Assessment of detection limits of fiber-optic distributed temperature sensing for detection of illicit connections

Jaap Nienhuis[1] , Cornelis de Haan[1], Jeroen Langeveld[1,2,*], Martijn Klootwijk[3], François Clemens[2]

[1] Royal Haskoning, the Netherlands, j.nienhuis@royalhaskoning.com, c.dehaan@royalhaskoning.com
[2] TU Delft, the Netherlands, j.g.langeveld@tudelft.nl*, corresponding author, f.h.l.r.clemens@tudelft.nl
[3] City of Breda, the Netherlands, m.klootwijk@breda.nl

ABSTRACT

Distributed Temperature Sensing (DTS) with fiber-optic cables is a powerful tool to detect illicit connections in storm sewer systems. High frequency temperature measurements along the in-sewer cable create a detailed representation of temperature anomalies due to illicit discharges. The detection limits of the monitoring equipment itself are well-known, but there is little information available on detection limits for the discovery of illicit connections, as in sewers mixing and attenuation also plays an important role. This paper describes the results of full-scale experiments aiming to quantify the detection limits for illicit connections under various sewer conditions. Based on the results, a new monitoring setup for (partially) filled sewer conduits has been proposed.

KEYWORDS

DTS, illicit connections, detection limit, temperature monitoring, foul sewer, storm sewer

1 INTRODUCTION

Illicit connections of foul sewage to storm sewers and stormwater to foul sewers are the main problem associated with separate sewer systems. The detection of these illicit connections has received a lot of attention in literature (Pitt et al., 1993). Most methods are not capable of dealing with the typical intermittent character of discharges from illicit connections, requiring information with a high temporal and spatial resolution.

Distributed Temperature Sensing (DTS) with fiber-optic cables is a newly developed tool to detect illicit connections. DTS generates high-frequent temperature measurements at many locations along a sewer. DTS uses a fiber-optic cable that is installed in the sewer under consideration. A laser-computer instrument sends pulsed laser light into the fiber-optic cable and processes the reflected signal into temperature values. Typically, temperature readings with a resolution of 0.01°C are obtained every 60 seconds and for every meter of the fiber-optic cable. An elaborate description of the DTS monitoring technique can be found in Hoes *et al*. (2009).

Figure 1 gives an example of monitoring results obtained using DTS to trace illicit connections in city of Breda, using the classification scheme described by Haan, de *et al.* (2011). The storm sewer in Breda, like many storm sewers in the Netherlands, discharges below the water table of the receiving waters. Consequently, the sewer is completely filled during normal operation. In this project, the DTS monitoring took place under normal conditions, i.e. the storm sewer being completely filled, and under conditions where the storm sewer has been emptied and kept dry.

