  Water Science & Technology | 79.2 | 2019

Detection of extraneous water ingress into the sewer system using tandem methods – a case study in Trondheim city

M. Beheshti and S. Sægrov

ABSTRACT

Infiltration and inflow (I/I) of extraneous water in separate sewer systems are serious concerns in urban water management for their environmental, social and economic consequences. Effective reduction of I/I requires knowing where excess water ingress and illicit connections are located. The present study focuses on I/I detection in the foul sewer network of a catchment in Trondheim, Norway, during a period without snowmelt or groundwater infiltration. Fiber-optic distributed temperature sensing (DTS) was used for the first time in Norway to detect I/I sources in tandem with closed-circuit television inspection (CCTV) and smoke testing. DTS was an accurate and feasible method for I/I detection, though it cannot identify exact types of failure and sources of I/I. Therefore, other complementary methods must be used, e.g. CCTV or smoke testing. However, CCTV was not completely useful in confirming the DTS results. This study provides practical insights for the rehabilitation and repair of sewer networks that suffer from the undesirable I/I of extraneous water.

Key words | CCTV, distributed temperature sensing (DTS), infiltration and inflow (I/I), separate sewer system, sewer infrastructure asset management, smoke testing

M. Beheshti (corresponding author)
S. Sægrov
Department of Civil and Environmental Engineering,
Norwegian University of Science and Technology (NTNU),
Trondheim,
Norway
E-mail: *maryam.beheshti@ntnu.no*

INTRODUCTION

Separate sewer networks efficiently and reliably convey foul sewage to wastewater treatment plants. However, large volumes of unwanted water infiltration and inflow (I/I) can pose serious management challenges. I/I from extraneous water and illicit connections can overload the sewer system, cause sanitary sewers to overflow, threaten public health, and increase energy and chemical consumption during treatment while decreasing overall treatment efficiency (Beheshti & Sægrov 2018a). This specific concern threatens sustainable asset management of sewer infrastructure in the long term and reduces environmental, social and economic sustainability (Beheshti *et al.* 2015; Beheshti & Sægrov 2018a).

The efficient reduction and removal of unwanted water from sewer systems require comprehensive and detailed understanding of I/I from illicit connections and extraneous water sources (Beheshti *et al.* 2015). Illicit connections, including unintended sewer cross-connections, are a major problem in separate sewers because sewage contaminates the storm sewers and stormwater can overload the foul sewers (Hoes *et al.* 2009; Beheshti & Sægrov 2018a). Extraneous water also contributes to I/I and includes stormwater, groundwater, and drainage water (Hoes *et al.* 2009).

In Trondheim, Norway (~200,000 residents), the sewer network includes both combined and separate sewers; about 52% of the total network is currently a separate system (Beheshti & Sægrov 2018b). A water balance of Trondheim's wastewater system from 2009 to 2011 indicated that extraneous water via I/I was about 46% of total water delivered to the wastewater treatment plant during dry weather conditions (Beheshti & Sægrov 2018b). This significant amount of unwanted water can increase even more during wet weather, so Trondheim municipality has made solving this problem a high priority.

There are no defined standards for detecting or locating I/I sources in sewer systems, though both conventional and high-tech techniques are being used, such as smoke testing, dye testing, closed-circuit television camera (CCTV),

doi: 10.2166/wst.2019.057

electro-scan and distributed temperature sensing (DTS) (Tuomari & Thompson 2003; Schilperoort *et al.* 2013; Beheshti *et al.* 2015). There are limitations to the common methods of I/I detection (e.g. dye testing), such as being labour intensive, requiring entrance into private premises and introducing environmental risks, in addition to high uncertainty to identify I/I sources (Hoes *et al.* 2009; Schilperoort *et al.* 2013; Beheshti *et al.* 2015). Smoke testing is another practical and reliable method for finding misconnections from stormwater outlets in separate foul sewers. Smoke is injected into the foul sewer system, and in the case of any defect or misconnection in the sewer network, the smoke leaks out, signaling the location of I/I sources (Hoes *et al.* 2009; Beheshti *et al.* 2015). CCTV is also commonly used for finding illicit connections, cracks, and problematic parts of the network. In this method, the sewer network is inspected by a sewer operator, who receives live footage inside the pipeline via a moving robot with attached CCTV camera. However, because of intermittent discharges from households, the chance of finding illicit connections with CCTV in storm sewers is low, making the results imprecise and inaccurate (Hoes *et al.* 2009).

Modern and high-tech I/I detection methods, such as DTS and electro-scan, have high accuracy and low environmental risks, in addition to requiring less analytical effort (Beheshti & Sægrov 2018a). Electro-scan is a new technique in sewer monitoring based on measuring the electrical resistance of the pipe wall. The principle behind this method is that the electricity flows through pipe defects and the electrical resistance indicates where there is water leakage (Harris & Dobson 2006; Tuccillo *et al.* 2011). Fiber-optic DTS was developed in the 1980s for telecommunication (Dakin *et al.* 1985; Tyler *et al.* 2009; Vosse *et al.* 2013). The method became widely applicable in different fields, such as for leakage control in the oil, gas and dam industries (Johansson 1997; Vosse *et al.* 2013), as well as for hydrologic applications (Selker *et al.* 2006; Westhoff *et al.* 2011), soil moisture studies (Jansen *et al.* 2011; Ciocca *et al.* 2012), power transmission (Yilmaz & Karlik 2006; Shen *et al.* 2016), air temperature measurement (Petrides *et al.* 2011; de Jong *et al.* 2015) and vegetation coverage in forests (Krause *et al.* 2013). DTS has been applied in urban sewer systems for pipeline monitoring and I/I detection since 2009 (Pazhepurackel 2009; Schilperoort & Clemens 2009). The principle of I/I detection in DTS is based on analysis of thermal behavior of sewage along a fiber-optic cable installed in the sewer network (Beheshti & Sægrov 2018a).

