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# Fibre-optic distributed temperature sensing in combined sewer systems

R. P. S. Schilperoort and F. H. L. R. Clemens

## ABSTRACT

This paper introduces the application of fibre-optic distributed temperature sensing (DTS) in combined sewer systems. The DTS-technique uses a fibre-optic cable that is inserted into a combined sewer system in combination with a laser instrument that performs measurements and logs the data. The DTS-technique allows monitoring in-sewer temperatures with dense spatial and temporal resolutions. The installation of a fibre-optic cable in a combined sewer system has proven feasible. The use of a single instrument in an easy accessible and safe location that can simultaneously monitor up to several hundreds of monitoring locations makes the DTS set-up easy in use and nearly free of maintenance. Temperature data from a one-week monitoring campaign in an 1,850 m combined sewer system shows the level of detail with which in-sewer processes that affect wastewater temperatures can be studied. Individual discharges from house-connections can be tracked in time and space. With a dedicated cable configuration the confluence of wastewater flows can be observed with a potential to derive the relative contributions of contributary flows to a total flow. Also, the inflow and in-sewer propagation of stormwater can be monitored.

**Key words** | combined sewer systems, distributed temperature sensing, fibre-optics, in-sewer processes, temperature monitoring

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## INTRODUCTION

In-sewer and on-line monitoring of wastewater quality and quantity parameters can be a challenging task considering the many examples in literature where extensive sensor calibration, frequent maintenance and a nearly immediate data validation are necessary to obtain a reliable, long-term data-set (see e.g. Gruber *et al.* 2006). To enhance in-sewer monitoring easily monitored (indicator-) parameters such as wastewater temperature and conductivity are considered (Schilperoort *et al.* 2006). A (for sewer applications) new monitoring technique allows monitoring of in-sewer temperatures with dense spatial and temporal resolutions. The technique, fibre-optic distributed temperature sensing (DTS), uses a fibre-optic cable that is inserted into a combined sewer system. A connected laser instrument performs the measurements and logs the data.

The objective of this paper is to introduce this DTS-method for application in combined sewer systems. It aims at examining the feasibility of the application of the monitoring technique in combined sewer systems. Also, it considers the possibilities the DTS data offers to study in-sewer processes that affect in-sewer temperatures. In the paper, the DTS technique is explained, a description of the application of the method in a Dutch municipality is described, and finally results of the experiments are presented and discussed.

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## FIBRE-OPTIC DISTRIBUTED TEMPERATURE SENSING

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

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 determined using the measured travel time and known travel speed (in optic fibres typically 2/3 of the speed of light in vacuum). The same reflected signal is then analysed for Raman backscatter. Raman scattering 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 (Lopez-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, with any DTS system there is a trade-off between temporal resolution, spatial resolution and temperature precision. In general, more available pulses – both in time and space – for a single measurement value lead to better temperature precision. As an example, a 2,000 m fibre-optic cable provides approximately 0.1°C precise temperature readings when measuring with a spatial resolution of 2 m and a temporal resolution of 1 minute. Increasing the measurement frequency to once per 15 seconds (and hence reducing the available pulses by approximately one fourth) reduces the precision to approximately 0.2°C.

In this paper's case-study a fibre-optic cable was 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, stainless steel, kevlar, metal braiding and PE. Notwithstanding the protective layers, tests on similar cables have shown that abrupt step-wise changes in temperature are almost fully apparent within the 15 seconds minimum time

