductivity (K_{fs}). The infiltration rate is thus dependent on the water level in the trench, and the sides and the bottom can be assigned different values of K_{fs}, as shown in equation 2:

$$Q_f = K_{fs,bottom} \cdot l \cdot w + K_{fs,sides} \cdot 2h \cdot (l + w) \qquad \text{Equation 2}$$

To simplify the comparison of infiltration rates, the same infiltration model has been employed in the current study.

2.2.2 Clogging

The formation of a clogging layer of fine particles between the trench and the soil has been modelled in this study (something that was not done in the initial investigation), to be able to predict the future performance and behaviour of the trench system. The thickness of the clogging layer is assumed to increase linearly with time, and an effective value of $K_{fs,bottom}$ can from this be derived based on the principle of orthogonal flow through layers with different hydraulic conductivities. Equation 3 shows the final expression for $K_{effective,bottom}$ as a function of time.

$$K_{effective,bottom}(t) = \frac{b_{tot}}{\sum_{i=1}^{N} \frac{b_i}{K_i}} \approx \frac{b_1}{\frac{b_1}{K_1} + \frac{b_2(t)}{K_2}} = \frac{b_1}{\frac{b_1}{K_1} + \frac{a \cdot t}{K_2}} = \frac{1}{\frac{1}{K_1} + c \cdot t} \qquad \text{Equation 3}$$

The parameter b denotes layer thickness; index 1 denotes the initial soil layer below the trench (thickness unknown) and 2 the clogging layer. The thickness of the latter is assumed to be negligible compared to the total thickness, and the total thickness is thus assumed to be equal to the thickness of layer 1. This leads to the simplification made above, and leads to an equation with one unknown, the parameter c which is dependent of the soil layer thickness (b_1), the thickness growth rate of the clogging layer (a) and the hydraulic conductivity of the clogging layer (K_2). The unknown parameter is estimated by fitting the model to the data from the two investigations.

The same clogging model has been used for modelling reduced infiltration rate through the bottom and through the sides. Often, only clogging of the bottom is assumed, but physical, chemical and biological processes that lead to clogging may also occur for the side walls. Suspended solids in the stormwater may for instance pass through the trench wall as water infiltrates, and deposit in the nearest soil layer which will lead to decreased infiltration rate (Bouwer, 2002).

2.3 Data analysis

The data from both studies have been analyzed with the aim of estimating infiltration rates from the trenches and to determine the extent of clogging. Data includes measurements of water level in trenches (recorded during both studies), inflow to the trenches and precipitation on the site (only the early investigation).

2.3.1 Selection of events

Since the initial investigation of the trench system contains continuous measurements from almost 3 years, it has been necessary to select a limited number of periods during this period for comparison with the new data. All events from the previous and the current study have been selected with care to ensure similar conditions and situations and allow for direct comparison of infiltration rates.

From the early study, three individual periods were selected for analysis. They were selected on the following principles:

- One event from each year should be selected (1995, 1996 and 1997). This is to ensure that any early tendencies of clogging or decrease in infiltration rate will be identified.

- The events should be during the same season (February-May) as the new study, to ensure that the physical conditions (temperature, soil moisture) are as similar as possible.
- The selected events should not lead to water levels above the connection point. This is because the new data was collected during a period with moderate rainfall intensities where water levels in general did not exceed the connection point.
- Data from the northern trench is excluded from the statistical analysis. This is since the new field campaign did not yield enough results for the infiltration rate in the northern trench.
- The selected periods only cover recession limbs (decreasing water levels) where no inflow or rainfall (or signs thereof) has been detected. This is done since the new study did not include any measurements of inflow or precipitation, and thus the only way of closing the water balance for the trenches is to assume no inflow during the analyzed period.

From the new observations, periods with no apparent inflow (usually visible on the recession limb of the water level curve) were selected from the south trench for further analysis. The water levels in the northern trench remained so low during the whole monitoring period that they were not useful for estimation of infiltration rate and they were therefore not further analyzed.

