Automated monitoring system for events detection in sewer network by distribution temperature sensing data measurement

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ABSTRACT

This study is related to distribution temperature sensing (DTS) in sewers for tracing illicit or unintended inflows to foul sewers. A DTS measurement is performed with a fiber optic cable that is installed at the invert of a sewer pipe in combination with a standalone laser/computer instrument. This set-up generates in-sewer temperature measurements with high resolutions in time (every minute) and space (every metre) along the cable over long periods of time (weeks on end). The prolonged monitoring period in combination with the high level of detail in the dataset allows the study of anomalies (i.e., unexpected temperatures and/or temperature variations at certain locations), even if these only occur very infrequently. The objective of this paper is to develop an automated tool to analyze the large data masses and identify anomalies caused by illicit or unintended inflows. In this study, an algorithm for detecting the temperature changes that are caused by both wastewater discharge and inflow of stormwater are developed. A comparison of the results of the automated procedure to the results of a manual assessment of the datasets (Elmehaven, Denmark) shows that the automated procedure performs very well.

Key words | automated tool, DTS, fiber optic cable, foul sewers, inflow stormwater, noise levels

INTRODUCTION

Distribution temperature sensing (DTS) is optoelectronic technology which makes continuous measurements of temperatures and this distributed sensing system is composed of two components: optical fiber cable is used as the sensor and detector system, which include a laser and a detector.

The technology of DTS was developed at the beginning of the 1980s in the United Kingdom (Dakin et al. 1985); since this time the DTS technique has been used for a variety of applications such as measuring atmospheric temperature (de Jong et al. 2015), ground surface temperature (Bense et al. 2016), forest (Krause et al. 2015), rocks (Read et al. 2013), surface water and groundwater (Westhoff et al. 2007; Mamer & Lowry 2013; Hare et al. 2015; Arricibita et al. 2018), lakes (Van Emmerik et al. 2013), hydrology (Selker et al. 2006), and leakage detection in dams (Khan et al. 2010), ditches and canals (Hoes et al. 2009a).

The application of DTS in sewer networks has been developed in many studies for different purposes and for different sewers. Apperl et al. (2017) have used DTS to detect pipe leakage in sewage pressure pipes in Austria. Hoes et al. (2009a) have used DTS to find illicit connections of wastewater to storm sewers in two municipalities in the Netherlands under different circumstances. The authors suggested to use only the dry weather results to detect illicit connections because the temperatures of warm water discharge were higher than the temperature in the storm sewer, and the time of the warm water discharges from individual houses showed an intermittent behavior. In addition, Langeveld et al. (2012) used a DTS monitoring system to analyze the performance of stormwater in separating manifolds.

To examine the feasibility of applying DTS in combined sewer systems, Schilperoort & Clemens (2009) used the monitoring technology in combined sewer networks of a Dutch municipality. They showed that the discharge from individual house connections could be detected by their higher temperature.

To identify illicit connections in storm sewers in the city of Breda, The Netherlands, de Haan et al. (2011) used DTS to detect their occurrence and determine their type. Schilperoort et al. (2015) searched for illicit stormwater

inflows and other extraneous water sources to foul sewers in the Netherlands and Germany and found for both drainage areas a number of stormwater inflows.

To quantify the detection limits when identifying illicit connections, Nienhuis et al. (2013) describes the results of full-scale experiments in Breda city. The results show that the DTS can be influenced by the volumes of discharges and the length of house connection.

Data collected from DTS analysis generates the temperature measurements in the sewer network along the fiber optic cable, with a high resolution in time (e.g., 24 hours divided by a 1 min temporal resolution) and space (e.g., 1 m spatial resolution), which represents more than a million individual temperature measurements per km of cable for each day.

The visualization and the interpretation of this amount of data have been done manually to search for anomalies from expected temperature. In order to reduce the manual labor needed to analyze the data as well as obtain a more objective detection which is less dependent on the operator, an automated procedure has been developed by Vosse et al. (2013) to scan the data for sudden temperature changes that are not caused by rainfall to detect the illicit connections in the city of The Hague (The Netherlands).