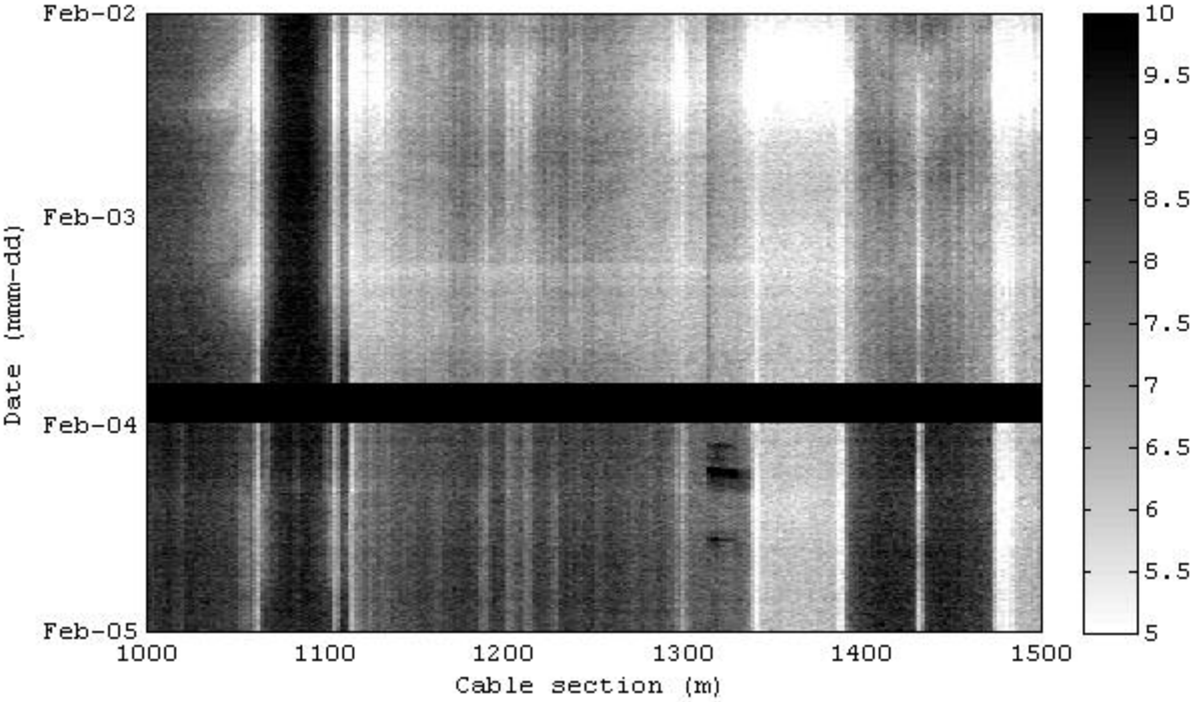

Figure 1: Results from a DTS project in Breda (feb 2012). Until feb 03, the storm sewer was completely filled. From feb o4 the system was kept empty. During the blacked period, measurements stopped because of extreme weather conditions (Air temperatures < -20^0C, which is beyond the operational limit of the monitoring equipment). At X= 1310, a clear intermittent discharge, resembling an illicit connection can be noted after feb 04.

Two noticeable different sections become apparent. While there clearly is an illicit connection at about 1310m, this only appeared after the system was put dry. In the period after February 3, about 6 spills per day were registered. In the 3 day period before, in a completely filled system, no traces of this illicit connection could be detected.

Although the performance of the DTS technique is well described in Hoes et al. (2009), a description of the detection limits in sewer applications is still lacking. The detection limits depend, apart from well known limitations in the DTS technique, on the attenuation of temperature and volume during the transport in the indoor plumbing, house connection, mixing in the sewer and other processes. To quantify the detection limits, a full scale experiment has been performed in the monitoring sewer in Breda, the Netherlands (STOWA and RIONED, 2009).

The objective of this paper is to discuss the practical detection limits for detection of illicit connections using DTS related to the monitoring set up and the hydraulic conditions in the sewer. This paper describes the set up and results of the experiments to determine the detection limits of DTS for detecting illicit connections of sewage on storm sewers. The paper concludes with a proposal to improve the monitoring set up for detecting illicit connections to storm sewers.

2 MATERIALS AND METHODS

The detection limits of illicit connections, or more specifically, a spill of sewage, using DTS are determined by the monitoring equipment, monitoring set up and the conditions in the sewer, see figure 2.

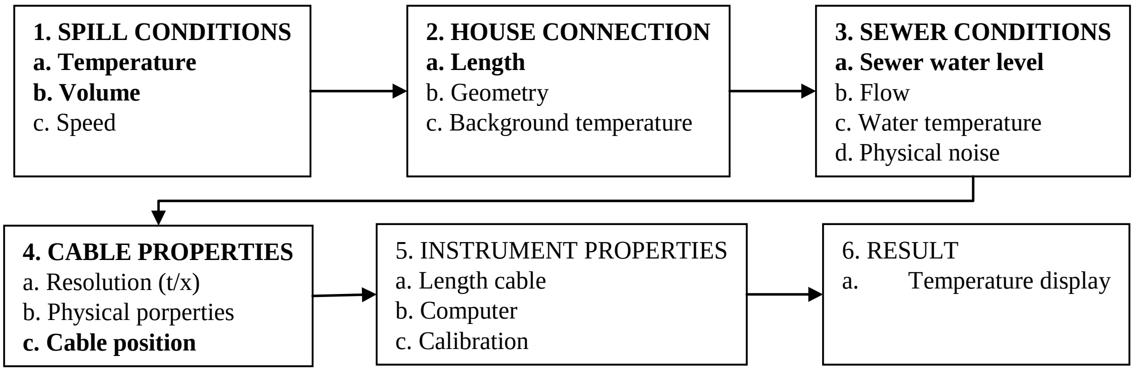

Figure 2: From spill to result, 6 steps determine the detection. In **bold** if included in this paper.

