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Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing

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ABSTRACT

A newly developed technique using distributed temperature sensing (DTS) has been developed to find illicit household sewage connections to storm water systems in the Netherlands. DTS allows for the accurate measurement of temperature along a fiber-optic cable, with high spatial (2 m) and temporal (30 s) resolution. We inserted a fiber-optic cable of 1300 m in two storm water drains. At certain locations, significant temperature differences with an intermittent character were measured, indicating inflow of water that was not storm water. In all cases, we found that foul water from households or companies entered the storm water system through an illicit sewage connection. The method of using temperature differences for illicit connection detection in storm water networks is discussed. The technique of using fiber-optic cables for distributed temperature sensing is explained in detail. The DTS method is a reliable, inexpensive and practically feasible method to detect illicit connections to storm water systems, which does not require access to private property.

1. Introduction

A separate sewer system consists of two parallel sewer pipe networks. One network is the sanitary sewer system, which transports household or industrial wastewater to a sewage treatment plant. The second network is the storm water system, which delivers clean rain or storm water to the surface water system without treatment. Ever since the introduction of separate sewer systems, system managers have been faced with illicit connections. These illicit connections are generally unintended hook-ups that either connect foul water outlets from residential or industrial premises to the storm water system or storm water outlets to the foul water system. For detecting storm water outlets that are connected to the sanitary sewer system, a reliable, inexpensive, and practically feasible detection method exists, namely the release of smoke in the sewer. Clearly, illicit connections that link foul water outlets to the storm water system are much more problematic, as these result in the release of untreated sewage in the surface water system. Yet, no straightforward method exists for detection of foul water outlets connected to storm water systems. All currently applied searching techniques come with disadvantages that reduce reliability, increase costs or make the method difficult to implement. Illicit connections contribute significantly to the pollution of receiving water bodies and their detection can be a demanding task.

A newly developed searching technique for illicit connection detection in storm water systems uses distributed temperature sensing (DTS). Introducing standard fiber-optic

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cables in storm water sewers allows monitoring of in-sewer temperatures with high spatial and temporal resolutions. Using the differences in temperature characteristics of storm water sewers and foul water discharges, it is possible to determine the time and location of most illicit foul water connections.

The objective of this paper is to introduce the DTS method for the purpose of illicit connection detection in storm water sewers. It aims at examining the possibilities the method offers as well as assessing the quality of the method in terms of reliability, implementation costs and practical feasibility. In the remainder of this paper we will first introduce illicit connections on occurrence, effects on receiving waters and current detection techniques. Next, the concept of using differences in temperature characteristics for the detection of illicit connections is discussed. The technique of using fiber-optic cables for distributed temperature sensing is explained. The DTS-technique has been tested in two municipalities in the Netherlands under different circumstances. The results of these experiments are presented and discussed.

2. Illicit connections in storm water systems

2.1. *Definition of an illicit connection*

Separate sewer systems have been widely introduced since the early 1970s to circumvent the drawbacks of combined sewer systems. Since then, it has become clear that separate sewer systems also come with disadvantages. A major drawback is the occurrence of illicit connections. For storm water systems the term ‘illicit connection’ has many meanings in regulations, literature and practice. The strictest definitions consider an illicit connection a connection with a discharge that is not entirely composed of storm water. The United States Environmental Protection Agency (US EPA, 2004), however, considers discharges to storm water systems to be illicit only if a flow during dry-weather conditions contains pollutants and/or pathogens. By this definition, discharges of for instance (unpolluted) groundwater are not considered improper. On the other hand, intended or accidental spills on paved areas of liquids such as oil, grease, paint or car wash water that enter the storm water system after surface run-off through a storm drain inlet are considered illicit discharges, but are not the result of an illicit connection. In the context of this paper, illicit connections to storm water systems are defined as unintended sewer cross-connections that connect foul water outlets from residential or industrial premises to the storm water system. The majority of these connections are caused by bad plumbing during construction or renovation of a property when outlets are connected to the closest available sewer pipe, which is not necessarily the designated sewer pipe. Infiltration and inflow of, for example, groundwater or drainage water are not considered illicit discharges, but are referred to as extraneous flows.

2.2. *Occurrence and effects of illicit connections*

Illicit connections to storm water systems are surprisingly common. Schmidt and Spencer (1986) report that more than one third of over 300 inspected businesses in a drainage basin in Ann Arbor (Michigan, USA) discharged wastewater to the storm water system. An extensive study in the Boston (Massachusetts, USA) area revealed a smaller percentage: 3% of nearly 5700 inspected buildings were found to have an illegal connection (Jewell, 2001). Other studies in the United States (US EPA, 2004) show similar percentages of illicit connections to storm water systems. Many of these illicit detection programs start with water quality problems at beaches and lakes (Boyd et al., 2004; Dickerson et al., 2007).

Illicit connections lead to direct transport of raw wastewater through storm drains to receiving waters. At the outfall of a storm drain there is often no treatment or only limited treatment in the form of a settling basin or plate separator. As a result, illicit connections can represent a major source of pollution to receiving waters. After an extensive monitoring program, van Sluis et al. (1991) concluded that mainly because of illicit connections the average annual pollution load discharged to receiving waters from storm water systems can be of the same order of magnitude as the pollution load discharged from combined sewer systems. In other words, the anticipated pollution reduction of a separate sewer system can be largely annulled by the presence of illicit connections. Logically, repairing illicit connections has a beneficial effect on receiving water. Taylor and Wong (2002) present the effects of illicit discharge elimination programs in various large cities. In one example, the changes in storm water quality before and after an elimination program were measured and analyzed using event mean concentrations averaged over four year intervals. The results include a reduction in event mean concentrations of −13% for total suspended solids, −17% for total phosphate and −18% for total Kjeldahl nitrogen.

2.3. *Present techniques for locating illicit connections*

Smoke testing is a reliable, inexpensive, and practically feasible method for the detection of storm water outlets connected to foul water systems. By introducing smoke into the foul water system and observing where the smoke surfaces (storm drain inlets, roof gutters, etc.) the exact locations of all wrongly connected storm water outlets can easily be found. The method works fast and does not require large equipment, making the application inexpensive. Also, the method only requires access to the foul water system, not to private premises.

Such a straightforward method for the detection of foul water outlets connected to storm water systems does not exist. The most common current searching techniques are (Jewell, 2001; Tuomari and Thompson, 2003; US EPA, 2004):

- Visual inspection and progressive sampling at manholes. The goal is to isolate the illicit discharge between two storm drain manholes for which visual inspection results (e.g. presence of flow, odors, deposits) or indicator sampling results (e.g. ammonia/potassium ratio, surfactants, caffeine) differ significantly.
- Dye testing. The introduction of a non-toxic dye into toilets, sinks, shop drains and other plumbing fixtures and the subsequent discovery of dye in the storm drain conclusively determines the existence of an illicit

connection to the storm sewer and immediately pinpoints to the specific source.