This study aimed to locate I/I sources from illicit connections and extraneous water into a foul sewer network by various techniques in tandem. Combining different detection methods reduces uncertainties and inaccuracies. DTS was used for the first time in Norway and was complemented by CCTV and smoke testing to detect I/I in the separate foul sewer network of the Lykkjbekken catchment (Trondheim). This study demonstrated that DTS in combination with supplemental methods is effective at locating individual I/I sources in sewer pipelines. By precisely identifying these sources, the municipality can prioritize rehabilitation and spot repairs, efficiently decreasing unwanted water ingress into the sewer system.

MATERIAL AND METHODS

DTS technology

DTS is a high-tech monitoring technique for detecting I/I sources from illicit connections and extraneous water in sewer networks (Pazhepurackel 2009; Schilperoort & Clemens 2009). This method is based on continuous temperature measurement along the fiber-optic cable in the wastewater network, up to several kilometers (Beheshti & Sægrov 2018a). Potential I/I sources can be located precisely by monitoring and analyzing the thermal behavior of sewage, so long as I/I water differs in temperature (Schilperoort 2011; de Jong *et al.* 2015; Beheshti & Sægrov 2018a). However, this technology has some limitations, such as high initial costs of the instrumentation and installation, and requiring a high-skilled operation.

The temporal resolution of DTS measurement is normally in the range of 18–60 s and the spatial resolution is 0.5 to 2 m, with thermal accuracy of ±0.1 to 0.2 °C (Hoes *et al.* 2009). DTS can be used in public parts of the sewer network without requiring entry to private premises. DTS uses mounted fiber-optic cables in the sewer pipeline and a control unit that consists of a laser instrument, an optoelectronic sensor and a computer (Beheshti & Sægrov 2018a). Figure 1 demonstrates the standard layout of the method.

Smoke testing

Smoke testing is a practical method to detect, identify and classify potential sources of I/I in a wastewater collection system, especially in detecting misconnected stormwater drains and outlets in separate foul sewers (Hoes *et al.* 2009; Beheshti *et al.* 2015). In this method, vegetable-based smoke, produced by a smoke generator, is injected into isolated parts of the sewer network, where I/I is suspected.

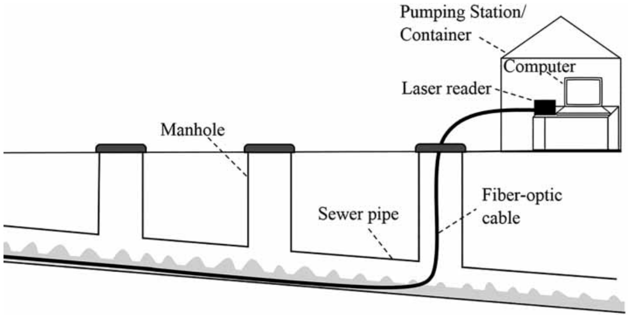

Figure 1 | Schematic outline of the DTS method in a sewer pipe and the control unit stored outside the sewer system in the pumping station (Beheshti & Sægrov 2018a).

The smoke, which tends to escape through openings and vents, pinpoints I/I sources in the separate sewer network (Figure 2).

Smoke testing is a practical method for finding the misconnected storm drains connected to separate sanitary sewers. This method is not feasible in finding all types of I/I sources in sewer networks; however, it can be effective in combination with other I/I detection techniques.

CCTV method

CCTV is a common method in sewer maintenance to inspect and assess the status of the wastewater network. In this method, a remote-controlled, closed-circuit video camera is inserted into the sewer network through a manhole and moves inside the sewer network by a small robot, allowing the operator to inspect the network and detect problematic parts via real-time visual inspection. However, it is difficult to detect all illicit connections from foul sewage outlets into the storm sewers when there is no continuous flow from households (Hoes *et al.* 2009). Additionally, the method is based on visual inspection, and there is the possibility of over- or underestimating the status of the network due to operator errors and invisible defects in the pipeline. Another drawback of CCTV in detecting I/I sources is its dependence on the presence of rainfall or a high groundwater table.

Case study

The study area for the present study was Lykkjbekken catchment in Trondheim, which is located near the main water source of the city, Lake Jonsvatnet (63°22′46″N 10°32′35″E - 63°21′47″N 10°29′16″E; see Figure 3(a)). Lykkjbekken catchment is a rural area, and the studied sewer section covers an area of around 10 km^2 with ~200 inhabitants. The catchment has a separate foul sewer system consisting of a pumping station and small PVC pipelines (160 mm internal diameter). The wastewater network was prone to high volumes of extraneous water I/I from unknown sources particularly during rainfalls, due to the increased water level in the pumping station that was likely to be from infiltration. However, the sewer network inspection by CCTV during the spring of 2015 with high groundwater table did not detect any pipe defect or groundwater infiltration in the under study sewer network. The I/I of unwanted water increased the probability of overloading the system, especially in wet seasons, and magnified the risk of contaminating the drinking water source due to sewer overflow from the pumping station. Therefore, DTS was applied to monitor the sewer network and detect I/I sources, especially the rainfall-derived infiltration and inflow sources.

