Exfiltration from gravity sewers: a pilot scale study

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Abstract Pilot-scale experiments were conducted on exfiltration of wastewater from gravity sewers. The effect of storm events, flushing of pipes and alternating infiltration/exfiltration were simulated. Exfiltration through different types of sewer leaks and into different soils were studied. It was found that the exfiltration rate became constant after some days of exfiltration. It stayed constant for the duration of the experiments, which typically spanned over some weeks. The exfiltration was governed by the development of a clogging zone at the sewer leak and could be characterized by a leakage factor. The leakage factor may then be used to estimate the risk of groundwater pollution from a sewer network.

Keywords Exfiltration; gravity sewers; leakage factor; leaks

Introduction

Sewer systems contain leaks, the effect of which can easily be observed by infiltration. Infiltration has been studied extensively and the negative effects thereof on the operation of the urban wastewater system are well documented (Ellis, 2001). However, it is reasonable to assume that when groundwater can infiltrate, wastewater may also exfiltrate under given conditions. However, little is known about the exfiltration mechanisms and the quantification of the exfiltrating wastewater and pollutants.

Before the 1960s all sewer pipes in Denmark were fitted together with materials that tended to degrade and erode rapidly and leave the pipe joints open. The pipe material was furthermore often of inferior quality, leading to rapid degradation of the materials and subsequently to leaks (Randrup and Faldager, 1997). Consequently, many leaks exist today. Not before the 1980s was the quality of sewer joints and materials known today reached. Today precautions are taken to minimize leaks: the pipe materials and joints must meet certain quality standards, as must the soil into which the sewer is laid. For example, in Denmark sewers must be laid in sandy soil without large stones and precautions are taken to avoid the opening of pipe joints. For intercepting and trunk sewers, it is common to test its tightness, pressurizing the system after construction.

A rather limited number of studies are available on exfiltration of wastewater and the consequences thereof upon the groundwater quality. A few of these studies attempt to quantify the exfiltration based on the urban groundwater pollution (Härig, 1991; Härig and Mull, 1992). However, they suffer from a number of difficulties, e.g. distinguishing between pollution from sewers and pollution from other sources (Mull, 1996). Other studies attempt to quantify the loss of water from the sewer due to exfiltration. They are either based on indirect determinations, or tracer-based in-sewer flow measurements. Common to these studies is that they show significant exfiltration: Jensen and Madsen (1996) found for a small urban catchment that exfiltration caused a water loss of up to 25%. In intercepting sewers, Knudsen et al. (1996) determined mean exfiltration rates of 3 l s⁻¹ km⁻¹. The indirect determinations of exfiltration have mainly been based on the water balance for a catchment (Härig, 1991; Jensen and Madsen, 1996). This method is believed to yield rather rough estimates because the determination of the individual contributions to the water balance holds significant uncertainties. Direct measurement of exfiltration using e.g.
tracers for flow measurement is in principle a ‘better’ approach (Knudsen et al., 1996; Ohlsen and Genders, 1993; Jensen and Madsen, 1996). However, measurement of flow in real sewers is a difficult task, especially when addressing small differences in flow. Consequently, reasonable accuracy is difficult to achieve and the results of these studies must be interpreted with care.

The literature agrees on TV-inspections being inconclusive when identifying if – and to what degree – wastewater is leaking from sewers (Eiswirth and Hötzl, 1994; Eiswirth et al., 1994; Knudsen et al., 1996; Ohlsen and Genders, 1993). In other words, not all damages of sewers are also leaks for exfiltration. The goodness of this postulate is difficult to assess as a missing correlation between damages found by TV-inspection and exfiltration could also be due to difficulties in the determination of exfiltration.

It is the objective of this work to contribute to the knowledge of the mechanisms controlling exfiltration as well as to quantify the exfiltration from leaky sewers. To achieve this, pilot scale experiments are conducted, allowing measurement of quantity and quality of the exfiltrating water.

**Methods**

The pilot scale experiments conducted in this study were located in an underground sewer monitoring station in Frejlev, Denmark. The catchment is 85 ha without significant industry and holds a population of approximately 2000 people. Due to the small size of the catchment the wastewater is rather fresh when it reaches the monitoring station (Schaarup-Jensen et al., 1998).