A significant problem with applying DTS is the noise level of the equipment. To calculate the noise level, Vosse et al. (2013) used 2 hours of data where all temperature variations could be attributed to the noise only. Vosse et al. (2013) used one threshold to detect temperature changes caused by house connection discharges. In the present work this approach is further developed and two noise levels are used to detect the temperature changes that are caused by both the wastewater inflow from house connection and the inflow of stormwater into the foul sewer network. A smart algorithm is designed, coded and implemented in Matlab to visualize and interpret DTS monitoring data from a sub-catchment of a Danish city and the results tested using field measurement datasets.

**METHODS**

**Acquisition principal and data description**

Figure 1 presents the standard lay-out of the applied DTS system. Above ground there is a trailer containing a data acquisition and transmission system. The data acquisition system is a Multi Sensor Board Linear Pro Series (N4386B-052) from AP-sensing, which logs the data on a standard laptop computer that transmits it to a server. The sensor board is linked to a fiber optic cable laid out in the sewer pipes.

The fiber optic cables used were carrying two glass fibers (outer diameter 6.0 mm Armored FO PBT patch cord 50/125 (OM2), Kaiphone, China).

**Experimental site**

Distributed temperature sensing was set up in Elmehaven, a sub-catchment of the town of Lystrup, Denmark. The sub-catchment is residential and the sewer system was constructed as a separate sewer system in 2005. The total inspected sewer length was 1,120 m. The optical fiber was installed in the foul sewer for detecting illicit or unintended inflows of surface runoff. A map of Elmehaven city and the fiber optic cable is presented in Figure 2.

**RESULTS AND DISCUSSION**

**Monitoring data results**

For each time step of 1 minute and each space step of 1 metre, a measurement of temperature is obtained. The
temperature measurements for each day are automatically presented as a matrix $M_{\text{day}_i}^{\text{temperature}}$ with rows representing the time and columns representing the distance.

$$M_{\text{day}_i}^{\text{temperature}} = \begin{bmatrix} T_1t_1 & T_1t_2 & \cdots & T_1t_m \\ T_2t_1 & T_2t_2 & \cdots & T_2t_m \\ \vdots & \vdots & \ddots & \vdots \\ T_nt_1 & T_nt_2 & \cdots & T_nt_m \end{bmatrix}$$ (1)

$T (^\circ \text{C})$: Temperature measurements by the fiber optic cable
$t (\text{min})$: Time. $t = 1, 2, \ldots n$
$l (\text{m})$: The position of the fiber optic. $l = 1, 2, \ldots m$.

Figure 3 presents an example of the results for the Elmehaven catchment area for the day of October 17th, 2013. The horizontal axis represents the length along the cable from $x = 0 \text{ m}$ to $x = 1,833 \text{ m}$ at the end of the cable. The fiber optic cable enters the sewer network at $x = 86 \text{ m}$. The vertical axis represents a time-span of 24 hours.

Figure 3 is obtained by plotted the matrix of temperature $M_{\text{day}_i}^{\text{temperature}}$.

Processing of measurements

Using the DTS monitoring from Elmehaven, an automated procedure has been programmed in Matlab to detect both
the positive and the negative events. Positive events are defined as the increase of the sewage temperature in the sewer pipes caused by extraneous water discharges and negative events are defined as the decrease of the sewage temperature in the sewer pipes caused by extraneous water discharges.

The method automatically performs the steps outlined in the following sections.

**Determine noise levels**

A significant problem with applying DTS for monitoring temperature in a sewer network is the noise level of the obtained temperature data (Vosse et al. 2013).

To determine the noise level, an algorithm was developed following these steps:

```matlab
for t = 1:1: n
    for l = 2:1: m
        C(t,l - 1) = M_temperature^day(i) (t,l) - M_temperature^day(i) (t,l - 1);
    end
end
```

- **C:** The matrix of the temperature variation between the elements of the matrix \( M_{temperature}^{day\;i} \).

To calculate the percentage of temperature changes, the matrix \( C \) was reshaped to the vector and this vector was sorted from the minimum temperature variation to the maximum temperature variation and divided by the intervals of 0.1 °C.

**Percentage of temperature changes**

\[
\frac{k}{k_{total}} \times 100
\]

- \( k \): Number of temperature variations in each interval of 0.1 °C
- \( k_{total} \): The total number of temperature variations of all intervals.