- Video reconnaissance. Guiding a mobile video camera through the storm drain pipes allows a visual inspection of sewer pipes and reveals connections (or cracks) that discharge during dry-weather conditions.

However widely applied, these techniques come with disadvantages. Visual inspection of manholes is subjective (Dirksen and Clemens, 2008) and not all water quality changes can be visually perceived, rendering the method unreliable. Progressive sampling at manholes depends on relatively expensive laboratory analyses, while results cannot locate illicit connections in between manholes. For dye testing the need to enter premises makes application in some areas practically infeasible. Moreover, the method is laborious with often many plumbing fixtures per connection. The chances of observing an intermittent domestic wastewater flow from an illicit connection with video reconnaissance are small. Butler et al. (1995) estimate that domestic discharges occur approximately 30 min (or 2% of 24 h) per person per day, which makes video testing unreliable for illicit connection detection.

3. Material and methods

3.1. *Temperature differences and variations*

For a reliable, inexpensive and practically feasible method to detect illicit connections, changes in water temperature over time and space can be considered. Temperature monitoring for the detection of extraneous flows has previously been used in other in-sewer applications (e.g. Wirahadikusumah et al., 1998). Monitoring in-sewer temperatures allows searching for anomalous temperatures and temperature variations that point to a disruption of usual conditions inside the storm water system. For illicit connection detection, this approach can be successful since the prevailing temperatures in storm water systems differ from the temperature characteristics of the foul water discharges from domestic and industrial premises that enter storm water drains. For dry-weather conditions, in-sewer temperatures in a ‘perfect’ storm water system without any illicit connections can only be influenced by surrounding air, soil and – in some cases – receiving water temperatures (e.g. Dürrenmatt and Wanner, 2008). In the Netherlands, values for soil temperatures at 1 m depth vary between 5 °C (winter) and 15 °C (summer); average air temperatures range from 3 °C for winter conditions to 17 °C for summer conditions (KNMI, 2008). Within these ranges, air, soil and receiving water temperatures are only subject to daily and seasonal variations. Consequently, expected in-sewer temperatures for a ‘perfect’ storm water sewer system during dry periods are in an approximate range of 5 °C–20 °C. Temperature variations in such a ‘perfect’ system can only occur on a daily and seasonal basis. Any deviant temperature values and/or deviant temperature variations indicate precipitation or a potential ‘imperfection’ in the storm water system.

Raw domestic wastewater often shows a highly variable temperature characteristic when considered at house connection scale. Over 60% of all household water usage is heated in showers, baths and household appliances (Achttienribbe, 1993; Butler et al., 1995). Water temperatures can rise to 35–40 °C for baths and showers or to 30–90 °C for household appliances. Before water is discharged into the sewer system, temperatures drop as energy is lost during transport through house drains. Nevertheless, a house connection intermittently produces wastewater that can be warmer than 20 °C.

3.2. *Fiber-optics distributed temperature sensing*

Fiber-optic distributed temperature sensing (DTS) is a widely applied technique for e.g. in industrial process control, leakage detection in dams and hydrology (Johansson, 1997; Selker et al., 2006a,b). The application of fiber-optic DTS in sewer systems is performed with a standard fiber-optic cable in combination with a standalone instrument that contains a laser, sensing optoelectronics and a PC. The fiber-optic cable is laid out on the bottom of a storm drain. At one end, the cable is connected to the computer/laser instrument that is generally stored outside the sewer system in a small container to protect it from weather and theft (see Fig. 1).

For a measurement, a pulsing laser light is emitted into the fiber-optic cable. Throughout the cable the laser light is reflected by imperfections in the glass fibers. Hence a pulse of duration Δt [s] gives a signal of reflection during a period of time usually longer than Δt, depending on the length of the

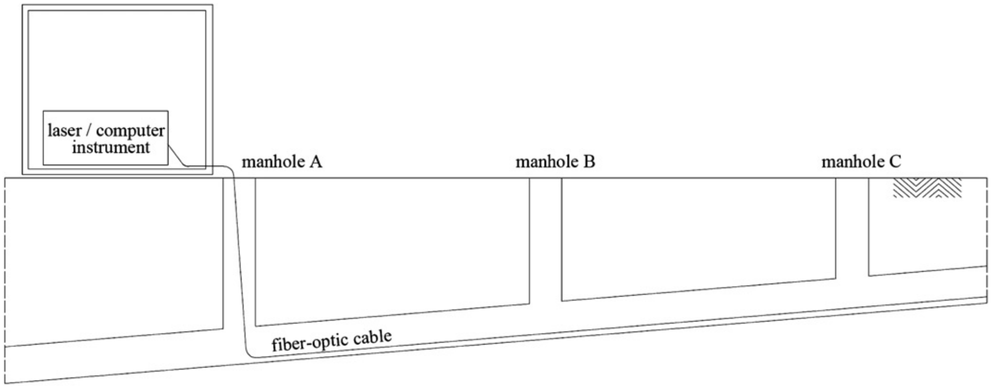

Fig. 1 – Set-up in-sewer DTS monitoring.

cable. With known travel time c [m/s] (in optic fibers typically 2/3 of the speed of light) the position from where the reflection of the pulse originates can be determined with spatial accuracy of c Δt.

The reflected signal is analyzed for Raman backscatter. Raman scattering produces two broadband components, the so-called Stokes and anti-Stokes emissions, at higher and lower frequencies than the main reflected signal. The ratio of the temperature-sensitive anti-Stokes intensity to the temperature-insensitive Stokes intensities is the basis of the DTS measurement (Lopez-Higuera, 2002).

In this paper's case-studies, fiber-optic cables were used carrying two glass fibers (Kaiphone Technology, Taiwan). The glass fibers (multimode 50/125 μm core/cladding diameter) are embedded in a gel to avoid direct stress on the fibers, as stress can affect the reflected laser signal. The fibers are further protected by subsequent layers of PBT, stainless steel spiral, aramid fiber, metal braiding and PE. Notwithstanding the protective layers, tests on similar cables have shown that abrupt step-wise changes in temperature are often apparent within the 15 s minimum time interval between readings (Selker et al., 2006a).