Two separate experimental setups were in use: one setup (S1) for investigation of the behavior of leaks during constant flow conditions and the other setup (S2) for investigation of various variable conditions, e.g. the effects of flow variations, different sizes and types of leaks and alternating infiltration/exfiltration. In each setup, wastewater was continuously circulated through a 110 mm diameter PVC pipe (Figure 1). Where the pipe passed through a column it held a leak (Figure 2 and Figure 3). Centrifugal pumps were used for the circulation of the wastewater. The circulating wastewater was continuously renewed with fresh wastewater taken from the bottom of the gravity sewer that passed through the monitoring station, resulting in a mean wastewater residence time in the setups of 2–5 minutes (Figure 3).

S1 contained 4 stainless steel columns, whereas S2 contained 2 stainless steel columns. In a few experiments, 2 PVC columns were added to S2 (Figure 2). At the bottom of the columns there was a stainless steel net of 1 mm mesh and a funnel that channeled the exfiltrating water into a beaker beneath the column (Figure 2 and Figure 3). Flow was measured by the amount of water running into the beaker. The 110 mm diameter PVC pipe that passed through the columns had a slope of 1.5–2.0%. When the pipe was flowing half-full, it corresponded to a flow velocity of approximately 1 m s⁻¹ and a shear stress of roughly 4.5 N m⁻². The temperature in the monitoring station and correspondingly the temperature of the soil in the columns was 7–9°C, i.e. equivalent to Danish soil temperatures.

![Figure 1](http://iwaponline.com/wst/article-pdf/47/4/69/422362/69.pdf) Layout of setup S1. S2 was constructed similarly, but in most cases operated with only two columns (Figure 2 and Figure 3)
In all experiments sandy soils were packed into the columns. In S1 sand was packed to the top of the pipe, in S2 sand was packed to 15–20 cm above the pipe. 2 artificial, well-graded sands (Sand I and II) and 2 natural sands (Sand III and IV) were used (Figure 4). In one experiment, 2 typical Danish loamy sand types (Table 1) were packed into the columns until 11 cm was beneath the pipe followed by Sand III to the top of the pipe. The loamy sand types were dried and subsequently moisturized to a homogenous moister content prior to application to the columns. To control a possible buildup of water on the interface between the soils, a drainage tube was placed 10 cm beneath the bottom of the PVC pipe (Figure 2). The packing of the columns was done by adding and compacting approximately 5 cm of sandy soil at a time. The columns were saturated with tap water prior to an experiment.

A total of 12 experiments were conducted (Table 2). Under constant flow conditions, open joints were always used as leaks (leakage area 18 cm², cf. Figure 2). Under variable conditions different types of leaks were studied in addition to the open joint, namely cracks in the pipe material and large holes at the bottom of the pipe. Furthermore, different operational conditions of the sewer were simulated, namely:

- Constant flow conditions. Half-full flowing pipe and a flow velocity of about 1 m s⁻¹.
- Flushing of the pipe. A brush connected to a water hose was used.
- Storm events. The outlet of the pipe was raised 1 m so that the pipe became pressurized and full flowing. The flow velocity was approximately 1 m s⁻¹.
- Alternating infiltration/exfiltration. The bottom of the column was closed and tap water (without chlorine) was continuously added so that the water level in the surrounding sand was well above the pipe. After about 1 day of infiltration, the water supply was turned off and the surplus water drained off. Hereafter the wastewater circulation was turned on.
- Inhibition of the biological activity. Sodium hypochlorite was added in such concentrations that the biological activity became inhibited. For practical reasons wastewater was not continuously replaced. The wastewater was consequently circulated in the setup, resulting in an increase in temperature to 31°C.

![Figure 2](image1.png) Columns used in setup S1 (left) and S2 (right). In S1 4 stainless steel columns were used, in S2 2 stainless steel columns were used and in some cases 2 PVC columns were added. In S1 the leak type was an open joint (cf. left), in S2 different types of leaks were tested.

![Figure 3](image2.png) The left photo shows the outtake of wastewater from the gravity sewer. The middle photo shows the setup S1. The right photo shows one of the columns of setup S2.
In experiment A, B, C and D, COD and nitrogen compounds were measured according to Standard Methods (APHA, 1995). E. coli was measured according to Grant (1997).

**Results**

Within a few hours of an experiment, the exfiltration rate showed a rapid decrease. The exfiltration rate continued to decrease for several days until a more or less constant rate was reached, i.e. the exfiltration from the leaks never ceased completely (Figure 5 and Figure 6). Now and then the exfiltration rate increased rapidly for a short period. The reason for this short-term break-through of wastewater is not known.