Two examples of a period of time of data collected have been selected. The first example is without events and the second example is with events.

The first example presents the period of time from 01:00 to 01:20 on October 18th, 2013 and positions from 360 m to 372 m. This period is selected from the data collected during the monitoring campaign because there were no runoff events affecting the temperature. The temperature changes in this period were hence caused only by the noise of the fiber optic cable.

This data is presented by the algorithm as a matrix of temperature \( M_{temperature}^{day\;October\;18th,\;2013} \); the lines of the matrix represent the time in minutes, the columns represent the distance in metres and the elements of the matrix represent the temperatures (°C) recorded by the fiber optic cable. The algorithm calculates the temperature variation between the elements of the matrix \( M_{temperature}^{day\;October\;18th,\;2013} \) for each position and for each minute. The result is presented in Figure 4(a).
The second example presents all the data collected from the monitoring campaign for the day October 18th, 2013 and there are many events occurring during this day. A matrix of temperature $M_{\text{temperature}}^{\text{day October 18th, 2013}}$ is elaborated and the temperature changes between the elements of the matrix for each position and each minute is calculated. The results are presented in Figure 4(b).

According to Figure 4(a) the results show that 100% of temperature changes are between $[-0.2 \, ^\circ\text{C}, 0.1 \, ^\circ\text{C}]$. This means that all the temperature changes within this interval are caused by the noise data because in this period there are no events.

Figure 4(b) presents the percentage of temperature changes for the day October 18th, 2013. The results show that 88.6% of the temperature changes are between $[-0.2 \, ^\circ\text{C}, 0.1 \, ^\circ\text{C}]$, 6.4% of temperature changes are between $[0.2 \, ^\circ\text{C}, 10 \, ^\circ\text{C}]$ and 5% are between $[-10 \, ^\circ\text{C}, -0.3 \, ^\circ\text{C}]$. This means that all temperature changes smaller than $-0.2 \, ^\circ\text{C}$ and larger than $0.1 \, ^\circ\text{C}$ are caused by the events.

After the determination of the noise level which is between $[-0.2 \, ^\circ\text{C}, 0.1 \, ^\circ\text{C}]$, two thresholds have been proposed:

- The first threshold when the temperature change is smaller than $-0.2 \, ^\circ\text{C}$, which means there is an event with a lower temperature (negative event). This threshold is denoted the negative threshold.
- The second threshold is denoted the positive threshold and occurs when the temperature change is larger than $0.1 \, ^\circ\text{C}$, which means there is an event with a higher temperature (positive event).

Automated detection

Based on the $M_{\text{temperature}}^{\text{day } i}$ temperature matrix in Equation (1) and the two thresholds calculated above, an algorithm was used to detect both the positive and the negative events.

To detect the positive events the algorithm follows Equation (2)

$t$ (min): Time. $t = 1, 2, \ldots, n$

$l$ (m): The position of the fiber optic. $l = 1, 2, \ldots, m$

$M_{\text{positive events}}^{\text{day } i}(t, l)$: Matrix of positive events with the values of 0 and 1.

In this example there are two events: the first starts at line three of the matrix, i.e., at $t = 3$ min and the first column position $l = 1$ m. The second events starts at first line $t = 1$ min and at the position $l = 5$ m.

The same procedure applies for the negative events; the only difference is the threshold.

The following sections explain the results of the algorithm for real issues like loops, cable lifted from wastewater, house connection discharges and inflow of stormwater to foul sewers.

Automated detection of loops

During installation of a fiber optic cable in the sewer, loops are formed in the manholes by the cable and this is for practical reasons when pulling the cable network to advance from manhole to the following manhole until the cable is connected to the control unit in a trailer. The loops are comparatively easy to detect manually. It is just an added benefit that the algorithm also detects those loops.

Loops are automatically detected using a period of time of data collected. To see clearly the results it is better to select a period of time with no external influences on the temperature values, which means that no event occurred...
in this period. The second step is to compare the matrix of temperature changes to the two noise levels chosen before (section ‘Determine noise levels’).

