Searching for storm water inflows in foul sewers using fibre-optic distributed temperature sensing
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ABSTRACT
A major drawback of separate sewer systems is the occurrence of illicit connections: unintended sewer cross-connections that connect foul water outlets from residential or industrial premises to the storm water system and/or storm water outlets to the foul sewer system. The amount of unwanted storm water in foul sewer systems can be significant, resulting in a number of detrimental effects on the performance of the wastewater system. Efficient removal of storm water inflows into foul sewers requires knowledge of the exact locations of the inflows. This paper presents the use of distributed temperature sensing (DTS) monitoring data to localize illicit storm water inflows into foul sewer systems. Data results from two monitoring campaigns in foul sewer systems in the Netherlands and Germany are presented. For both areas a number of storm water inflow locations can be derived from the data. Storm water inflow can only be detected as long as the temperature of this inflow differs from the in-sewer temperatures prior to the event. Also, the in-sewer propagation of storm and wastewater can be monitored, enabling a detailed view on advection.

INTRODUCTION
In the Netherlands, nearly 25% of all households discharge wastewater through a separate sewer system. In Germany this is the case for over 40% of households. A major drawback of separate sewer systems is the occurrence of illicit connections: unintended sewer cross-connections that connect foul water outlets from residential or industrial premises to the storm water system and/or storm water outlets to the foul sewer system. The majority of these connections are caused by bad plumbing during construction or renovation of a property or area. In this paper the focus is on storm water outlets connected to foul sewers.

The amount of unwanted storm water in foul sewer systems can be significant (Bareš et al. 2009). Figure 1 presents an example for a pumping station in a foul sewer system in the Netherlands. For the considered catchment area the theoretical domestic dry weather flow adds to roughly 10 m³/h (∼2000 inhabitants × 120 L/(inh·d)). Measured flows, however, are much larger: during dry weather the base flow varies between 20 and 50 m³/h but during storm events flows can be as large as 140 m³/h. The large base flow can be attributed to continuous groundwater infiltration to the foul sewer system. Flow peaks systemically coincide with storm events, leading to the conclusion that peak flows are caused by direct inflow of storm water into the foul sewer system. In this example the volume of storm water direct inflows into the foul sewer system is estimated to be approximately 25%.

The introduction of storm water to the foul sewer system has a number of detrimental effects on the performance of the wastewater system (DWA 2012). Foul sewer systems are not designed to handle large amounts of storm water, which consequently may lead to local flooding or sanitary sewer overflows. Also, an increase of pumped volumes results in a larger energy consumption. Furthermore, the dilution of wastewater with storm water has its negative effects on treatment plant capacity and efficiency (Langeveld 2004).

Efficient removal of storm water inflows into foul sewers requires knowledge about the locations of the inflows. For localization purposes a number of techniques are currently available such as smoke injection, sound testing and dye mark.
testing (Pitt et al. 1993; Tuomari & Thompson 2005). The application of these techniques can be rather labour-intensive and may require entrance onto private premises, while inflows are often only detected by chance. This paper presents an alternative technique: distributed temperature sensing (DTS). DTS has already been shown to enable detection of discharges of foul water to storm sewers (Hoes et al. 2009). Discharges of foul water typically show an intermittent character and, in addition, the temperature of foul water is typically higher than the temperature in a storm sewer, whether empty or not. In contrast, the detection of storm water inflows to foul sewers is more demanding, as storm water can be warmer but also cooler than the ambient in-sewer temperature (Schilperoort & Clemens 2009). In addition, storm water discharges only occur during storm events, which requires longer monitoring periods than the detection of foul water discharges to storm sewers. Finally, storm water inflows can only be detected as long as they cause a noticeable temperature change, which typically only occurs at the onset of storm events as long as the system is not entirely filled with storm water (Langeveld et al. 2012).

In this paper the technique is explained and two examples of DTS monitoring campaigns in the Netherlands and Germany to detect storm water inflows to foul sewers and their results are presented. As such, this paper builds on previous applications of the DTS technique, i.e. detection of foul sewage inflows to storm sewers (Hoes et al. 2009), studying the performance of combined sewers (Schilperoort & Clemens 2009) and analyzing the performance of storm water separating manifolds (Langeveld et al. 2012) by adding a new application.