Comparison of the 4 sand types showed no systematic difference between the exfiltration rates after some days (Figure 5). After 2–3 days of exfiltration, the average exfiltration in experiments A, B and C became 0.3 l d⁻¹. In experiment D the exfiltration reached a rate as low as 0.08 l d⁻¹ (Figure 6). No wastewater drained from the tube placed 1 cm over the loamy sand/Sand III interface, i.e. water did not build up in the sand above the loamy sands. Consequently, the reduced flow out of the columns was not due to a reduced permeability of the loamy sand types.

**Table 1** Loamy sand types

<table>
<thead>
<tr>
<th></th>
<th>Loamy Sand I</th>
<th>Loamy Sand II</th>
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<tbody>
<tr>
<td>Sand (%)</td>
<td>76.9</td>
<td>89.6</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>11.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>9.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Humus (%)</td>
<td>2.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Organic C (%)</td>
<td>1.52</td>
<td>1.12</td>
</tr>
<tr>
<td>pH (H₂O)</td>
<td>7.1</td>
<td>6.1</td>
</tr>
<tr>
<td>CEC (meq 100g⁻¹)*</td>
<td>15.13</td>
<td>8.78</td>
</tr>
</tbody>
</table>

* Cation exchange capacity

**Table 2** Experiments conducted in the two setups S1 and S2

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (S1)</td>
<td>Sand I, II, III and IV, each in a column. 9 days of half-full flowing pipe. Type of damage: open joint.</td>
</tr>
<tr>
<td>B (S1)</td>
<td>Sand I, II, III and IV, each in a column. 24 days of half-full flowing pipe. Type of damage: open joint.</td>
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<tr>
<td>C (S1)</td>
<td>Loamy Sand I and II in each 2 columns. Loamy sand from the bottom to 11 cm beneath the pipe. Sand III to the top of the pipe. 47 days of half-full flowing pipe. Type of damage: open joint.</td>
</tr>
<tr>
<td>D (S1)</td>
<td>Sand I and II in 2 columns each. Sodium hypochlorite added to inhibit biological activity. 18 days of half-full flowing pipe. Type of damage: open joint.</td>
</tr>
<tr>
<td>E (S1)</td>
<td>Sand III and IV in 2 columns each. Sodium hypochlorite added to inhibit biological activity. 18 days of half-full flowing pipe. Type of damage: open joint.</td>
</tr>
<tr>
<td>F (S2)</td>
<td>Sand III. 8 days of half-full flowing pipe, intermitted by 3 × 1 hour of pressurized flow. Then flushing of pipe. Type of damage: 2 columns with holes, area 15 cm².</td>
</tr>
<tr>
<td>G (S2)</td>
<td>Sand III. 8 days of half-full flowing pipe, intermitted by 3 × 1 hour of pressurized flow. Then flushing of pipe. Type of damage: 2 columns with cracks, area 3 cm².</td>
</tr>
<tr>
<td>H (S2)</td>
<td>Sand III. 4 days of half-full flowing pipe, intermitted by 3 × 1 hour of pressurized flow. Then flushing of pipe. Type of damage: 2 columns with open joints, area 18 cm².</td>
</tr>
<tr>
<td>I (S2)</td>
<td>Sand III. 5 days of half-full flowing pipe, intermitted by 3 × 1 hour of pressurized flow. Type of damage: 2 columns with holes, area 46 cm².</td>
</tr>
<tr>
<td>J (S2)</td>
<td>Sand III. 11 days of half-full flowing pipe, intermitted by 9 × 1 hour of pressurized flow. Type of damage: 2 columns with holes, area 15 cm²; 2 columns with open joints, area 18 cm².</td>
</tr>
<tr>
<td>K (S2)</td>
<td>Sand III. 2 days of half-full flowing pipe, followed by 3 × 1 day of infiltration and water drain-off, divided by 1–3 days of half-full flowing pipe. Type of damage: 2 columns with open joint, area 18 cm².</td>
</tr>
<tr>
<td>L (S2)</td>
<td>Sand III. 16 days of half-full flowing pipe. Type of damage: 2 columns with holes, area 46 cm²; 2 columns with holes, area 84 cm².</td>
</tr>
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</table>
Exfiltration after simulated storm events were investigated in experiments F, G, H, I and J (cf. Table 2). The experiments showed that the exfiltration during the simulation of the storm events decreased until a constant rate was reached after about 5 events (Figure 7). When the simulated storm event ceased, the exfiltration immediately dropped to a rate close to the level reached before the event. Within a day or so, the flow was back at the rate before the simulated storm event.