2.3.2 Estimation of infiltration rate

According to the infiltration model described in equation 2 above, the infiltration rate is dependent of the water level and the field-saturated hydraulic conductivity (K_{fs}) for the bottom and sides respectively. The value of K_{fs} is assumed to be constant during each event but varying between events. According to this principle, equation 2 can be rewritten to form a linear relationship between the infiltration rate Q_f and the water level h as shown in equation 4 (Warnaars et al., 1999):

$$Q_f = \alpha \cdot h + \beta; \quad \alpha = 2 \cdot K_{fs,sides} \cdot (l + w); \quad \beta = K_{fs,bottom} \cdot l \cdot w \qquad \text{Equation 4}$$

The infiltration rate is calculated for each time step by the formula shown in equation 5.

$$Q_f = -l \cdot w \cdot \varphi \cdot \frac{\Delta h}{\Delta t} \qquad \text{Equation 5}$$

Q_f can then be plotted as a function of h, and the parameters α and β be calculated by performing a linear regression of the plotted data. Through this procedure, event-specific values for K_{fs} are derived.

The data was filtered and reduced to 1 hour averages before the linear regression was performed in order to reduce the impact of measurement error on calculations of Δh. If one minute data is employed the method does not work well because Δh in equation 5 is then dominated by measurement error.

2.3.3 Comparison with old data

To evaluate whether the infiltration rate of the southern trench has decreased during the 15 years of operation, the calculated values of K_{fs} from the selected events in the 1990's and 2009 were subject to a hypothesis test (t-test). The null and alternative hypotheses are given below (μ_{Kfs} denotes the average K_{fs} value for the indexed period):

$$H_0 : \mu_{Kfs,1990's} = \mu_{Kfs,2009}$$

$$H_1 : \mu_{Kfs,1990's} > \mu_{Kfs,2009}$$

The t-test is performed twice since the infiltration model distinguishes between the field-saturated hydraulic conductivity of the sides and bottom of the trench. The distribution of K_{fs} is assumed to be lognormal.

2.3.4 Evaluation of performance so far and predictions of future performance

The mass balance model described in section 2.2.1 has been used to evaluate the performance of the infiltration system in terms of number of overflows per year and total annual overflow volume from the two trenches after 0, 15, 40 and 100 years of operation. (An overflow event is defined as a continuous period where the water level in the trench does not fall below 0.6 m) Rain data from a nearby rain gauge operated by the Danish Meteorological Institute has been used in combination with equation 6 to generate inflow data. If the total amount of rainfall since the start of the rain event exceeds the initial loss (I) then the inflow is calculated according to equation 6, otherwise it is 0.

$$Q_{in} = i \cdot \Phi \cdot A \qquad \text{Equation 6}$$

Parameter *i* denotes rainfall intensity. The runoff coefficient in table 1 is an estimate from the initial study in 1994-1997 (Mikkelsen et al., 1998). The K_{fs} values employed in the infiltration model are the averages of the calculated values based on measurements (previous and current study) or predictions generated by the clogging model (future predictions).

Table 1. Parameters for computing inflow from runoff based on equation 6

Parameter	Symbol	Value
Runoff coefficient	Φ	0.86
Runoff area	A	600 m^2
Initial loss	I	0.4 mm

3 RESULTS AND DISCUSSION

3.1 Field study results

Figure 4 shows the water level in the south trench during 5 days in 1995 and 2009 (the respective time periods are chosen to create equal initial conditions and thereby facilitate comparison). The initial recession limb clearly shows the difference in infiltration rate between the two periods. Figure 5 shows data for the north trench, also indicating lower infiltration rate in 2009 compared to 1995. The period shown in figure 5 is the only event during the 4 months of monitoring in 2009 where there is any substantial amount of water in the north trench. Due to this, the north trench has been omitted from further analysis concerning current infiltration rate and clogging, since the data is too scarce to be able to draw any conclusions.

Note on figure 5 that the water levels are not recorded properly for very low water levels (below approximately 5 cm). This is since the pressure transducers are suspended a couple of centimetres above the bottom of the trenches.