The laser/computer instrument used is a HALO DTS (Sensornet, London, England). With any DTS system there is a trade off between temporal resolution, spatial resolution, length of the cable, temperature precision, and retail price. In general, more measurements – both in time and space – over shorter cables lead to better temperature precision. As an example, the HALO instrument in combination with a 2000 m fiber-optic cable provides approximately 0.1 °C precise temperature measurements when measuring with a spatial resolution of 2 m and a temporal resolution of 1 min. Increasing the measurement frequency to once per 15 s reduces the precision to approximately 0.2 °C. For illicit connection detection with foreseen temperature differences in the order of several degrees, this precision is sufficient. Note that we do not want to measure the temperature accurately, but are looking for temperature change detection. So, absolute accuracy is less important, and we need precision here (Tyler et al., 2009).

Calibration of the instrument typically requires a value for temperature offset and a slope parameter that adjusts the offset with distance from the instrument. A calibration can be carried out by placing the entire cable in an environment of known constant temperature, attaching the cable to the instrument and taking a long-time measurement (Selker et al., 2006b). Logically, this kind of calibration must be carried out before installation of the cable in a storm water system. Alternatively, after installation calibration is possible by inserting two small and well-separated sections of the cable (e.g. two 5 m sections 500 m apart) in an environment of known temperature such as an ice-bath. In Fig. 2, temperature readings of two temperature sensors installed directly next to the fiber-optic cable at locations 1 and 2 give an offset and slope parameter to calibrate the raw DTS data.

Installation of the cable in a storm drain requires pulling a rope from manhole A to manhole B (see Fig. 1) 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 fiber-optic cable that is attached to the end of the rope can be pulled from A to B by hand. Pulling the cable manually assures that, in case of sudden blockage, no damaging excessive forces are exerted on the cable. Steps are repeated to move from manhole B to manhole C. Installation of a 1300 m cable takes a 5-persons team approximately 4 h. This can be improved by using pulleys to reduce friction in combination with a longer hose on the sewer flushing device to skip manhole B, and start from manhole C. Bends or loops in the cable with a radius less than 10 cm should be avoided to prevent loss of laser signal in the cladding which has a lower refractive index than the core of the fiber.

After connecting the fiber-optic cable to the HALO DTS system and a short initialization, results are immediately available in ASCII data files per time step. For high spatial and temporal resolutions, the amount of data quickly becomes substantial. A one-week monitoring campaign using a 1000 m cable with 30 s measuring interval and 2 m spatial resolution gives a dataset containing approximately 10^7 temperature observations. Costs for a one-week monitoring campaign using a 1000 m DTS system are of the order of $10000.- ($10.-/m). These costs comprise (1) purchase of the fiber-optic cable at ±$2.-/$m^1$, (2) $1000.- for depreciation of the DTS-computer, (3) $2000.- personnel costs for cable installation, (4) $2000.- for rental of a sewer flushing truck for cable installation and (5) $3000.- personnel costs for data collection, processing and interpretation.

3.3. *Test sites Korendijk and Groningen*

For illicit connection detection in storm water systems, the DTS method has been tested in two catchment areas in the Netherlands. The areas are situated in the municipalities of Korendijk (N 51°47′36″, E 4°16′51″) and Groningen (N 53°11′46″, E 6°32′01″). Preparatory visual inspections of sewers as well as residents' complaints inventories had already revealed the presence of illicit connections in the selected areas. Their exact locations however, were unknown. Table 1 presents some area characteristics and monitoring parameters for each catchment area.

The areas differ in type (residential versus industrial) which allows studying both domestic and commercial discharges. In the Groningen case-study results are available for both empty and submerged dry-weather sewer conditions, demonstrating the differences in monitoring results. Both the Korendijk and Groningen results include data gathered during storm events which open up the possibility to study the influence of precipitation on the measurements. For both case-studies a time interval of 30 s and a spatial resolution of 2 m were used. As a result, the measurements have a precision of approximately 0.1 °C.

4. Results

4.1. *Korendijk*

Fig. 3 presents the results of DTS-monitoring in the Korendijk catchment area. The horizontal axis represents the length along the cable from $x = 0$ m at the HALO instrument to

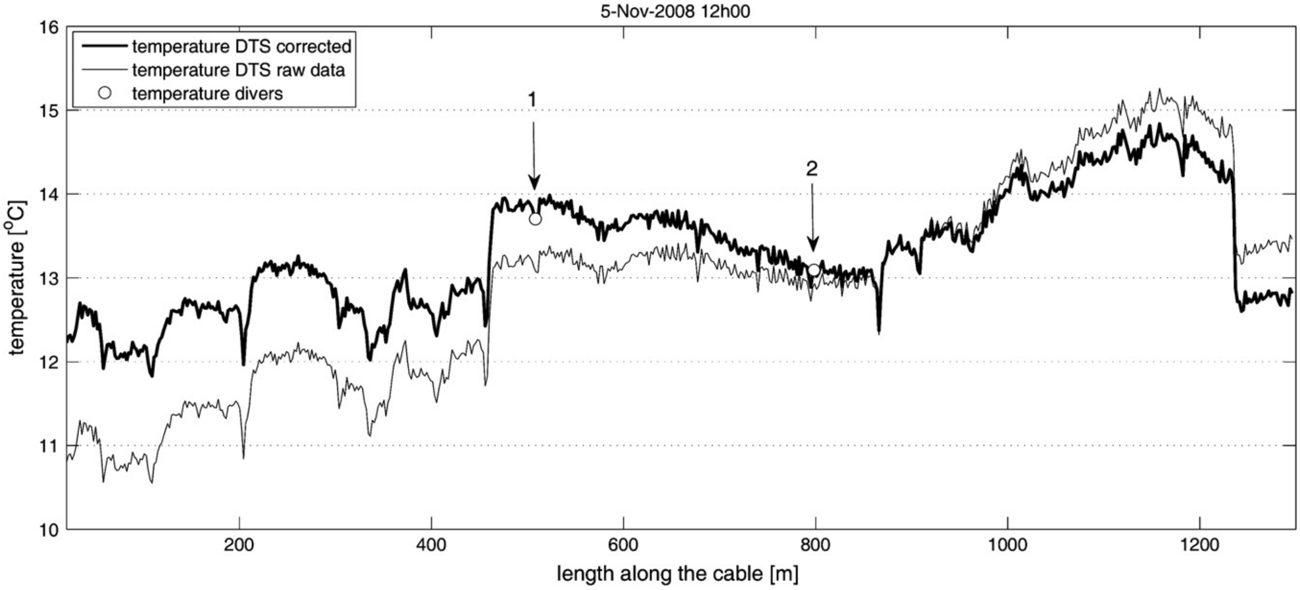

Fig. 2 – Calibration of a DTS measurement.