For the 2 columns with a hole in the bottom of the pipe (Figure 7), the rate reached during the simulated storm events was 20 times the rate for the pipe flowing half-full, i.e. the exfiltration rate increased by the same factor as did the water pressure on the leak. For the columns with the open joints, the corresponding rate was 56 times the exfiltration rate during half-full flowing pipe conditions.

Exfiltration after infiltration was simulated in experiment K (Figure 8). When wastewater started circulating through the pipe after the water had been drained of the sand, the exfiltration was around 20 l d⁻¹. However, the rate rapidly dropped and within approximately one day it reached the level from before the infiltration. Exfiltration after flushing of the pipe was simulated in experiments F, G and H (Table 2). It had a similar effect as the other perturbations: the exfiltration increased immediately after the perturbation, but dropped rapidly to the same rate as before the disturbance. In the experiments, the exfiltration increased to 4 times the rate from before the flushing, and was back at the initial rate within hours.

Inhibition of the biological activity was studied in experiment E. Also in this case exfiltration reached a constant rate. However, the rate was several times higher compared with biological active wastewater. Part of the higher rate could be contributed to a difference in
water viscosity as the experiments were conducted at different temperatures. Correction for
this effect resulted in a steady state rate of 0.9 l d⁻¹.

The material in the immediate vicinity of the leaks had a higher content of organic matter
than the sand into which the pipe was laid, namely between 1.5% and 24% whereas the dif-
ferent sand types contained less than 0.4% of organic matter. Furthermore, the sand materi-
al close to the leaks had a blackish color and was typically found 1–2 cm into the sand bed.

In the beginning of some of the experiments A, B, C and D, *E. coli* counts showed up to a
few hundred *E. coli* per ml. However, after some days of exfiltration, this number was in all
cases reduced to a few *E. coli* per ml. COD was more or less constant throughout the experi-
ments. In experiment A, B and C, the average COD in the exfiltrating water was 29 g COD m⁻³ (std. dev. 13 g COD m⁻³) for Sand I and II (artificial, well-graded sands) and 6 g COD m⁻³
(std. dev. 6 g COD m⁻³) for Sand III and IV (natural sands). In experiment D, the average
COD content was 36 g COD m⁻³ (std. dev. 14 g COD m⁻³) for Loamy Sand I and 14 g COD m⁻³
(std. dev. 21 g COD m⁻³) for Loamy Sand II. However, some of the organic matter may be
contributed to a release from the soil itself as it had been dried prior to the experiment. The
artificial sand types (Sand I and II) allowed ammonia to break through a few days after the
start of the experiments, whereas no ammonia was found for the natural sand types (Sand III
and IV). Neither did the loamy sand types allow ammonia to pass. Non or only a little nitrite
was found in the leakage. However, nitrate was found in all cases and after some weeks nitrate
increased significantly, in one case to nearly 50 g N m⁻³.

**Discussion**

The high exfiltration rate in the beginning of the experiments was due to exfiltration taking
place into clean sand. A few days after the start of an experiment, a clogging zone with a rel-
atively high concentration of organic matter had developed and exfiltration decreased and
stabilized at a constant rate. In real sewers, exfiltration typically continues for a long time,
and clogging zones must hence be well established. Applying the information obtained in
the pilot scale experiments on exfiltration from real sewers, it is consequently necessary to
look at the exfiltration after the rate has become constant, i.e. not immediately after a per-
turbation like a flushing of the sewer. Comparing such exfiltration rates per unit area of
leakage shows a good deal of scatter (Figure 9). However, there is a clear tendency towards
an increase in exfiltration when the leakage area increases. Furthermore, there seems to be a
clear difference between open joints and holes/cracks. Open joints give on average rise to
exfiltration rates of 0.02 l d⁻¹ cm⁻² whereas holes and cracks yield 0.06 l d⁻¹ cm⁻².

Taking into account that these exfiltration rates were found for a water depth of 5 cm, the
rates correspond well with the findings of Jenssen (1984), who under laboratory conditions
found that the wastewater infiltration capacities of sandy soils are between 0.001 l d⁻¹ cm⁻²
(sandy moraine) and 0.02 l d⁻¹ cm⁻² (sandy gravel).