The characteristics of the spill taken into account are the temperature and volume, see table 1. Other properties, such as the discharge speed or density, are not taken into account. The spill characteristics at source change during the transport to the sewer depending on the length of a house connection and soil temperature. Inside the sewer, the water level and flow determine the relative effect of the spill. Other changes in the temperature are difficult to measure, and are therefore characterized as physical noise.

Table 1. Indicative average volumes and temperature per usage

Source	indicative average volume per usage (L)	average discharge temperature (°C) (STOWA, 2010)
Bath	100	30
Shower	50	35
Toilet flush	5	18
Washing machine	40	30
food preparation	1,5	50

The cable and DTS technique settings also influence the resulting temperature. Thicker cables and the resolution in time and space, determine the delay and averaging of the signal. In addition, a part of the random variation is inherent in the DTS technique, being instrument noise.

Section 2.3 discusses the applied parameter space of the properties marked in green. Other properties are set constant at assumed values. This is treated in section 2.4.

2.1 Monitoring location

The monitoring sewer in Breda is a full scale Ø 600 mm 50 m underground test rig, with monitoring and flow regulating equipment (STOWA and RIONED , 2009). This enables full control of the hydraulic conditions in the sewer. In order to simulate illicit connections, three house connections with different lengths have been installed and connected to the test rig. Figure 3 provides a schematic overview of the rig.

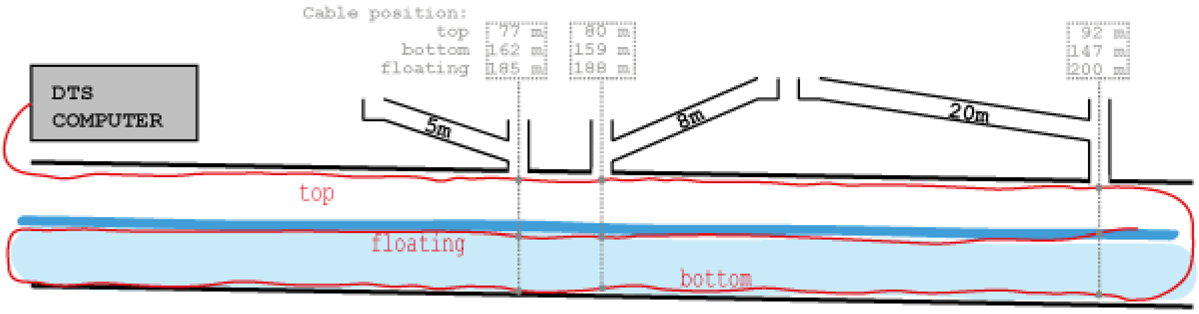

Figure 3: Schematic of test rig and the cable location showing in grey the cable position in m from the DTS computer and relative to the discharge locations.

In order to be able to detect temperature gradients in the sewer, three cable positions were tested by placing one fiber-optic cable (Ø 6mm) mounted at the invert (bottom), on the soffit (top) and on the water level (floating), as displayed in red in Figure 3. The top-mounted part is placed directly under the house connections, such that test volumes come in contact with the cable. There are house connections of 5, 8 and 20 meter. These connections make it possible to look at the temperature attenuation in comparison to discharging directly onto the conduit.

2.2 DTS installation

DTS measurements have been performed with two systems; the HALO and the ORYX, for product info see http://www.sensornet.co.uk/technology/distributed-temperature-sensing/halo-dts in a single-ended setup. These computers allow temperature monitoring of up to 4km (HALO) and 5km (ORYX) of fiber-optic cable, with a temperature resolution of 0.01^{0}C. The product specifications, however, specify a temperature accuracy of 0.1^{0}C, due to instrumental noise. During the experiments, a noise of 0.15 ^{0}C has been observed, see figure 6, having the same order of magnitude as described by Tyler *et al*. (2009). Throughout the tests, the spatial resolution is set at 2 meter. Every minute, there is 30 seconds of data collection. The measurements were calibrated with an analogue hand-thermometer pragmatically and certificated digital thermometer with 3 digits reading. Calibration required an adjustment of the offset with -3 ^{0}C.