$x = 1264$ m at the end of the cable; the vertical axis represents a time-span of 21 h: Thursday October 9th 18h00 through Friday October 10th 15h00 2008. The figure consists of 632 × 2520 pixels that each represent a measured temperature value (1264 m divided by the 2 m spatial resolution gives 632 columns and 21 h divided by the 30 s temporal resolution gives 2520 rows). A longitudinal profile of the storm drain is given directly above the temperature graph. The numbers (1–26) represent manholes that vertically correspond to locations in the temperature graph. Any side-connections to other storm drains are indicated by circles.

Over the first 20 m the fiber-optic cable is not in the sewer system and hence records temperatures outside the sewer system. Inside the storm drains, the mean temperature is around 16 °C.

Table 1 – Area characteristics and monitoring parameters of case-study areas.

Area characteristics	Korendijk	Groningen
Type of area	Residential	Industrial
Number and type of premises along studied sewer stretch	102 Bungalows + terraced houses	11 Large multiple company buildings
Year of construction of storm drains	2000	2003
Empty or (partially) submerged storm drains for dry-weather conditions	Empty	Empty and submerged
Date of monitoring campaign	02–16 April 2008 + 09–10 October 2008	19 June–04 July 2008
Precipitation during monitoring	Yes	Yes
Length of the cable [m]	1264	1160

At six locations (‘a’ through ‘f’) anomalous temperatures above the ambient temperature are observed. High-temperature plumes have a distinct shape; a sharp upstream temperature rise during a certain time-span with energy transfer and dissipation in the downstream direction. Note that the downstream direction differs per plume. E.g. at location ‘c’ the slope of the sewer is from left to right, and at location ‘d’ the slope of the sewer is from right to left.

Between manholes 23 and 24 at locations ‘e’ and ‘f’ intermittent temperatures well above 19 °C are recorded. The majority of these recordings are concentrated during early morning and evening hours, whereas almost no temperature increases occur between 00h00 and 06h00. For the Korendijk area a verification of the results was performed in the afternoon at October 10th, 2008: opening warm water taps at suspected premises resulted in either visual or auditive confirmation of water entering the storm drains. Also, monitoring results showed increasing temperature values.

4.2. *Groningen*

Since receiving water levels in the Groningen catchment area exceed storm drain invert levels, a layer of water (±30 cm) is normally present in the storm water sewers. In this partially filled system, a first monitoring campaign was set-up (19–26 June 2008). A second campaign (26 June–4 July 2008) was initiated after separating the storm drains from the receiving waters and emptying the drains for the duration of the measurement. Results are given in Fig. 4.

The first 27 m of the fiber-optic cable were not in the sewer system and hence recorded outside temperatures. Ambient in-sewer temperatures differ for both graphs. In-sewer surface water temperatures range between 15 °C and 17 °C whereas air temperatures in the emptied storm drains vary between 17 °C and 19 °C.

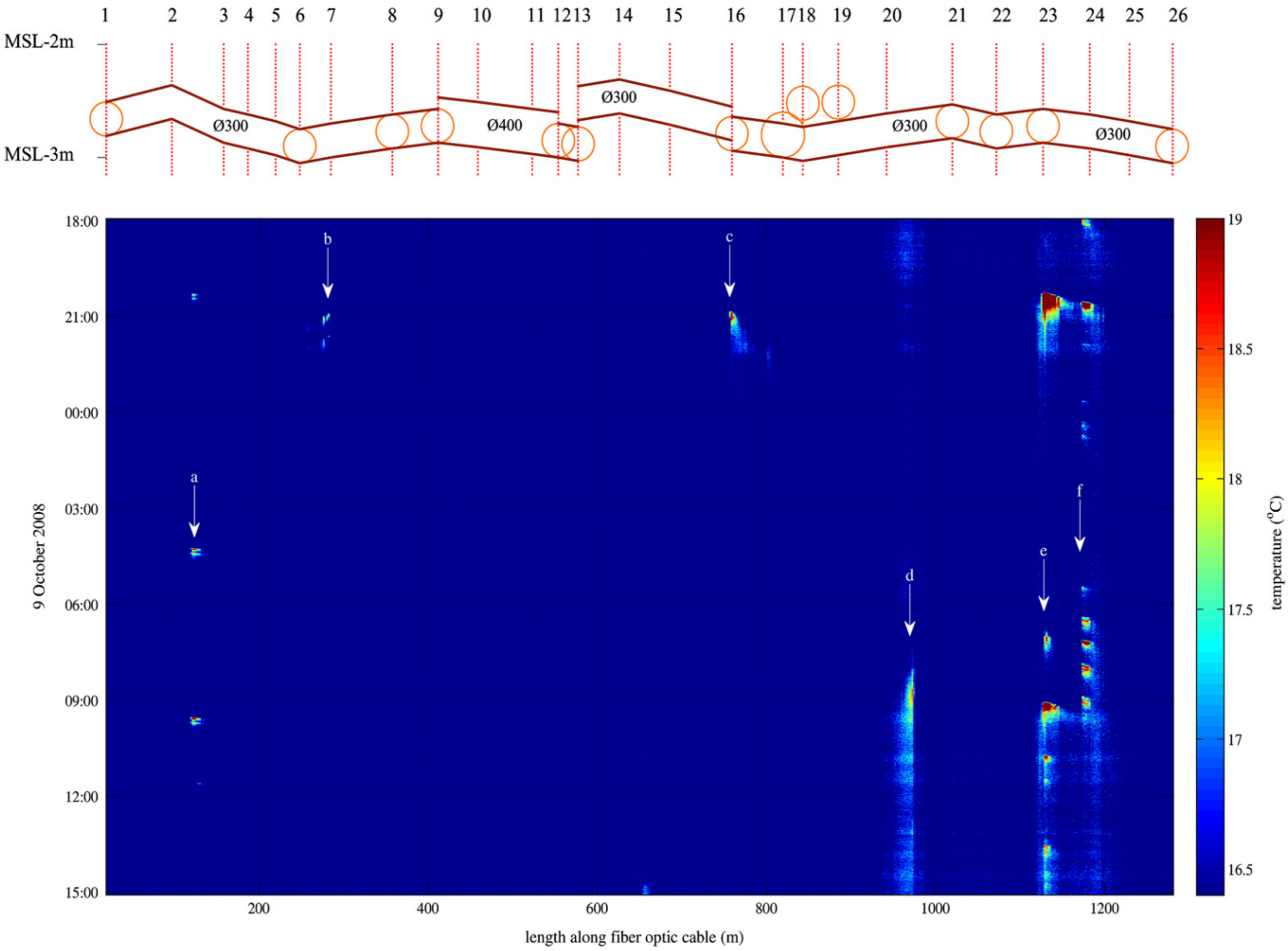

Fig. 3 – Longitudinal profile of the storm drain and DTS-monitoring results in Korendijk, 9–10 October 2008. The numbers (1–26) represent manholes. Side-connections are indicated by circles. At six locations ('a' through 'f') anomalous temperatures are observed.