The fiber-optic DTS cables were installed in the separate foul sewer of Lykkjbekken catchment over a length of 4.8 km (see Figure 3(b)). The monitoring campaign was

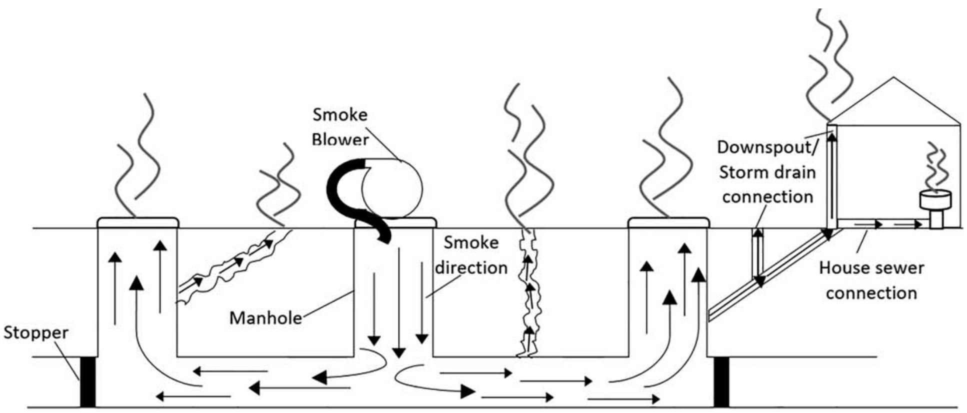

Figure 2 | Schematic outline of the smoke testing process to find potential sources of I/I in a foul sewer system (Beheshti *et al.* 2015).

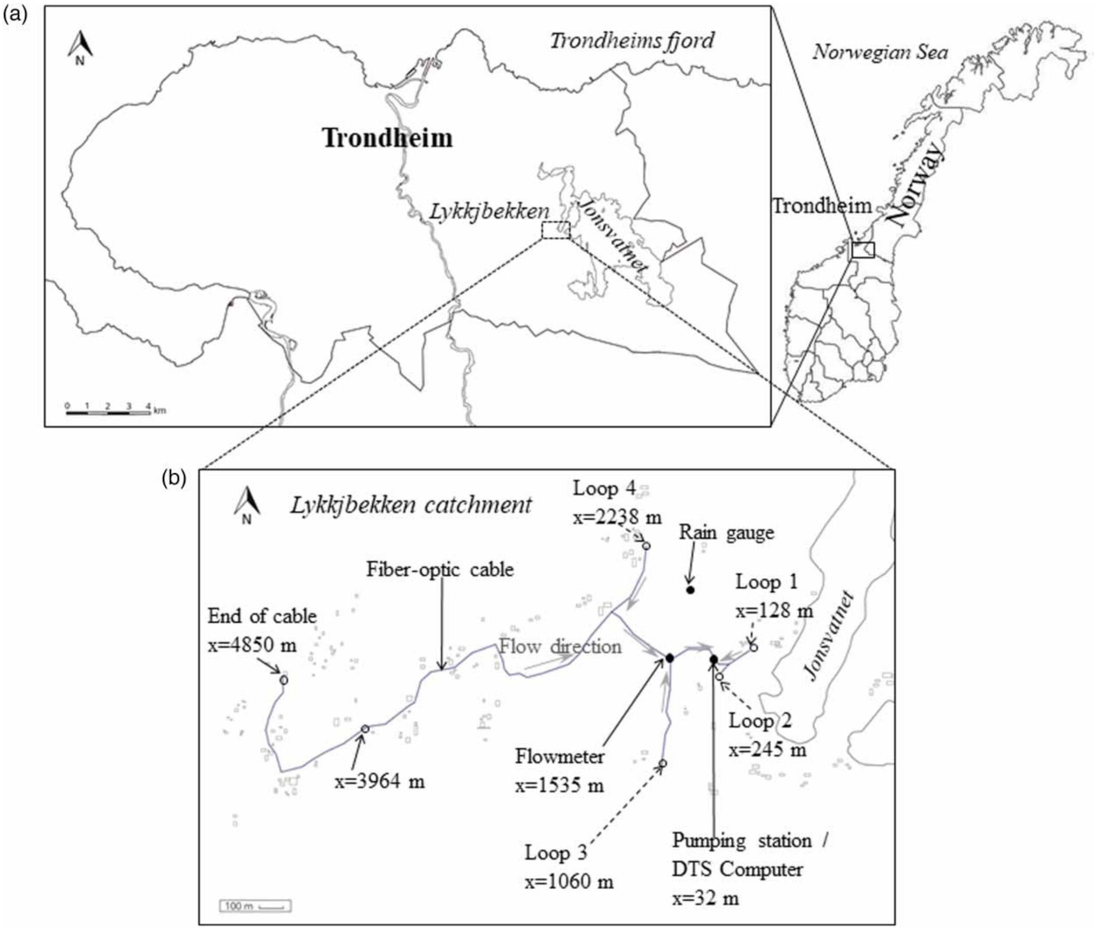

Figure 3 | (a) The location of Lykkjbekken catchment in Trondheim, Norway, (b) DTS cable installation in Lykkjbekken catchment.

from August 23 to November 20, 2015, while an in-sewer temperature measurement with a resolution of 0.01 °C was recorded every 18 s for each 50 cm interval of the cable. The DTS computer and laser reader was a Yokogawa DTSX3000 unit, stored outside the sewer network in the pumping station, and was connected to one end of the cable downstream of the sewer network. For monitoring several sewer sections simultaneously with a continuous monitoring system, the cable was looped into and then out of pipeline branches at four locations (Figure 3(b)). As a consequence of these loops, the temperature was recorded twice, effectively providing replicate temperature measurements at the four pipeline branches.