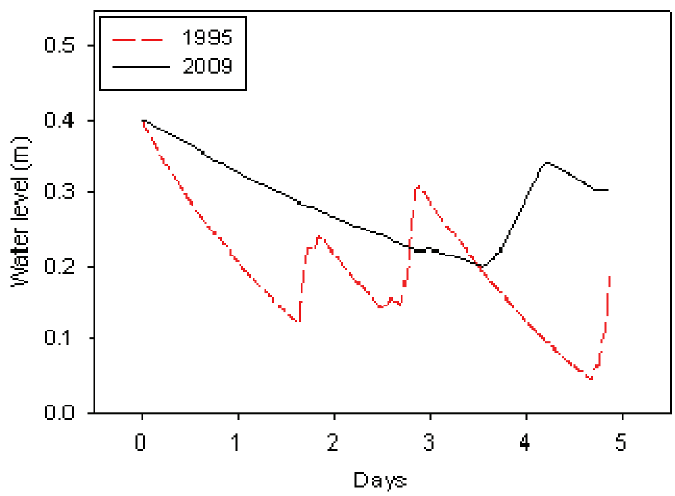

Figure 4. Water levels in the south trench during 5 days in 1995 and 2009

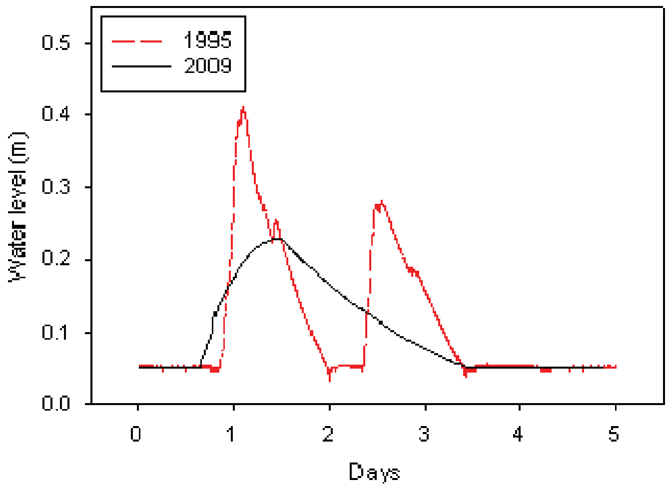

Figure 5. Water levels in the north trench during 5 days in 1995 and 2009

3.2 Estimation of infiltration rate

Figure 6 shows an example of the regression method used to estimate the infiltration rate and values of K_{fs} for each event. The data points in the plot contain water level and infiltration rates with a 1 hour resolution. The coefficients from the regression are used as described in section 2.3.2 to calculate K_{fs}, and the average values of the three analyzed events in the 1990's, and the seven analyzed events in 2009 are shown in table 2.

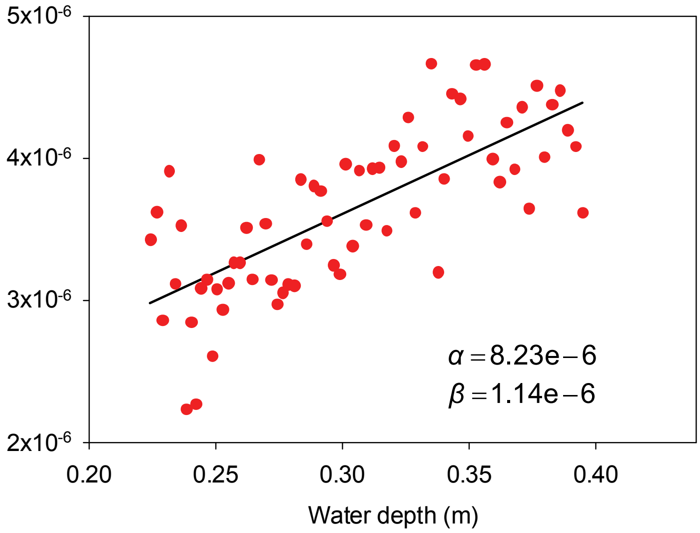

Figure 6. Regression for estimating K_{fs} values for an event on Feb 12, 2009

Table 2. Average values of K_{fs} for the 1990's and 2009

	$K_{fs,sides}$ (um/s)	$K_{fs,bottom}$ (um/s)
Average 1990's	0.89	0.28
Average 2009	0.29	0.075

3.3 Comparison with previous observations

Figure 7 below shows the calculated values of K_{fs} for the ten analyzed events, and trendlines showing how the values for the sides and bottom respectively seem to have developed over time. They both show a decreasing trend with time, and the hypothesis tests (t-tests) confirm that the average values from 2009 are lower than the corresponding values from the 1990's ($p<0.01$ for both sides and bottom).