2.3 Test setup

Test volume temperatures range from 6^{0}C to 76^{0}C, with sewer temperatures between 15^{0}C and 20^{0}C, so both the effect of relatively warm and cold water on a DTS cable is observed. Applied volumes range from 0.2L (a coffee cup) to 46L (a shower), and have been discharged in the various house connections as well as directly into the sewer. Water levels in the sewer were fixed at 0, 15, 30 and 60cm, equivalent to a filling degree of 0, 25, 50 and 100% respectively.

2.4 Assumptions

Background temperatures (i.e. of the surrounding soil) are assumed to be constant throughout a test. The small error made with this assumption is acceptable as DTS is applied in this case to detect swift changes in temperature with a timescale of minutes. Flow is considered negligible in the attenuation of the tests.

3 RESULTS AND DISCUSSION

This section describes and discusses the results of the tests performed.

3.1 Influence of test volume size

Figure 4 shows the observed cable response of the cable placed on the sewer invert in degrees Celsius for a range of spill types, defined by the energy difference between the water in the sewer and the spill. This energy difference is defined as $V\cdot\Delta T$, the volume of the spill multiplied by the temperature difference between the test volume and the water in the receiving sewer. The response is the DTS measurement difference between resulting peak and the background temperature. The results show that the response depends to a large extent on the degree of filling of the sewer. At higher filling degrees, the cable response decreases rapidly.

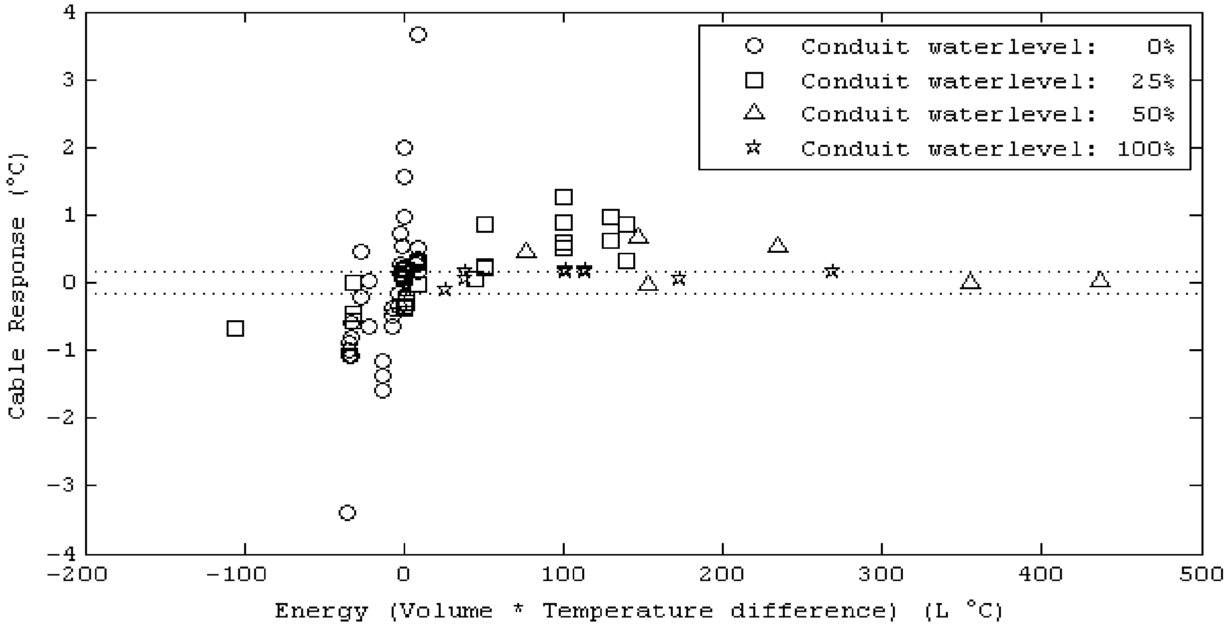

Figure 4: Effect of increasing test volume energy on cable response for the cable at the sewer invert with four different in-sewer water levels. Dotted lines are drawn at $\pm 0.15^0$C, between which characterizing spills becomes difficult. Negative values occur when test volume temperatures are lower than background temperatures. Resulting cable response then is also negative.