MATERIALS AND METHODS

Distributed temperature sensing

Fibre-optic DTS is a widely applied technique in, for example, industrial process control, leakage detection in dams and hydrology (Johansson 1997; Selker et al. 2006a, b). The application of fibre-optic DTS in sewer systems is performed with a standard fibre-optic cable in combination with a control unit that contains a laser and sensing optoelectronics. The fibre-optic cable is laid out at the invert of a sewer. The cable is inserted by pulling a rope from manhole A to manhole B by first letting a water-jet-propelled sewer flushing device make its way from B to A and – after attachment of the rope – by mechanically pulling the device back to manhole B. Consequently, the fibre-optic cable that is attached to the end of the rope can be pulled from A to B. At one end, the cable is connected to the control unit that is generally stored outside the sewer system in a small container to protect it from weather and theft, see Figure 2. Experience from over 20 DTS projects shows that the cable can safely stay in the sewer for a period of months, provided that it is firmly attached to the sewer system at a number of locations. An exception to this rule is small diameter (250 mm) foul sewers, where blockage can easily occur, limiting the monitoring period to a few weeks.

For a measurement, a continuously pulsing laser light is emitted into the fibre-optic cable. At many locations along the cable each laser pulse is partially reflected by imperfections in the glass fibres. The reflected signals are ‘read’ by the optoelectronics and interpreted by the computer software. For each reflected signal the location of reflection can be

![Figure 1](image-url)
determined using the measured travel time and known travel speed (in optic fibres typically two-thirds of the speed of light in vacuum). The same reflected signal is then analysed for Raman backscatter. Raman backscattering produces two broadband components at higher and lower frequencies than the main reflected signal, the so-called Stokes and anti-Stokes emissions. The ratio of the temperature-sensitive anti-Stokes intensity to the temperature-insensitive Rayleigh or Stokes intensities determines the temperature at the location of reflection (López-Higuera 2002). This way, each laser pulse yields temperature values at many locations along the fibre-optic cable. The results of all pulses emitted during a certain time-span that are reflected over a certain length along the cable are used to obtain a single temperature value for that specific time and location. Hence, results are ‘averaged’ over typical time and space resolutions of, for example, 1 minute and 1 m, resulting in temperature data sets with the same time and space resolutions.

In this paper’s case-studies fibre-optic cables were used carrying two glass fibres (Kaiphone Technology, Taiwan). The glass fibres (multimode 50/125 μm core/cladding diameter) are embedded in gel to avoid direct stress on the fibres, as stress can affect the reflected laser signal. The fibres are further protected by subsequent layers of PBT (polybutylene terephthalate), stainless steel, kevlar, metal braiding and PE (polyethylene). The used control unit is a Halo DTS (http://www.sensornet.co.uk). The maximum length of this cable combined with the Halo DTS to be applied is 2,000 m, but from a practical point of view a shorter length of cable is to be preferred. For longer cables, a high-performance control unit is required. The precision of the used equipment (i.e. the repeatability of data results in time at the location furthest from the control unit) is approximately 0.1 °C (Nienhuis et al. 2013). The temperature accuracy (i.e. the difference between DTS temperature and true temperature) is not determined but also not relevant, as the detection of illicit connections is based on temperature differences between discharges and ambient in-sewer temperatures. Consequently, there is no need to calibrate the equipment for this application. Elaborate descriptions of monitoring accuracy, temperature adaptation time of the cable, and other monitoring characteristics can be found in Selker et al. (2006a) and Tyler et al. (2009).

The resources required depend on the size of the project. For a project of 1,500 m sewer length, the typical total costs are 10–12 €/m, comprising 30% for data analysis, 30% for installation in the sewer, 25% for equipment (cable and control unit) and 15% project management/organization.

**Catchment areas**

In this paper the application of the DTS monitoring technique in two different catchment areas is presented: Woensdrecht in the Netherlands and Wuppertal in Germany.