At locations A (378 m) and B (500 m) intermittent high-temperature plumes are visible for working days, but not during weekends (21–22 and 28–29 June). The plumes have different characteristics for partially filled versus empty situations. In partially filled situations, temperature differences are small (0.5 °C) and spread out in time and space, whereas temperature differences in empty systems are larger (1.5 °C, despite higher in-sewer temperatures) and more concentrated in time and space. Excavation work at the exact location of the observed high-temperature plumes confirmed the existence of illicit connections in Groningen.

5. Discussion

5.1. *Predominant in-sewer temperatures and temperature variations*

For both the Korendijk and the Groningen cases, mean in-sewer temperatures are presented in Fig. 5. The data constitute in-sewer temperatures for three consecutive dry-weather days at two locations along the studied sewer sections for which no anomalies in temperature readings have been recorded (Korendijk $x = 500$ m; Groningen $x = 880$ m). For these April results, Korendijk in-sewer air temperatures show a diurnal variation with values ranging between approximately 9 °C and 10 °C. This diurnal cycle can be attributed to heat exchange via storm drain inlets, manhole covers and outfalls. Superimposed on this diurnal variation is a high-frequent variation (≈1 cycle per hour) with an amplitude up to 0.4 °C. The origin of the latter has not been found, but can possibly be attributed to instrument noise or drift.

In Groningen, in-sewer air temperatures in an empty storm sewer also show a diurnal variation with values varying between 18 °C and 19 °C. Compared to the Korendijk data in-sewer air temperatures in Groningen are higher due to a change in season. The Groningen data were recorded in summer, whereas the Korendijk data were recorded in spring and autumn. When partially submerged, the same Groningen storm water system shows in-sewer water temperatures around 16 °C *without* a distinguishable diurnal variation. The large water mass in a water-filled storm drain prevents relatively quick diurnal variations whereas the limited air mass in empty sewers is more easily influenced by outside temperature variations.

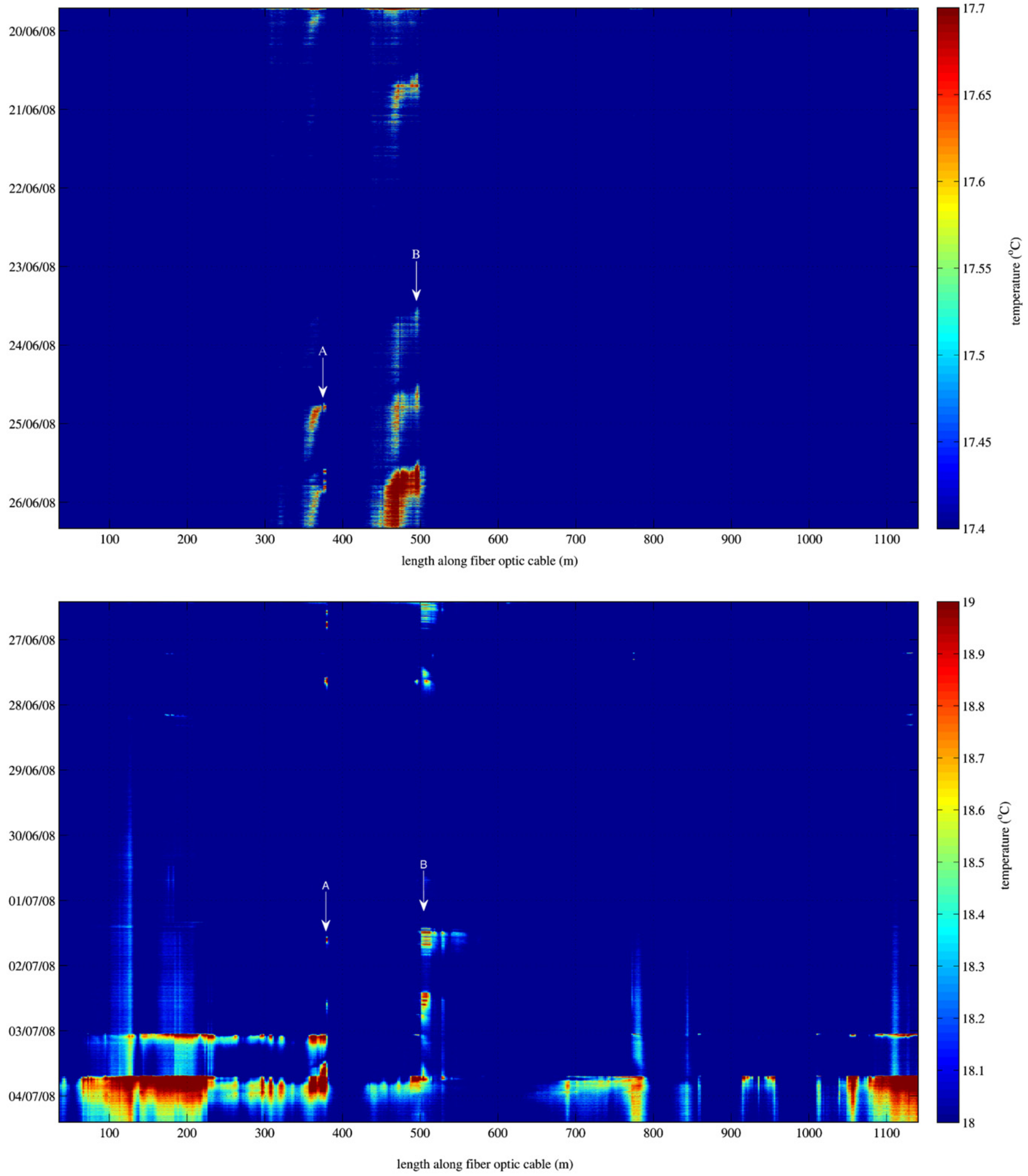

Fig. 4 – DTS-monitoring results in Groningen: above partially submerged storm water system June 19–26, 2008 and below emptied storm water system June 26–July 4, 2008. The storm water system filled up with storm water at July 3, 2008.