Figure 5 presents a zoom of the temperature changes along the fiber optic cable for the day October 18th, 2013 and for a selected period of time from 03:48 to 04:28; no event occurred in this period. The results show there are two columns of black and white circles detected by the automated procedure. The black circles mean there are temperature changes from the high temperature to low temperature and the white circles represent the temperature changes from the low temperature to the high temperature. These temperature changes can be explained only by the cable being lifted from the wastewater and tied in loops in the manholes, because there is not an event in this period. For example, before the first loop at distance $x = 256$ m there are no temperature changes (it is the temperature of the wastewater in the pipe); at the distance $x = 256$ m there are temperature changes where the cable enters the manholes (it can be the temperature of the wastewater in the manhole or the temperature of the air in the manhole) and at $x = 266$ m there is another temperature change where the cable enters again into the wastewater. The black column represents the beginning of the loop in the manhole and the white column represents the end of the loop in the manhole. In this case study there are five loops: the first loop between $x = 256$ m and $x = 266$ m, the second loop between 436 m and 446 m, the third loop between 621 m and 638 m, the fourth between 977 m and 993 m and the fifth loop between 1,305 m and 1,330 m.

Cable lifted from wastewater

When the cable is lifted above wastewater level, air temperatures are recorded instead of wastewater temperature. This phenomenon can be caused by installation problems, for example if the cable was pulled sufficiently taut during installation or there was an obstacle at the sewer invert. It is very important to identify such positions where the cable is lifted from the wastewater because these will give false positives and hence must be excluded by the data handling following the automatic detection.

Figure 6 presents a zoom of the temperature changes along the fiber optic cable for October 17th, 2013, a selected period of time from 09:18 to 10:58, and between two distances 97 m and 250 m. Two events occurred in this period. The results show that there are two columns of black and white circles cutting the event in many parts because the cable was lifted from the wastewater (the same principal as loops). In this example the cable was lifted from the wastewater at the positions $x = 116$ m, $x = 168$ m, $x = 189$ m and $x = 233$ m.

The automated procedure was tested for many days using the positive threshold equal to 0.2 and negative threshold equal to 0.2. The results show that the cable was lifted from wastewater at positions $x = 116$ m, $x = 168$ m, $x = 189$ m, $x = 235$ m, $x = 825$ m, $x = 849$ m, $x = 1,555$ m, $x = 1,580$ m, $x = 1,599$ m, $x = 1,620$ m, $x = 1,675$ m, and $x = 1,688$ m. To validate the results of the automated procedure, these results were compared to the manual assessment, which showed that there was no difference for almost all these distances, and for a few of the distances there is a difference of one metre ($\pm$ or $-1$ m).

Figure 5 | Automated procedure to detect loops, October 18th, 2013.
House connection discharges

To determine the importance of using two thresholds to detect both the positive and the negative events, a zoom of the temperature changes along the fiber optic cable for the day October 21st, 2013 is selected for a period of time from 00:00 to 04:10 and the distance 748 m to 850 m. Figure 7 shows the different scenarios used in this study.

Figure 7(a) shows that there are two events at the distance 761 m along the fiber optic cable, which means that there is a house connection at this distance. The first is a positive event (caused by an increase in the temperature) that occurred at 13 minutes after 00:00 and the second is a negative event (caused by a lowering of the temperature) that occurred at 228 minutes.

Figure 7(b) has been obtained for the positive threshold $= 0.3 \, ^\circ C$ and the negative threshold $= -0.3 \, ^\circ C$. The algorithm detects the beginning and the end of both events. When the positive threshold $= 0.4 \, ^\circ C$ and the negative threshold $= -0.4 \, ^\circ C$, the algorithm found the beginning and the end of the positive event; for the negative event only the beginning has been found (Figure 7(c)). Figure 7(d) shows the results with the positive threshold $= 0.6 \, ^\circ C$ and the negative threshold $= -0.6 \, ^\circ C$. The algorithm detects only the positive event.

Figure 7(e) shows the scenario with only the positive threshold $= 0.3 \, ^\circ C$. The algorithm has found the positive event and the end of the negative event. Figure 7(f) shows the scenario with only the negative threshold $= -0.3 \, ^\circ C$. The algorithm has found the end of the positive event and the beginning of the negative event.
Table 1 shows the ability of the automated procedure for detecting positive and negative events by applying different thresholds.

This application shows that it is very important to use two thresholds to detect both the positive and the negative events.