These results confirm the situation described in figure 1, where a cable placed in a completely filled sewer at invert level was not able to detect illicit connections. In addition, the results show that in a dry sewer, a cable placed at the invert is very sensitive to detect spills. Even spills with a $V\ \Delta T$ as low as $10L^0$C, being a cup of coffee, result in a cable response above the instrumental detection limit of 0.15^0C.

3.2 Influence of cable position

Three cable positions have been tested: (i) soffit level (top), (ii) invert level (bottom) and (iii) floating. Figure 5 shows these mounting positions and their effect on the resulting signal. These tests have been performed with a drowned system (100% full, between 11:00 and 13:00) and with 30cm of water (50% full, between 13:00 and 15:00).

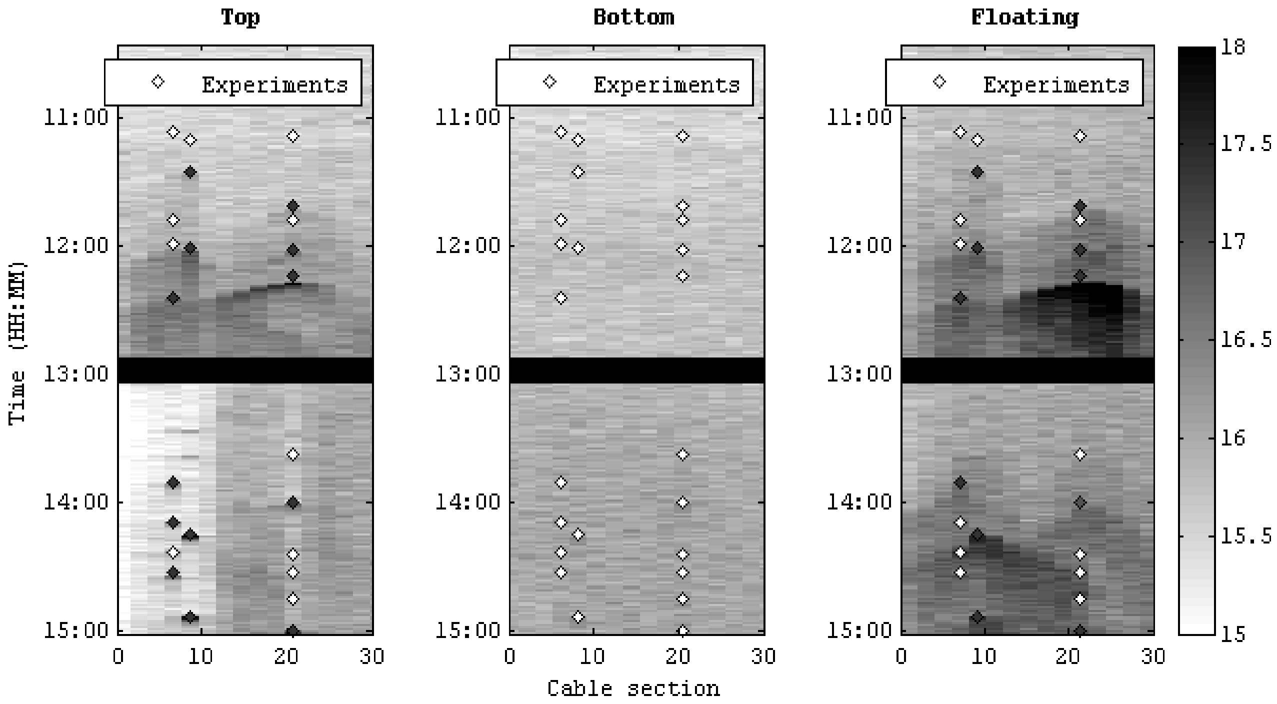

Figure 5: Influence of cable positioning on spill detection. Three plots show the measured temperature (in ^{0}C) along 30 meters of optic-fibre cable and along about 4.5 hours of measuring. The markers indicate time and place of the test volumes, in grey when the data showed a significant response, i.e. when a change in temperature was detected above the noise level of 0.15 ^{0}C. Before 13:00, the water level is 100%. After 13:00, the water level is lowered to 50%.