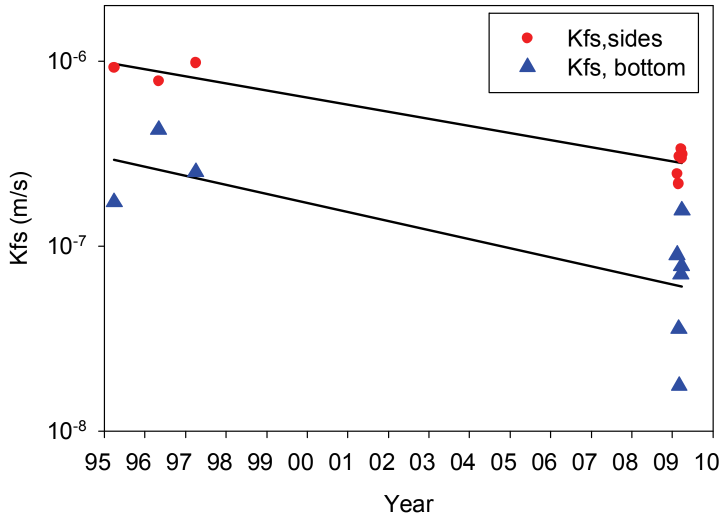

Figure 7. Calculated values of K_{fs} for the south trench and trendlines

Thus, it seems that clogging of the south trench has occurred during the past 15 years of operation. It is worth noticing that not only the infiltration through the bottom is affected, but also the infiltration through the sides. The reason for this may be, as discussed earlier, deposition of suspended solids in the soil layer near the trench walls, or a result of chemical or biological clogging. The decrease in infiltration rate through the sides was noticed in the initial project report (Mikkelsen et al., 1998) and the suggested reason was soil compaction. However there is no apparent explanation to why this compaction should have continued for 15 years, since the trenches are located in a closed yard where no vehicles or heavy machinery can enter. Further investigations are needed to determine the cause of the clogging both through the sides and the bottom, and would be of great interest to provide a better understanding of the clogging phenomenon.

3.4 Prediction of future performance

The clogging model described in section 2.2.2 was fitted to the data to obtain an estimate of how K_{fs} evolves over time. The average values of K_{fs} (in µm/s) from the 1990's and 2009 respectively (shown in table 1) were inserted as K_{eff} in equation 3, along with the time in years since the establishment of the trenches (1994 is year "0"), which led to equations 7 and 8 for describing future values of K_{fs}:

$$K_{fs,sides}(t) = \frac{1}{0.73 + 0.19 \cdot t} \quad \text{Equation 7}$$

$$K_{fs,bottom}(t) = \frac{1}{2.8 + 0.7 \cdot t} \quad \text{Equation 8}$$

These two equations have been used to evaluate the expected performance of the system in the future. Figure 8 shows the predicted evolution of K_{fs} over a period of 100 years according to the clogging model plotted together with the observed data. The largest decrease in infiltration rate is observed during the first years of operation.

The expected number of overflows and total overflow volume from the two trenches, as calculated by the mass balance model according to the description in section is 2.3.4, are shown in figure 9. The results may be slightly overestimated since it is based on K_{fs} values from relatively low water levels, and the previous study by Warnaars et al. (1999) indicates that K_{fs} values are higher at the top of the trenches.

Although these are very rough estimates, it is obvious that the clogging may have severe effects on the performance of the trenches, which after 100 years of operation are estimated to discharge around 10 times more runoff to the sewers compared to the first year after installation. Eastern Denmark receives around 700 mm of rainfall per year, which together with the parameters listed in table 1 would mean that the trenches receive about 360 m^3 of runoff per year. The predicted overflow volume 100 years after operation is around 200 m^3, or around 60% of the total incoming runoff. In other words, if the reduction in infiltration rate continues to the same degree as seen so far in this study, some kind of maintenance will be required if the infiltration system is to function properly in the future.

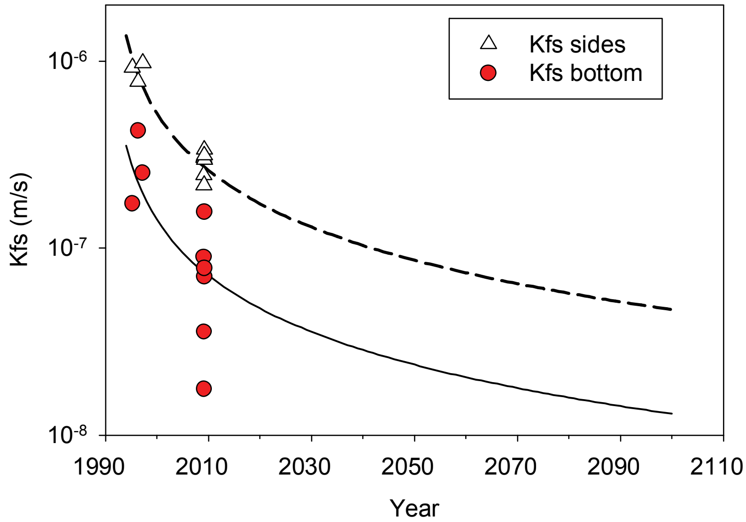

Figure 8. Calculated K_{fs} values and prediction of the evolution of K_{fs} according to the clogging model