**Woensdrecht**

In the municipality of Woensdrecht the DTS monitoring technique has been applied in a storm water sewer as well as in the parallel foul sewer, see Figure 3(a). The total cable length is 1,500 m, evenly divided over both sewer systems. The two fibre-optic cables have been monitored using the same computer installed in a container at the north end of the considered sewer section. A 2-week monitoring campaign (22.04–06.05.2011) has been performed. During that time-span in-sewer temperatures have been measured with
a temporal resolution of 1 minute and a spatial resolution of 2 m.

As visual inspection by opening manhole covers revealed discharges of wastewater to the storm sewer and an overloaded pumping station indicated storm water inflows into the foul sewer, the municipality decided to monitor both systems simultaneously.

**Wuppertal**

In the framework of a city-wide project to reduce infiltration water in foul sewers carried out by the Wuppertaler Energie und Wasser AG (Hoppe et al. 2011), the catchment of an overloaded pumping station downstream of a residential area was analyzed. The problem here was suspected to be associated with (large) storm water inflows, but the exact locations of the inflows were unknown. Tests with smoke injection and camera analysis were unsuccessful in finding the locations of inflow. Therefore, fibre-optic cables have been installed in the complete foul sewer system with the DTS computer in a container next to the pumping station. In total, 1,200 m of sewer system have been observed, divided over three sewer sections each of 400 m, see Figure 3(b). A 4-week monitoring campaign (17.08–13.09.2011) has been performed with a temporal resolution of 1 minute and a spatial resolution of 2 m.

**Data analysis**

In a first step, the DTS monitoring data from the foul sewers of Woensdrecht and Wuppertal are divided into days with and without storm events using local rain gauge data. The data on dry weather days are used to determine the locations of the inflow of foul sewage and to detect anomalies which are not related to storm water inflow. This allows dry weather and storm water inflows to be distinguished. For days with a storm event, the DTS data are analyzed to detect the locations of storm water inflows.

The monitoring data of the two cases of this paper were analyzed manually. A logical next step in the development of the methodology would be automated data analysis.

**RESULTS AND DISCUSSION**

Figure 4 presents DTS monitoring results in the foul sewer of Woensdrecht. The horizontal axis represents length along the fibre-optic cable in the sewer system. In this case, monitoring results span from cable position $x = 120$ m up to $x = 920$ m (the first hundred meter of cable was not installed in the sewer system). The vertical axis represents a time-span of roughly 2 h in April 2011. The figure consists of $400 \times 120$ pixels (respectively $800$ m divided by a 2 m spatial resolution and $2$ h divided by a 1 minute temporal resolution). Each pixel presents a measured temperature value, coloured according to the colour bar on the right with temperatures ranging between 14 and 17°C. Flow direction in the graph is from right to left (the DTS computer is positioned at the most downstream end of the sewer section).

Between 04.00 and 04.30 temperatures between 15 and 17°C are observed. Temperatures along the upstream cable section are somewhat higher than the downstream section, but only minor temporal variations in temperatures are...
observed. A few minutes past 04.30 a storm event occurs in the area (based on local precipitation measurements). After a few minutes, sudden temperature decreases at a number of locations along the sewer section can be observed. At for instance cable location $x = 785$ m a reduction in temperature of approximately 2°C can be seen. These are expected to be associated with the inflow of storm water, which was in this case relatively cold. From this location storm water starts flowing in a downstream direction (in the graph from right to left). At cable location $x = 900$ m a more delayed reaction to the storm event can be seen: only 10 minutes after the onset of the event temperatures decrease. This is likely caused by storm water inflows further upstream the sewer section where no fibre-optic cable has been installed.

After approximately 30 minutes the inflow of storm water has cooled down the foul water system by 1 to 2°C. Around 05.45 the first discharge of wastewater can be observed that is associated with a rise in temperature. The higher gradient of the arrows (dx/dt) in the solid oval compared to the arrow in the dashed oval shows that during the inflow of storm water the flow velocity is higher ($\pm 0.2$ m/s) than during the inflow of foul sewage ($\pm 0.1$ m/s). This example demonstrates that DTS can be used to monitor the propagation of flow and therefore is an interesting technique to study advection processes in sewers.