The results in Fig. 5 confirm the notion that expected in-sewer temperatures for a 'perfect' storm water system without illicit connections are in the approximate range from 5 °C to 20 °C with major variations only on daily and seasonal basis.

5.2. *Anomalous in-sewer temperatures and temperature variations*

The Korendijk and Groningen monitoring results in Figs. 3 and 4 include multiple locations for which temperatures and

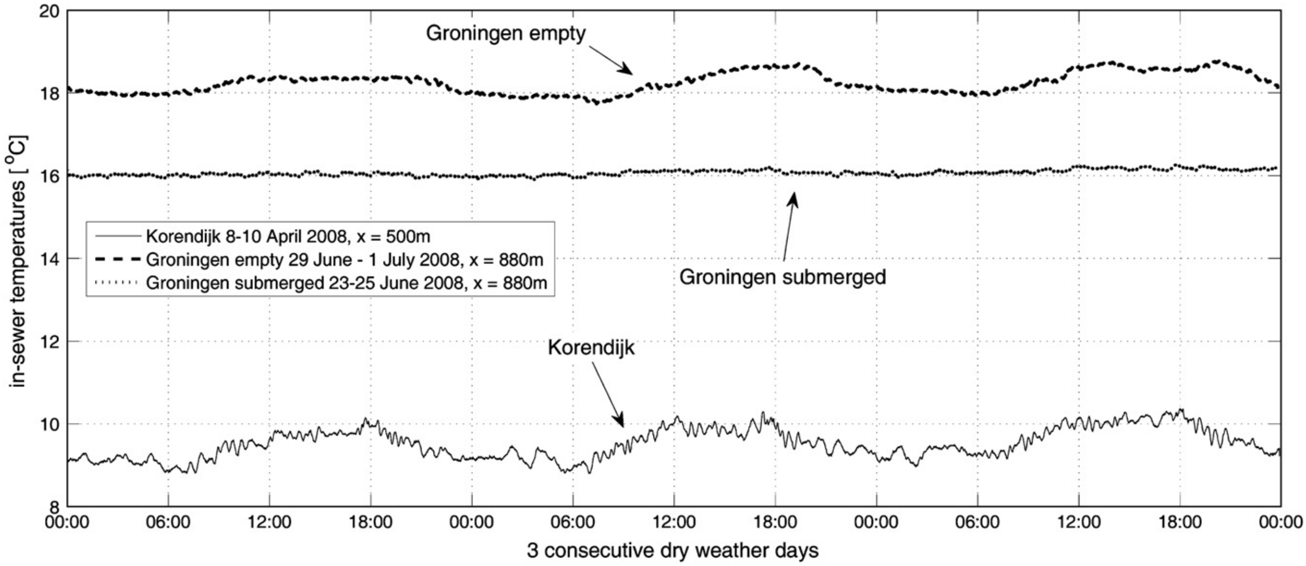

Fig. 5 – In-sewer temperature variations for three consecutive dry-weather days in Korendijk and Groningen, both empty and submerged storm water system.

temperature variations have been recorded that deviate from predominant in-sewer temperature behavior. As an example from the Korendijk data, at $x = 1127$ m intermittently temperatures well above normal values are recorded (see Fig. 6). During the night (00h00– 06h00) in-sewer temperatures are relatively stable at a value of approximately 12 °C, but during day and evening hours temperatures can intermittently rise up to 27 °C.

It can be argued that these temperature increases are due to domestic wastewater discharges spilled to the storm water system. First of all, water is the likely bearer of the energy that causes the temperature rises since peaks always move downstream along the considered sewer section (see Fig. 3 for an overview and Fig. 7 for the presentation of a warm water plume in detail). Secondly, the hours of the day and, for the Groningen case, also the days of the week for which temperature peaks occur, coincide with peaks in human activities. Human involvement in the spills is further confirmed by the absolute temperature values of the spills, for in the Netherlands no natural sources are known that produce water over 20 °C. Finally, the intermittent character as well as the duration of the peaks correspond well with the characteristics of normal use of household appliances such as showers, laundry machines, etc. Although these four arguments make

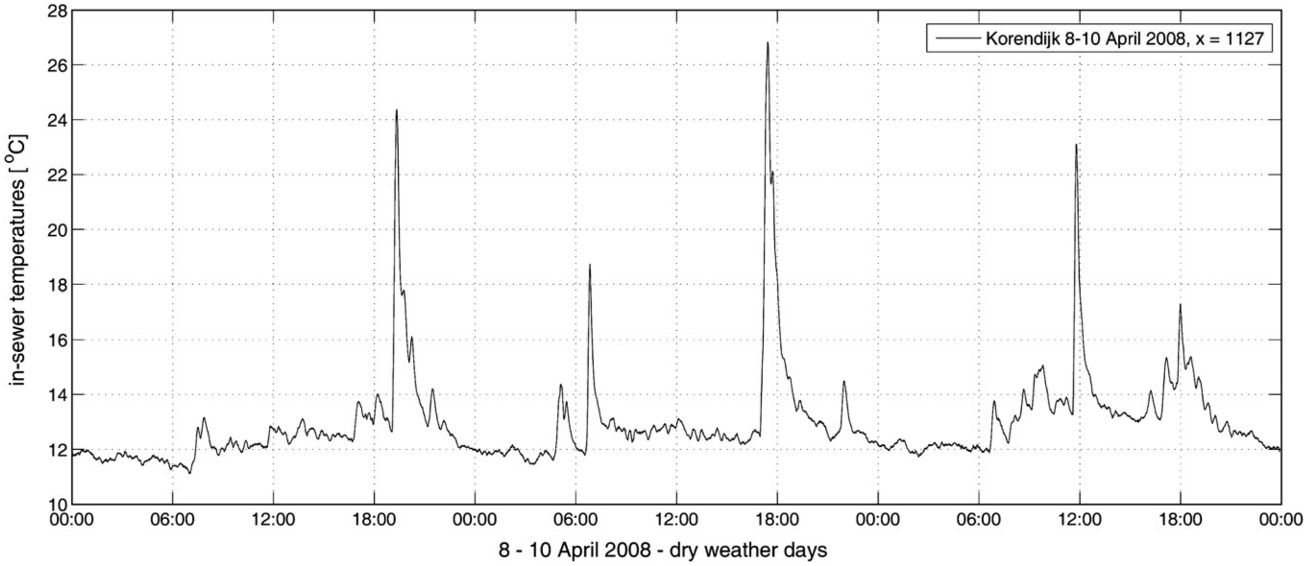

Fig. 6 – DTS-monitoring results for Korendijk, 8– 10 April 2008 at $x = 1127$ m.