Precipitation and temperature measurement

Precipitation measurement is a key parameter for assessing rainfall-derived I/I in separate sewer networks (Beheshti & Sægrov 2018a). To assess the impacts of rain and stormwater into the sewer network, a tipping bucket rain gauge with the standard resolution of 0.2 mm was installed in the catchment to record precipitation during the monitoring campaign.

Air temperature and the presence of snow in the catchment affects the thermal behavior of the sewer network. Several hydrological studies in runoff and stream water temperature have found that the air–water temperature relationship can be modeled with an S-shaped, non-linear regression, which is linear for air temperatures of 0 to 20 °C (Stefan & Preud'homme 1993; Mohseni & Stefan 1999; Webb *et al.* 2008; Ficklin *et al.* 2012). Rainfall-derived I/I has a similar temperature to ambient air temperature and can therefore be modeled using the linear regression (Beheshti & Sægrov 2018a). However, in the presence of snow, the temperature of the extraneous water from the snowmelt runoff can be set to 0.1 °C (i.e. just above the freezing point of water), regardless of the ambient air temperature (Ficklin *et al.* 2012; Beheshti & Sægrov 2018a).

RESULTS AND DISCUSSION

The performance of the foul sewer system of Lykkjbekken catchment in Trondheim was assessed for detection of rainfall-derived I/I sources and illicit connections by various methods. An initial CCTV inspection was conducted in the network, and no defects in the pipeline were detected. Afterward, the sewer network was monitored by DTS while there was no snowmelt or groundwater inflow. DTS technique was used during both wet and dry weather conditions to investigate the effects of extraneous water and illicit connections on the thermal behavior in the sewer system and locate I/I sources. The case study was located in a catchment with low wastewater flow and high probability of sedimentation of debris and toilet papers on the fiber-optic cables. Therefore, maintenance of the installed cables was important to avoid any blockage by carrying out regular sewer flushing during the monitoring campaign (Beheshti & Sægrov 2018a).

Figures 4 and 5 display the DTS monitoring data during storm events on August 27–28 and November 11, 2015, respectively. In these heat-maps, the vertical axis presents the time and the horizontal axis demonstrates the length of 'x' along the fiber-optic cable from x = 32 m, where the cable enters the sewer system, to the end of the cable at x = 4,850 m. The fiber-optic cable acts as a linear temperature sensor and measures the temperature during the monitoring campaign with spatial and temporal resolutions of 0.5 m and 18 s, respectively. Each pixel in these graphs represents a recorded temperature for a single spot and time along the cable. The recorded temperatures (°C) are colored according to the color gradient on the right side of the DTS monitoring graph. Precipitation and air temperature were measured simultaneously to control for their effects on I/I. The flow direction is generally from right to left, except in the replicated sides of loops at the four pipeline branches.

By analyzing the sewage thermal behavior during wet conditions after the start of rainfall in Figures 4 and 5, the I/I locations experienced unexpected temperature changes. The abrupt thermal changes at locations x = 3,964 m, 128 m and 245 m on the cable can be associated with stormwater inflow. However, x = 128 m and 245 m were located at loops 1 and 2, where the cable did not continue upstream; the I/I could therefore be caused by stormwater inflow where there was no cable present.

The inflows into the sewer network with different temperatures than the in-sewer wastewater can be detected in DTS monitoring graphs as sudden thermal changes. The heat spread is quite visible along the wastewater flow and illustrated by some arrows in Figures 4 and 5. The gradient of the arrows changes due to the velocity, volume, and temperature of the in-sewer wastewater and external inflows. Additionally, the larger the time horizon is, the steeper is the arrow (Figure 4(a)), and in the higher time resolutions, the thermal diffusion of the inflows are indicated by lower gradients (Figure 4(b)).

The DTS results in Figure 4 demonstrated an increase in the downstream temperatures of potential I/I locations (x = 3,964 m, 245 m and 128 m), relative to their upstream temperature after a heavy rainfall began on August 27, 2015. However, in the rainfall on November 11 (Figure 5), the potential I/I locations experienced a decrease in sewage temperature. This can be justified by comparing the temperatures of air and wastewater. Figure 6 presents the time transect of x = 3,964 m during the rainfall on November 11, 2015. Temperature variations upstream and downstream of that point illustrate the impacts of rainfall-derived I/I and air temperature on thermal behaviors of the sewer network in a linear graph.

The corresponding rainfall-derived I/I on August 27, 2015 (Figure 4) occurred during a night with the air temperature of 12–19 °C, which was warmer than the sewage temperature (~8 °C). Because rainfall-derived I/I has a similar temperature to air temperature when there is no snow in the catchment, the I/I increased water temperatures in the sewer. In contrast, rainfall-derived I/I on November 11, 2015 (Figure 5) coincided with a cold night (~3 °C), and the corresponding I/I was colder than the wastewater (8 °C). Thus, temperature of rainfall-derived I/I water can be either lower or higher than the wastewater, depending on ambient air temperature.