Several interesting things can be noticed. In a drowned system, cables mounted at the top and floating cables give qualitatively similar results. Very large test volumes, such as the one at 21 meters at 12:15, which was 24L and 37^{0}C (a laundry machine), is not detected by a cable mounted at the bottom. Clearly, no ideal mixing takes place in the storm sewer, limiting the detection ability of the monitoring set up. In a partially filled conduit, the top-mounted cable provides the clearest indications of spill location and time. Conduction and convection make this more elaborate and error-prone in the floating cable. Also remarkable is the difference of 2^{0}C in bottom and top temperature.

3.3 Influence of house connection length

The discharge volumes and corresponding temperatures per type of use of table 1 correspond to the temperature at source. In order to assess the impact of the house connection, a series of tests have been performed on an empty sewer by testing house connections of different lengths, 5 and 8 meter, and by discharging directly into the sewer. The results of a number of these tests are shown in figure 6.

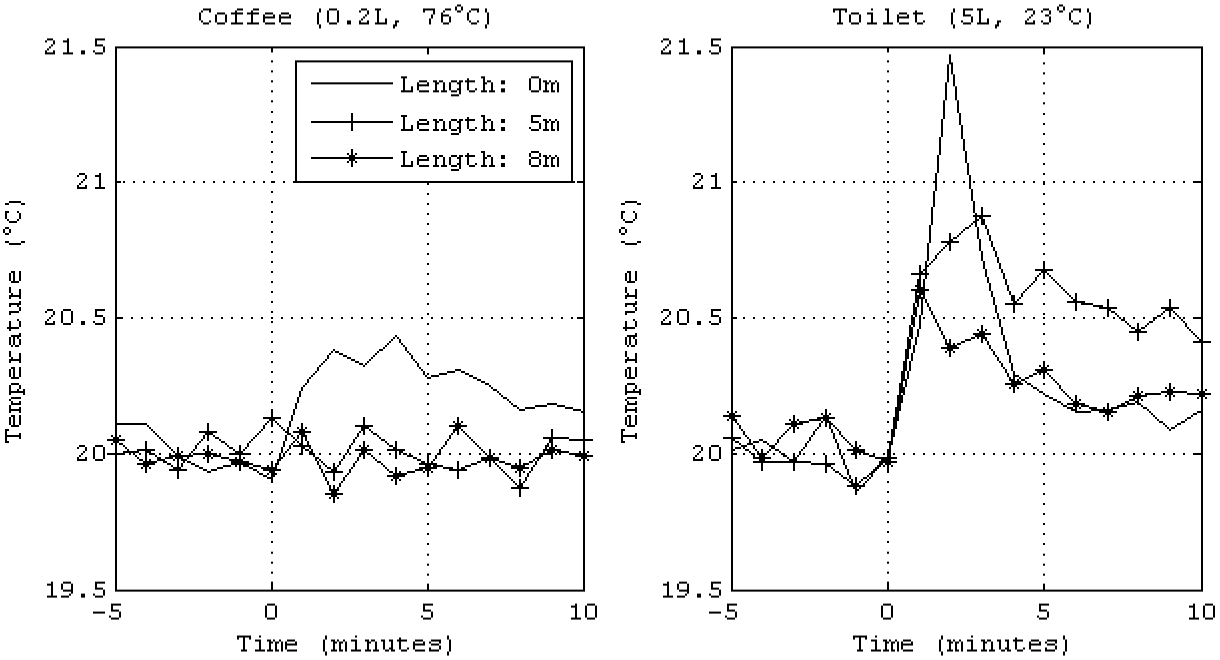

Figure 6: Response of two different test volumes on an empty sewer with a bottom-mounted cable.