Combining the results showing 1) the development of a clogging zone around the
leaks, 2) an independence of the exfiltration rate for the sand types, and 3) an increase in
exfiltration with increasing water pressure and leakage area, it is reasonable to conclude that the exfiltration is governed not by the material into which the pipe is laid, but by the clogging zone. Treating the clogging zone as a thin, semi-permeable layer and applying Darcy’s law, a leakage factor can describe its properties (Eq. (1)) and Eq. (2) can be formulated (Rauch and Stegner, 1994):

\[
L_{\text{leak}} = \frac{k_f}{\Delta l} \tag{1}
\]

\[
Q_{\text{leak}} = A_{\text{leak}} \Delta h L_{\text{leak}} \tag{2}
\]

where \(L_{\text{leak}}\) is a leakage factor \([s^{-1}]\), \(k_f\) is the permeability of the clogging zone \([m \cdot s^{-1}]\), \(\Delta l\) is the thickness of the clogging zone \([m]\), \(Q_{\text{leak}}\) is the flow from the leakage \([m^3 \cdot s^{-1}]\), \(A_{\text{leak}}\) is the leakage area \([m^2]\) and \(\Delta h\) is the water pressure on the leak \([m]\).

The leakage factor characterizing the clogging zone beneath the holes and cracks can now be found as the leakage flow divided by the water pressure on the leak:

\[
L_{\text{leak}} = \frac{0.06 l \cdot d^{-1} \cdot cm^{-2}}{5 \cdot cm} \approx 1.4 \times 10^{-4} s^{-1}.
\]

Assuming a thickness of the clogging zone of 1–2 cm, the permeability of the clogging zone is found from Eq. (1) to be approximately \(2 \times 10^{-6} m \cdot s^{-1}\). For the open joint the leak stretches from the water surface to the bottom of the pipe. Therefore, the mean water pressure on the leak (3.2 cm) should be used:

\[
L_{\text{leak}} = \frac{0.02 l \cdot d^{-1} \cdot cm^{-2}}{3.2 \cdot cm} \approx 0.7 \times 10^{-4} s^{-1}.
\]

Assuming a thickness of the clogging zone of 1–2 cm, the permeability of the zone is consequently found to be about \(1.1 \times 10^{-6} m \cdot s^{-1}\).

The clogging zone is likely to be responsible for the observed reduction of \(E. coli\) as the pore size in the clogging zone is reduced with time and bacteria are thereby easier trapped. On the other hand, the aerobic nitrification did probably not occur in the clogging zone but in the soil beneath it. Consequently, under normal operational conditions and when the sewer is situated in soil without macroscopic pores, the bacterial pollution of the groundwater will most likely be insignificant whereas it must be assumed that all ammonia contained in the exfiltrating wastewater will be nitrified and nitrate leaking to the groundwater taking place.

Assessing the risk of groundwater pollution from a known leak calls for reliable information on the type and area of leaks, the operation of the sewer, the occurrence of the pollutants in question and their transport and transformation behavior. In this study \(E. coli\), nitrogen and COD were given as examples of such pollutants. Generally, when such knowledge is available, a groundwater pollution risk assessment can be made using the results gained in this study. It is furthermore suggested to use general knowledge on construction techniques and materials together with TV-inspections to assess the type and area of the leaks. However, it must be kept in mind that all observed damage is not necessarily also leaks.

**Conclusion**

Under constant flow conditions, exfiltration rapidly reached a rate that remained constant for experiments lasting over 7 weeks. Simulation of storm events, flushing of the pipe and alternation between infiltration and exfiltration all resulted in an increase in the exfiltration...
rate. However, following such perturbation, the flow rapidly dropped to its previous, constant rate. These effects were in all cases reversible. The exfiltration rate was independent of the type of sand into which the pipe was laid. However, the type and the size of the leaks and the pressure on the leaks were found to play an important role for the magnitude of the exfiltration.

The rate of exfiltration was governed by the development of a biologically active clogging zone. This zone could be characterized by a leakage factor and the leakage factor then used to assess the exfiltration from real sewer systems. Applying knowledge of the sewer system, the type and extent of leaks and the behavior of pollutants transported in soil systems, an estimate of the risk of groundwater pollution from the urban wastewater system can be made. The results from this study indicate that the exfiltration rate from leakages in sewer networks is less significant than reported in most other studies.

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References