DTS locates the problematic parts of the network but is not practical to identify potential I/I sources. Therefore, supplemental methods are needed to inspect locations with I/I. In this study, a CCTV inspection was conducted to inspect and verify the results from DTS. However, this inspection was not helpful in verifying the sources of I/I. Therefore, smoke testing was used to inspect potential problems detected by DTS. In this case, the smoke identified misconnected downspouts (yard and roof drain) at x = 3,965 m and 128 m as sources of I/I. Location x = 245 m was placed on loop 2, and the inflow could be caused by stormwater upstream of that point, where no fiber-optic cable was installed. CCTV was not effective in detecting the misconnected storm drain outlets, as they were connected to foul

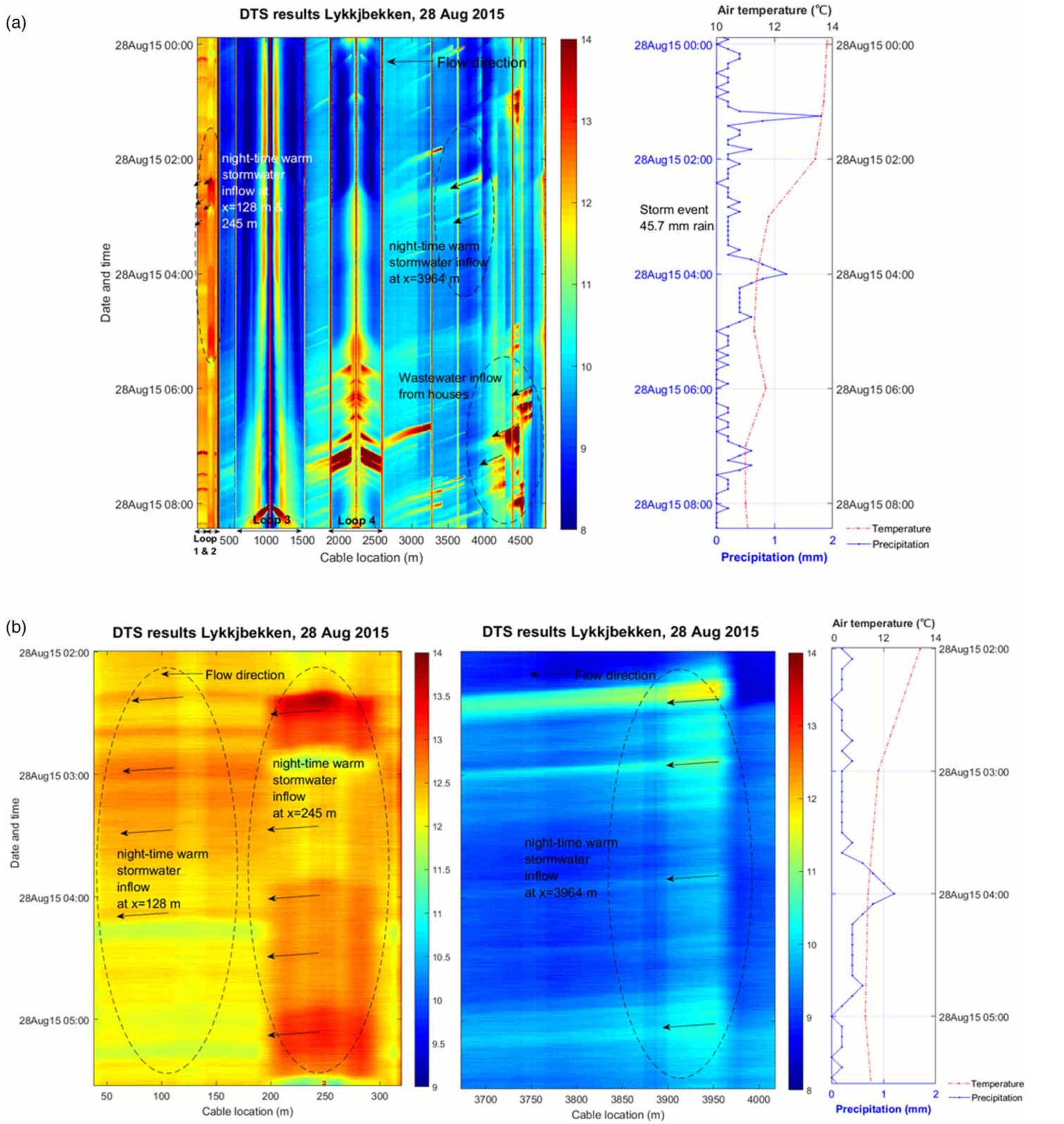

Figure 4 | (a) DTS monitoring results in foul sewer network of Lykkjbekken catchment (left), with 5 min precipitation and hourly temperature data (right), 27–28 August, 2015, and (b) a closer view of rainfall-derived I/I at x = 128 m and 245 m (left) and x = 3,964 m (middle), with 5 min precipitation and hourly temperature data (right). Color-gradient scales indicate temperature (°C).

sewers as house connections and could not be identified via camera inspection.