Spilling a coffee cup, Figure 6a, generates a modest response in temperature. Temperature and volume attenuation through 5 and 8 meter house connections leave no detectable signal of such a small volume. Smaller temperature differences and larger volumes, such as a toilet flush, create a completely different response. A 3^0C difference between sewer and spill temperature generates a peak of more than 1.5^0C, which is reduced by more than 50% through the house connections. Note that when soil temperatures deviate from sewer temperatures, house connections can also have a positive effect on detection limits.

3.4 Influence of sewer water level

The influence of the degree of filling of the sewer as shown in figure 1 is analysed by comparing the observed temperature response in the cable with the theoretical temperature response assuming complete and instant mixing over the cross section under study according to:

$$T_{new} - T_{old} = \frac{T_{spill} \cdot V_{spill}}{V_{sewer,rep}} \tag{1}$$

Where $V_{sewer,rep}$ stands for the representative volume in the sewer, a function of the water level and conduit dimensions. These tests were performed by discharging directly into the sewer, i.e. with a house connection of a length of 0 m.

Figure 7 shows the difference between the expected response, based on complete mixing, and the actual response in a sewer filled 25%. The actual temperature response of the cable is a factor of 4 to 5 less than the maximum temperature response assuming instant mixing. This example shows that even for moderate water levels of 15 cm, the impact of mixing conditions is already affecting the temperature response of the cable and ultimately affecting the detectability of spills.

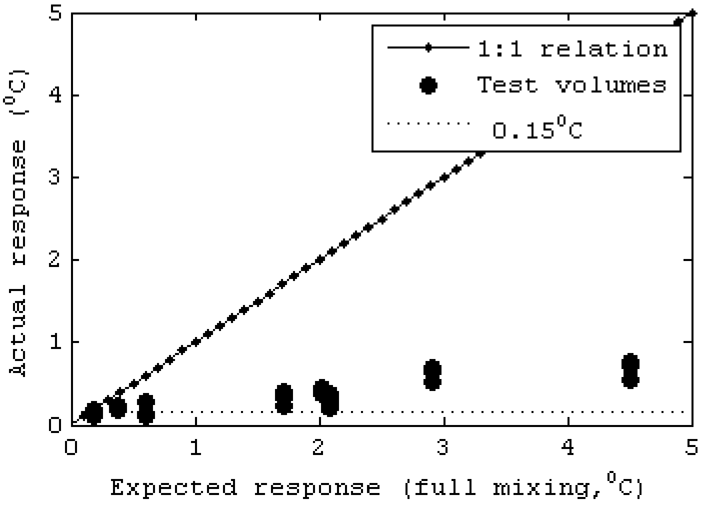

Figure 7: DTS response compared to expected water temperature increase (^{0}C). Conduit fill is 15cm.

4 CONCLUSION

DTS is a powerful tool to detect illicit connections of foul water to storm sewers. The results obtained with DTS testing of storm sewers have already contributed to the reduction of the impact of illicit connections. The uncertainty associated to the methodology, however, still remained unclear.

This paper presents the results of experiments that have been conducted in a full scale monitoring sewer in Breda, the Netherlands, to study the relative impact of the monitoring lay out, the sewer conditions and spill characteristics on the detection limits of illicit connections.

Based on the results presented, it is concluded that:

- the water level in the sewer is the dominant factor with respect to the detect ability of spills. Even at relatively small water levels (0.15 m) the lack of mixing of the spill and the water in the sewer limits the detectability of a cable placed at invert level. This limitation, however, can be overcome by placing the DTS cable on the top of the pipe or to install a floating cable.
- the temperature difference between the spilled volume and ambient conditions in the sewer, being the main driving force for detection, varies during the year, as the soil temperature varies between 0 and 20 °C, depending on the season, ground water table and the depth of the sewer. Consequently, the detection limits vary over the year and depending on the local conditions, this should be taken into account when planning a DTS monitoring campaign.
- the length of a house connection also has a significant impact on the temperature difference between the spilled water and the water in the sewer and consequently on the possibility of detection. This means that for longer house connections, only larger volumes can be detected. This limits the applicability of the DTS technique, as not all individual discharges of e.g. a wash tables can be detected. However, the larger volumes, such as associated with a toilet flush, shower or washing machine, can be detected.

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