**Application of the developed procedure**

Inflow of stormwater to foul sewers can be observed during the days with rain events by the lower temperatures or higher temperatures, depending on the time of year (Schilperoort & Clemens 2009; Schilperoort et al. 2013). In this case there is a lower temperature in the sewer network (Figure 8).

Figure 8 presents a zoom of the temperature changes along the fiber optic cable for October 20th, 2013 and a selected period of time from 00:00 to 05:40.

The results show that there is an event caused by inflow of stormwater, represented by the column of white dots for each 1 minute at the position $x = 1,206$ m. The analysis was made applying a negative and positive threshold equal 0.4 °C. A manual assessment of the data was performed which identified an inflow at $x = 1,206$ m, the same results as for the automated program.

Over the past few years, a significant number of studies have reported the application of DTS in sewer networks to locate illicit connections in storm sewers, inflows in foul sewers and in combined sewers (Hoes et al. 2009a, 2009b; Schilperoort & Clemens 2009; Schilperoort et al. 2013). All these studies have been done manually to visualize the data and look for anomalies in temperature. Compared to these studies, in this work all these tasks have been done automatically by an algorithm.

The only study that used an automated procedure to detect the illicit connection into storm sewers is that of

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<td><strong>Figure 7 part</strong></td>
<td>Positive threshold (°C)</td>
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**Figure 8** | Automated procedure to detect event inflow stormwater, October 20th, 2013.
Vosse et al. (2013), who used one threshold to detect temperature changes caused by house connection discharges. Compared to the study of Vosse et al. (2013), two thresholds have been used to detect both temperature changes caused by wastewater inflow from house connection and the inflow of stormwater into the foul sewer network.

First, the noise level which is caused by the fiber optic cable is determined by choosing a period of time when there is no event, and the temperature changes are caused only by the noise data. The result shows that 100% of the temperature changes are between $[-0.2 \degree C, 0.1 \degree C]$, which means that all these temperature changes in this interval are considered as noise data (see Figure 4(a)). The temperature changes of more than 0.1 $\degree C$ and less $-0.2 \degree C$ are considered as an event (see Figure 4(b)).

Many scenarios have been used to determine the importance of using two thresholds; for example, when the negative threshold was omitted the algorithm successfully identified the positive event but was not able to detect the negative event (see Figure 7(e)). When the algorithm was applied without the positive threshold, the results showed that the negative event was found but the positive event was missed (see Figure 7(f)). In the present study, the value of the positive and the negative threshold was found to differ. An example has been taken when the positive threshold $=\text{negative threshold} = 0.6 \degree C$. The results show that the positive event is detected but the negative event is missed (see Figure 7(d)).

The most significant problem with DTS, after the noise, is related to the installation of the cable. In locations where the cable is lifted from the wastewater, the fiber optic cable records the air temperature instead of wastewater temperature. The algorithm determined all the points where the fiber optic cable was out of the wastewater.

CONCLUSION

In this work, DTS has been applied for detecting inflow of stormwater to foul sewers in a residential catchment (Elmehaven) in Denmark. Data was collected from a 1,835 m long fiber optic cable with spatial and temporal resolutions of 1 m and 1 min, respectively.

The purpose of the study was to automate the elaborate and time-consuming data processing associated with analyzing DTS data. For this, a smart algorithm has been developed to identify temperature changes caused by inflow and to reject temperature changes associated with measurement noise. Data analysis showed that temperature changes caused by measurement noise were between $-0.2 \degree C$ and $0.1 \degree C$.

For noise rejection, two temperature thresholds have been chosen to detect the events.

- The negative threshold is used to detect the lower temperature changes smaller than $-0.2 \degree C$ considered as a negative event.
- The positive threshold is used to detect the higher temperature changes larger than $0.1 \degree C$ considered as a positive event.

It is more important that the algorithm can detect the inflows. The cable lifts and the loops can comparatively easily be detected manually. It is just an added benefit that the algorithm also identifies those. Compared to the manual assessment, almost all of these results are the same results as for the automated procedure or there is a difference of one metre ($+ \text{ or } -1 \text{ m}$).

The manager of the sewer network can use this automated procedure to detect the inflow stormwater in the foul sewer network.

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