After finding and identifying the I/I sources, it is important to prioritize them for rehabilitation by assessing their severity. In misconnected storm drains to sanitary sewers, this can be estimated roughly by comparing the size of the impervious areas connecting to storm drains. However, this method is not so precise and is not applicable in all

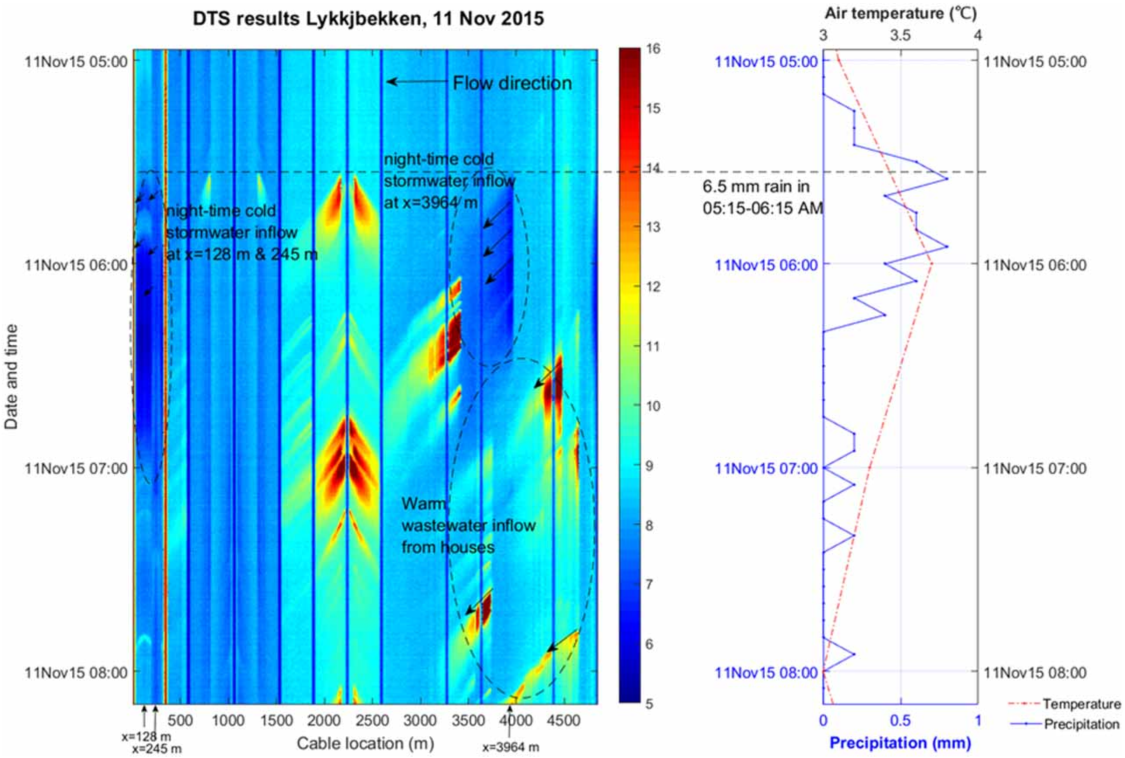

Figure 5 | DTS monitoring data in foul sewer network of Lykkjbekken catchment (left), with 5 min rainfall depth and hourly temperature data (right) for November 11, 2015. Color-gradient scales indicate temperature (°C).

types of I/I sources, and therefore a more accurate method is needed. To accurately quantify the unwanted water I/I from individual sources, the thermal behavior of wastewater and unwanted water I/I should be analyzed by the help of conservation of mass and energy, which was described in detail in an article by Beheshti & Sægrov (2018a).

In general, DTS technology is an accurate and applicable method for sewer monitoring and I/I detection. Continuous sewage temperature measurement over long periods gives the possibility to monitor thermal behavior in the sewer network under different conditions and locate potential I/I sources from groundwater, rainfall, snowmelt, and illicit connections. Furthermore, the frequency of sporadic I/I failures in pipelines can be detected with long-term temperature monitoring, which is an important factor in evaluating pipeline needs and determining I/I rehabilitation measures (e.g. spot repair, renovation or replacement). Although DTS is feasible and has advantages over alternative methods for detecting I/I, there is a high initial cost for instrumentation and installation. Furthermore, expert technicians are required for installation, operation and data analysis. Therefore, further development is necessary to make DTS a practical and widely available method for sewer monitoring.

CONCLUSIONS

In this study, the DTS technique was applied for the first time in Norway in tandem with CCTV and smoke testing to detect I/I sources in a separate sewer network. The application of DTS in the Lykkjbekken catchment in Trondheim was demonstrated to be a strong and feasible method for I/I detection. DTS detected three more I/I sources than CCTV. Smoke testing confirmed the DTS results by identifying illicit stormwater connections from downspouts in two of the I/I sources.

Rainfall-derived I/I affects the thermal behavior of sewage to a great extent. Rainfall inflows coinciding with warm days (relative to in-sewer water) can be detected as warm spills into the sewer networks, while cold I/I corresponds to rain events on cold days. Therefore, assessing the surrounding air temperature is essential in similar studies.