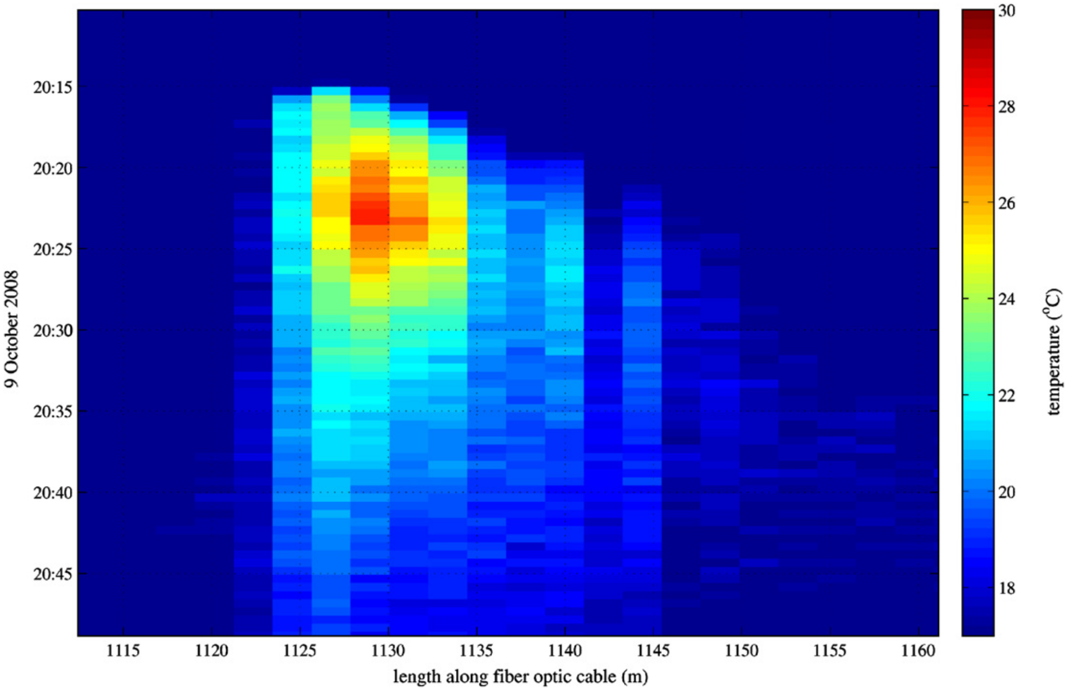

Fig. 7 – DTS-monitoring results for Korendijk, zoom on a warm water plume at $x = 1125$ m for 9 October 2008 20h15. Downstream direction in the presented sewer drain is from left to right.

domestic wastewater discharges the probable source for the observed anomalous in-sewer temperatures, they do not prove causality. Conclusive evidence linking observed temperature peaks to domestic wastewater discharges was found during on-site verification of results by excavation and testing.

Warm water plumes in the Korendijk results are more pronounced for section [900–1200 m] than for section [100–300 m]. At the latter section a larger amount of water in the storm drain (even under dry-weather conditions) absorbs the energy of the illicit discharges more easily resulting in smaller temperature differences. Temperatures in storm drains that are in the direct downstream vicinity of regular warm water discharges tend to remain relatively high compared to neighboring stretches, even after warm water discharges have ceased. Apparently, some energy is stored during discharges (in concrete, sewer sediments, etc.) and released afterwards.

5.3. *Empty versus submerged storm water systems*

Results of the Groningen case reveal warm water plumes for both the empty as well as the partially submerged storm water system for the same two locations (Fig. 4, at $x = 378$ m and $x = 500$ m). The plumes have different characters. For the submerged system, temperature variations are slower and spread out in time and space whereas temperature variations for the empty system are faster with discharged water remaining closer to its origin and cooling down more quickly. This is further illustrated in Fig. 8. The graph presents temperature variations for both the empty and submerged systems during a three-day dry-weather period at two distinct locations. Measurements at $x = 880$ m represent normal in-sewer temperature variations, namely a diurnal pattern for the empty system and a nearly constant temperature value for the submerged system (see Fig. 5). Measurements at $x = 500$ m, however, show deviations from these standard patterns. In the emptied system, anomalies (area A) take the shape of relatively quick variations that cause slightly higher temperatures ($\pm 0.5\,^\circ$C) than expected considering the data for $x = 880$ m. Areas B, C and D show that anomalies in a submerged system take a different form with gradual variations over the day that cannot be observed for locations without illicit connections.

Despite their different appearances, anomalies in temperatures and temperature variations are detectable for both types of systems. As a result, in both empty and submerged storm water systems illicit discharges can be detected using the DTS-monitoring system. Emptying a (partially) filled storm water system is not required for DTS-monitoring to be successful. However, if discharges are small compared to the stagnant in-sewer water mass, temperature differences might become smaller than the monitoring precision, rendering results unreliable. Emptying the storm water system can improve performance in these situations.

5.4. *Influence of precipitation*

During the monitoring campaigns in both Korendijk and Groningen precipitation influenced some of the results. For Korendijk, small storm events have been recorded for 6 April 01h00 (≈ 5 mm) and 03h00 (≈ 3 mm). Relatively cold storm water run-off entering the storm drains causes a temperature reduction over parts of the cable. Temperature reductions