The total lifetime of an infiltration trench without maintenance, and the required maintenance frequency, will, apart from site specific factors such as initial infiltration rate, dimensions etc., also depend on the local requirements for maximum allowed overflow frequency or required runoff reduction. If, for instance, the local requirement for this system is that 75% of the runoff should be infiltrated, the trench has a lifetime of approximately 30 years (without maintenance). It should be noted that the performance decreases more rapidly during the first years after installation, and that the number of overflows doubles during the first 10 years of operation. This must be taken into account when estimating lifetime and maintenance plans for soakaways and infiltration trenches.

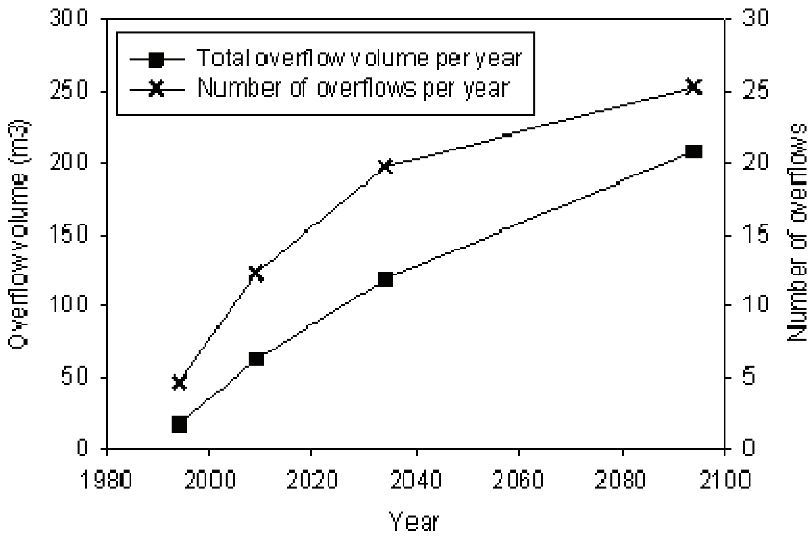

Figure 9. Predicted number of overflows and overflow volumes per year

Maintenance of infiltration trenches is particularly difficult since they are underground and not easily accessible. If maintenance cannot be conducted then an alternative is to account for clogging during the design phase and expect a limited lifetime.

A study of one infiltration trench is not enough to draw general conclusions on how clogging should be accounted for during dimensioning, or on the total lifetime of an infiltration trench. More studies are required to develop reliable design procedures that can account for clogging processes.

4 CONCLUSIONS

Infiltration trenches are often installed in order to significantly reducing the load of stormwater runoff in combined sewer networks. This study has evaluated the functioning of an infiltration trench system after 15 years of operation to verify if a reduction in performance could be seen. The results show that the infiltration system is not functioning as well as it did at installation. The infiltration rate of the south trench has decreased significantly since the first monitoring campaign. This is probably due to clogging of the bottom and sides, by settling of fine particles on the trench bottom and inside the trench walls, and other unknown factors. The reduced infiltration rate leads to more overflows from the trenches to the sewer system and prevents the system from functioning as intended.

A new, physically based, modelling concept for clogging and infiltration rate prediction has been developed and fitted to the observed data. The model shows that the performance decreases more rapidly in the initial phase after installation, and that the infiltration rates are decaying at a rate inversely proportional to time.

Predictions based on the data collected in this field study and data collected during a previous study, show that the performance of the infiltration system will continue to decrease if the reduction of infiltration rate continues as it has done so far. Rough estimates indicate that the overflow volume from the trenches may be around 60% of the total incoming runoff after 100 years of operation, which is far from the intended performance of this system. Thus, some kind of maintenance or other method for restoring the initial capacity of the infiltration system will be necessary if the system should continue to operate and contribute to a sustainable management of rainwater resources in Copenhagen in the future. Furthermore, the decrease in hydraulic performance due to clogging needs to be taken into account when designing the system. More studies of this kind are needed to draw up general guidelines on design, lifetime and maintenance requirements of these kinds of systems.

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