After detecting the I/I sources, their status and severity can be assessed to prioritize them in sewer rehabilitation plans. In misconnected storm drains, this can be roughly evaluated by comparing the size of the impervious areas connecting to misconnected storm drains. However, analyzing the thermal variations of the wastewater in I/I locations

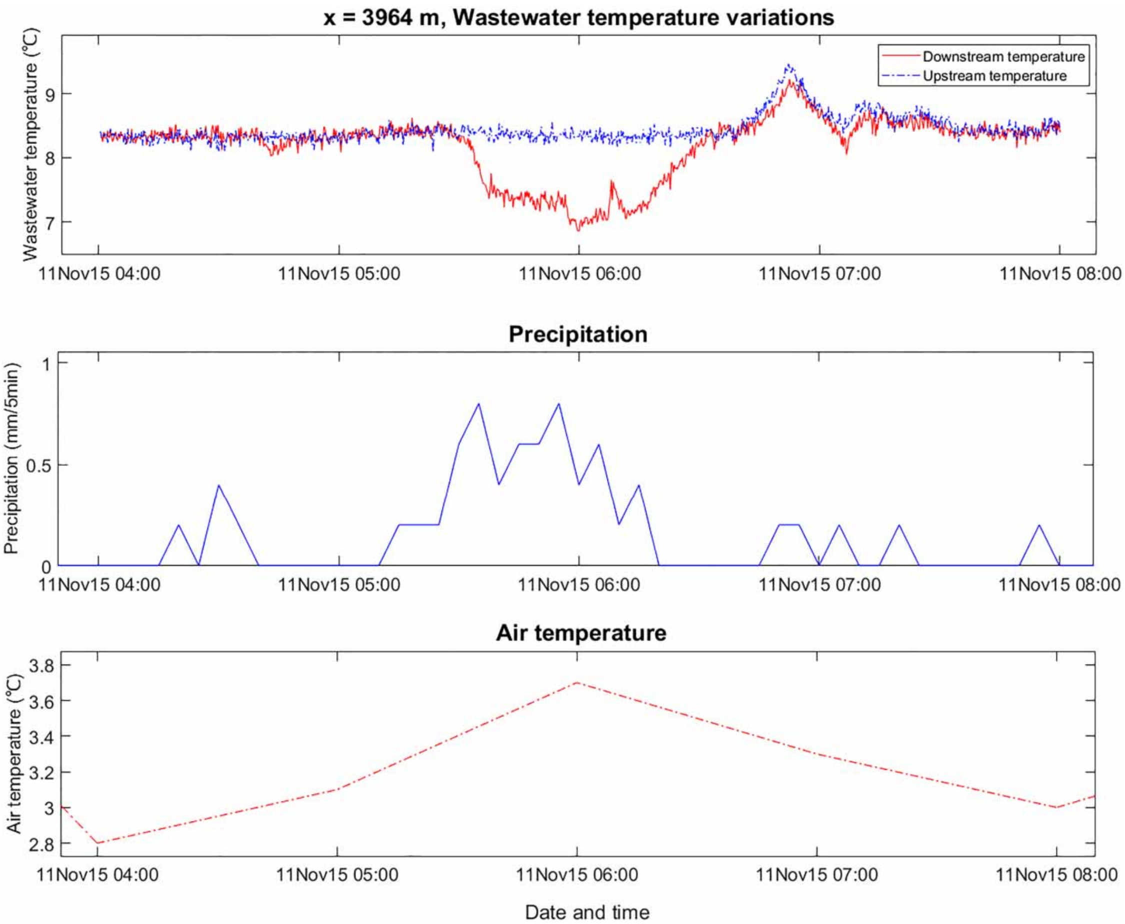

Figure 6 | Time transect of wastewater temperature variations in upstream and downstream of a rainfall-derived I/I source in x = 3,964 m in addition to rainfall intensity, and air temperature on November 11, 2015.

is an accurate way to quantify all types of I/I in the sewer network and assess the status of individual I/I sources (Beheshti & Sægrov 2018a).

This case study provides sewer operators a framework for identifying problematic parts of a pipeline and make smart decisions (i.e. spot repairing, renovation or full replacement of the sewer pipeline). Identifying and remedying I/I sources decreases extraneous water in the sewer system, which is essential for sustainable sewer asset management. However, DTS is a semi-commercial technique with the high initial cost and requirements to expert installation and operation, so improvements are necessary before the method becomes more practical and widely accessible for I/I assessment.

ACKNOWLEDGEMENTS

The authors acknowledge the wastewater department of Trondheim Municipality, as well as its personnel, especially Kristin Greiff Johnsen and Vidar Figenschou for their support. Thanks also to Remy Schilperoort, Cornelis de Haan and Erik Liefting at PARTNERS4URBANWATER for their invaluable advice and cooperation. The authors are also grateful to Michael Waak at NTNU for his valuable help and comments.

REFERENCES

Beheshti, M. & Sægrov, S. 2018a Quantification assessment of extraneous water infiltration and inflow by analysis of the thermal behavior of the sewer network. *Water* **10** (8), 1070.

Beheshti, M. & Sægrov, S. 2018b Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway. *Urban Water Journal* **15** (1), 1–8.

Beheshti, M., Sægrov, S. & Ugarelli, R. 2015 Infiltration/inflow assessment and detection in urban sewer system. *Vann* **1**, 24–34. Available at: https://vannforeningen.no/wp-content/uploads/2015/01/Beheshti.pdf.

Ciocca, F., Lunati, I., Van de Giesen, N. C. & Parlange, B. M. 2012 Heated optical fiber for distributed soil-moisture measurements: a lysimeter experiment. *Vadose Zone Journal* **11** (4).

Dakin, J. P., Pratt, D. J., Bibby, G. B. & Ross, J. N. 1985 Distributed optical fibre Raman temperature sensor using a semiconductor light source and detector. *Electronics Letters* **21** (13), 569–570.

de Jong, S. A. P., Slingerland, J. D. & van de Giesen, N. C. 2015 Fiber optic distributed temperature sensing for the determination of air temperature. *Atmospheric Measurement Techniques* **8** (1), 335–339.