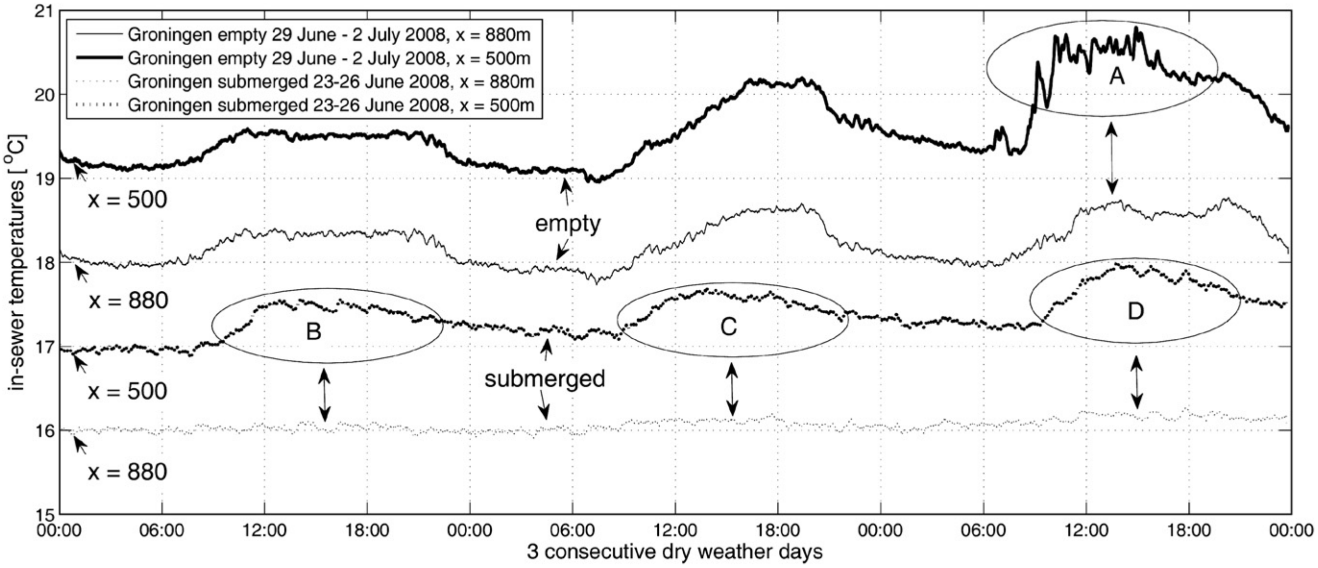

Fig. 8 – DTS-monitoring results for Groningen. Results for three consecutive dry-weather days at $x = 500$ m (illicit connection) and $x = 880$ m (normal conditions) for both an empty and a partially submerged storm water system.

are inhomogeneously distributed over the cable due to differences in run-off surfaces and an unbalanced run-off of storm water to available storm drain inlets. Fig. 9 demonstrates that temperature variations due to precipitation (areas A, B and C) can have the same characteristics as temperature variations due to illicit discharges (e.g. areas D and E): a sudden temperature change within minutes with a recovery to normal temperatures within hours. For the Korendijk results, temperature changes due to precipitation (area C) can be identified as such since precipitation causes temperature *reductions* whereas illicit discharges cause temperature increases (areas D and E).

The Groningen results, however, show that precipitation can also cause a temperature *increase* in a storm water sewer. A small storm event has been recorded for 3 July 00h15 (≈2 mm), followed later that day by a larger storm event (≈14 mm) between 16h00 and 23h00 (see Figs. 4 and 9). During run-off, storm water was warmed up over heated asphalt surfaces after relatively warm days with maximum temperatures around 34 °C. Again, only parts of the cable see this effect. Other parts of the storm drain may have received no storm water or storm water from different surfaces. Since the characteristics of in-sewer temperature variations are the same, the effects of illicit discharges on in-sewer

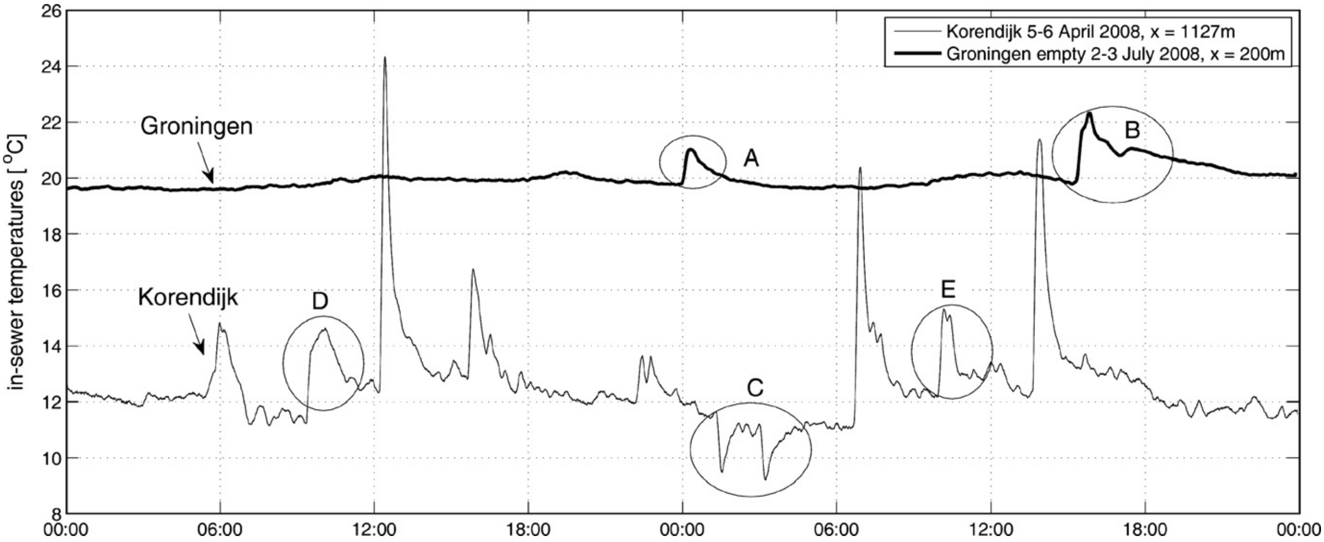

Fig. 9 – DTS-monitoring results for Groningen ($x = 200$ m, 2–3 July 2008) and Korendijk ($x = 1127$ m, 5–6 April 2008). The influence of precipitation on monitoring results can be observed at areas A, B and C.

temperatures can no longer be distinguished from the effects of precipitation. Hence, when searching for illicit connections, a correct interpretation of DTS-monitoring results requires using dry-weather data only.

6. Conclusions

Distributed temperature sensing with fiber-optic cables is a powerful tool to search for illicit connections in storm water systems. Its near-continuous temperature monitoring in both time and space allows recording any discharge of water with temperatures or temperature variations that differ from 'normal' storm water system temperature characteristics. Normal characteristics for this paper's case-studies constitute temperature values between 5 °C and 20 °C showing only small daily and larger seasonal variations. Domestic wastewater flows often show much higher temperatures with an intermittent character ('warm water plumes') and are hence easily detected. Excavation work and other result verification have confirmed the presence of illicit connections at the exact locations where warm water plumes have been observed.

Precipitation can influence monitoring results. The case-studies have shown both temperature rises as well as temperature reductions as a result of inflowing storm water run-off. Hence, only dry-weather results should be used for illicit connection detection. Monitoring results for empty sewers differ from those collected in partially filled pipes, but illicit discharges remain visible for both situations. To maximize chances of observing an illicit discharge it is, however, recommended to empty the storm water system before performing measurements with the DTS system.

Compared to other searching techniques the DTS method is relatively reliable due to its near-continuous monitoring in time and space. Also, the method is practically feasible since it does not require access to private property.

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