Figure 5 presents DTS monitoring results of one of the three foul sewer sections in Wuppertal (cable 1, see Figure 3(b)) for a dry weather situation. Again, the horizontal axis represents length along the fibre-optic cable, in this case from cable position $x = 545$ m (the location of the monitoring computer) up to $x = 900$ m. The vertical axis represents a time-span of roughly 4.5 h in August 2011. Flow direction in the graph is again from right to left (the DTS computer is positioned at the most downstream end of the sewer, next to the pumping station). The figure shows typical DTS data for a foul sewer during dry weather conditions: almost no discharges during the night, but with multiple discharges of foul water starting in the early morning at a number of locations (indicated with black arrows at the bottom of the figure). Two locations along the cable are of special interest. The manhole at position $x = 575$ m is the confluence of the sewer with the sewers in which cables 2 and 3 are installed, see Figure 3(b). This confluence is clearly noticeable in the data as an increase in temperature: the water from the other two sewer sections is warmer. In the manhole at position $x = 750$ m visual inspection revealed the inflow of water from a creek, being directly connected to the manhole. This inflow is clearly visible as a strong decrease in temperature, occurring at all time-steps during the 4-week monitoring period, indicating a continuous inflow. At this same location ($x = 750$ m) around 06.30, a clear discharge of relatively warm foul water is observed. This is the reason the illicit discharge of the creek had not been revealed earlier using CCTV footage: it is not suspected when a discharge of water is observed at a house connection during inspection.

In Figure 6 between 19.30 and 19.50 on 18 August 2011 two wastewater inflows can be observed: the remnants of a discharge prior to 19.30 around cable location $x = 860$ m and one large discharge at cable location $x = 750$ m. For the latter, the duration of the discharge can be well observed as well as the transport of the ‘warm water plume’ through the sewer pipe. Also, the temperature decrease due to the mixing with other (waste)water can be noted.
A few minutes past 19.50 a storm event occurs in the area (recorded by several local rain gauges). Analogous to the Woensdrecht case, a reaction in terms of a temperature variation can be observed in the foul sewer system. The direction of the temperature change however differs. In Woensdrecht a temperature decrease could be observed whereas the Wuppertal results show a temperature increase at various locations along the fibre-optic cable. The difference can be explained by considering the meteorological conditions during the respective monitoring periods. The Woensdrecht data results were collected in April on a normal spring day; the Wuppertal results, in contrast, were...
generated in August after a relatively warm summer day. During the latter day it is suspected that asphalt road covers had warmed up significantly, transferring their heat to the storm water during run-off, resulting in relatively warm storm water discharges into the foul sewer system.

For the Wuppertal case it has been noted that the locations of inflowing storm water coincide with the exact locations of the manholes in the considered sewer sections. After careful considerations it has been concluded that the design of manhole covers (with a large number of ventilation openings, see Figure 7) allows storm water to enter the foul sewer system and hence contribute to the overloading of the local pumping station.

CONCLUSIONS

Fibre-optic DTS is a powerful tool to study several in-sewer processes that influence (wastewater) temperatures. The installation of a fibre-optic cable in a foul sewer system has proven feasible. The use of a single instrument that performs the measurements and logs the data in an easily accessible and safe location and that can simultaneously monitor up to several hundreds of monitoring locations makes the DTS set-up easy to use. Moreover, the technique requires no entrance onto private premises, which offers an advantage over other searching techniques for illicit connections.

Data from two monitoring campaigns in foul sewer systems show the level of detail with which in-sewer processes can be studied. Storm water inflow can be detected as long as the temperature of this inflow differs from the in-sewer temperatures prior to the event. Temperature increases (during warm summer days) as well as the more ‘standard’ temperature decreases have been observed. Also, the in-sewer propagation of storm water can be monitored, enabling a detailed view on advection. The DTS technique could therefore contribute to enhanced understanding of the transport processes in sewers and to improved sewer process models. In addition, these temperature data could be used to study exchange of heat from sewers with the surrounding soil.

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