Ficklin, D. L., Luo, Y., Stewart, I. T. & Maurer, E. P. 2012 Development and application of a hydroclimatological stream temperature model within the Soil and Water Assessment Tool. *Water Resources Research* **48** (1), 1–16.

Harris, R. J. & Dobson, C. 2006 Sewer Pipe Infiltration Assessment: Comparison of Electro-Scan, Joint Pressure Testing and CCTV Inspection. In: *Pipeline Division Specialty Conference 2006*. American Society of Civil Engineers (ASCE), Chicago, IL, USA.

Hoes, O. A. C., Schilperoort, R. P. S., Luxemburg, W. M. J., Clemens, F. H. L. R. & van de Giesen, N. C. 2009 Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing. *Water Research* **43** (20), 5187–5197.

Jansen, J., Stive, P., Van de Giesen, N., Tyler, S., Steele-Dunne, S. & Williamson, L. 2011 Estimating soil heat flux using distributed temperature sensing. *IAHS Publications* **343**, 140–144.

Johansson, S. 1997 *Seepage Monitoring in Embankment Dams*. PhD thesis, Royal Institute of Technology, Sweden.

Krause, S., Taylor, S. L., Weatherill, J., Haffenden, A., Levy, A., Cassidy, N. J. & Thomas, P. A. 2013 Fibre-optic distributed temperature sensing for characterizing the impacts of vegetation coverage on thermal patterns in woodlands. *Ecohydrology* **6**, 754–764.

Mohseni, O. & Stefan, H. G. 1999 Stream temperature/air temperature relationship: a physical interpretation. *Journal of Hydrology* **218** (3–4), 128–141. Available at: https://www.sciencedirect.com/science/article/pii/S0022169499000347.

Pazhepurackel, V. 2009 *Fremdwasserbestimmung in Kanalisationen Mittels Faseroptischer Temperaturmessungen. (External Water Determination in Sewer Systems by Fiber-Optic Temperature Measurements.)*. MSc thesis, ETH Zürich, Switzerland.

Petrides, A. C., Huff, J., Arik, A., Van de Giesen, N., Kennedy, A. M., Thomas, C. K. & Selker, J. S. 2011 Shade estimation over streams using distributed temperature sensing. *Water Resources Research* **47** (W07601).

Schilperoort, R. 2011 *Monitoring as A Tool for the Assessment of Wastewater Quality Dynamics*. PhD thesis, Delft University of Technology, Delft, The Netherlands.

Schilperoort, R. P. S. & Clemens, F. H. L. R. 2009 Fibre-optic distributed temperature sensing in combined sewer systems. *Water Science and Technology* **60** (5), 1127.

Schilperoort, R., Hoppe, H., De Haan, C. & Langeveld, J. 2013 Searching for storm water inflows in foul sewers using fibre-optic distributed temperature sensing. *Water Science and Technology* **68**, 1723–1730.

Selker, J. S., Thévenaz, L., Huwald, H., Mallet, A., Luxemburg, W., van de Giesen, N., Stejskal, M., Zeman, J., Westhoff, M. & Parlange, M. B. 2006 Distributed fiber-optic temperature sensing for hydrologic systems. *Water Resources Research* **42** (W12202).

Shen, X., Yang, Y., Cong, B., Ding, F., Qiu, B. & Ye, L. 2016 Temperature measurement of power cable based on distributed optical fiber sensor. *Journal of Physics: Conference Series* **679** (12053), 1–2.

Stefan, H. G. & Preud'homme, E. B. 1993 Stream temperature estimation from air temperature. *JAWRA Journal of the American Water Resources Association* **29** (1), 27–45.

Tuccillo, M. E., Wilmut, C., Feeney, C., Martel, K. & Selvakumar, A. 2011 Field demonstration of electro-scan defect location technology for condition assessment of wastewater collection systems. *Water Environment Federation* **17**, 265–281.

Tuomari, D. & Thompson, S. 2003 Sherlocks of storm water' effective investigation techniques for illicit connection and discharge detection. In: *Proceedings of the National Conference on Urban Storm Water*, February 17–20, 2003, Chicago, IL, USA.

Tyler, S. W., Selker, J. S., Hausner, M. B., Hatch, C. E., Torgersen, T. & Thodal, C. E. 2009 Environmental temperature sensing using Raman spectra DTS fiber-optic methods. *Water Resources Research* **45** (4).

Vosse, M., Schilperoort, R., de Haan, C., Nienhuis, J., Tirion, M. & Langeveld, J. 2013 Processing of DTS monitoring results: automated detection of illicit connections. *Water Practice and Technology* **8** (3–4), 375–381.

Webb, B. W., Hannah, D. M., Moore, R. D., Brown, L. E. & Nobilis, F. 2008 Recent advances in stream and river temperature research. *Hydrological Processes* **22** (7), 902–918.

Westhoff, M. C., Gooseff, M. N., Bogaard, T. A. & Savenije, H. G. H. 2011 Quantifying hyporheic exchange at high spatial resolution using natural temperature variations along a first-order stream. *Water Resources Research* **47** (W10508).

Yilmaz, G. & Karlik, S. E. 2006 A distributed optical fiber sensor for temperature detection in power cables. *Sensors and Actuators A: Physical* **125** (2), 148–155.

First received 13 July 2018; accepted in revised form 2 January 2019. Available online 13 February 2019