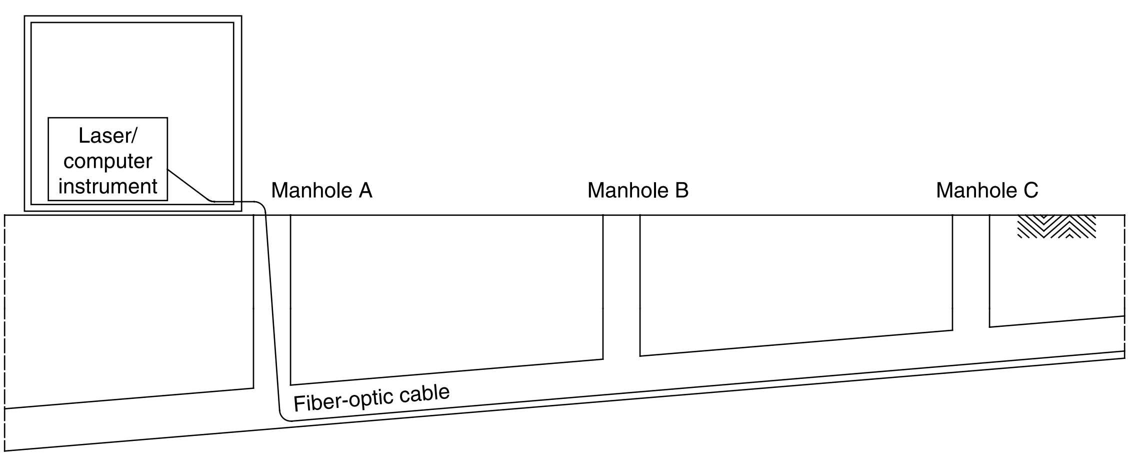


**Figure 1** | Set-up of in-sewer DTS monitoring.

interval between readings (Selker *et al.* 2006*a*). The used laser/computer instrument is a HALO DTS (Sensornet, London, England).

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.* 2006*b*). Naturally, this kind of calibration must be carried out before installation of the cable in a sewer system. Alternatively, the cable can be calibrated after installation by inserting two small and well-separated sections of the cable (e.g. two 8 m sections 500 m apart) in an environment with a known constant temperature (e.g. ice-bath). In Figure 2 temperature readings of two diver sensors installed directly next to the fibre-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 sewer pipe requires pulling a rope from manhole A to manhole B (see Figure 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 fibre-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. After pulling the entire length of the cable from A to B, steps are repeated to get from manhole B to manhole C. This way, the installation of a 1,000 m cable takes a 7-persons team approximately 1 day. This can be improved using e.g. a longer hose on the sewer flushing device to increase lengths between A and B. Bends 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 fibre. After connecting the fibre-optic cable to the HALO DTS system and a short initialization, results are immediately available in ASCII data files per time step. For small spatial and temporal resolutions data quickly builds: a one week monitoring campaign using a 2,000 m cable with a 30 seconds measuring interval and a 2 m spatial resolution gives a dataset containing approximately $20 \times 10^6$ temperature observations.

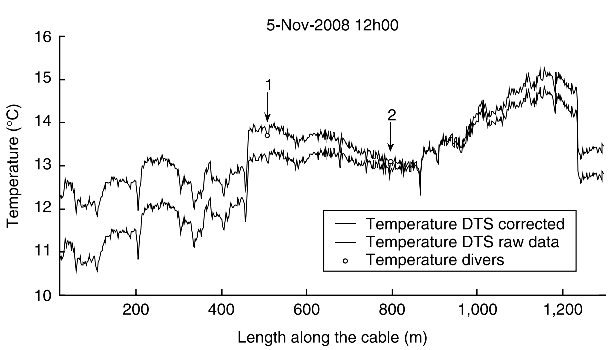


**Figure 2** | Calibration of a DTS measurement.

## APPLICATION IN A COMBINED SEWER SYSTEM

A DTS monitoring system has been set up in the Rietkampen area in the municipality of Ede in the Netherlands. A fibre-optic cable was introduced in a combined sewer system over a length of approximately 1,850 meters. This sewer section drains an area of about $2\,km^2$ with a predominant residential function (± 15,000 inhabitants) and some light commercial functions (shops, cinema). Figure 3 (lower graph) shows a longitudinal profile of the considered sewer section. At the most downstream manhole, which is just upstream a pumping station that pumps the wastewater to a nearby treatment plant, the computer/laser instrument was stored outside the sewer system in a mini sea-container. Over the first 850 meters the sewer is merely a collector sewer (pipe diameters ranging from 800 to 1,500 mm) without individual house-connections. At nine locations side-connections contribute wastewater to the collector sewer, in the graph indicated by circles. Between $x = 850$ m and $x = 1{,}250$ m the considered sewer is a transport line that carries the wastewater underneath a main road without any house- or side-connections. A combined sewer overflow can be found at $x = 1{,}280$ m. Further upstream, the cable is situated in a 'normal' sewer system with many individual house-connections and contributary connections. For dry weather situations flow increases in downstream direction: the most upstream section can be without flow whereas flow measurements at the most downstream section show normal DWF values of around $200\,m^3/h$.

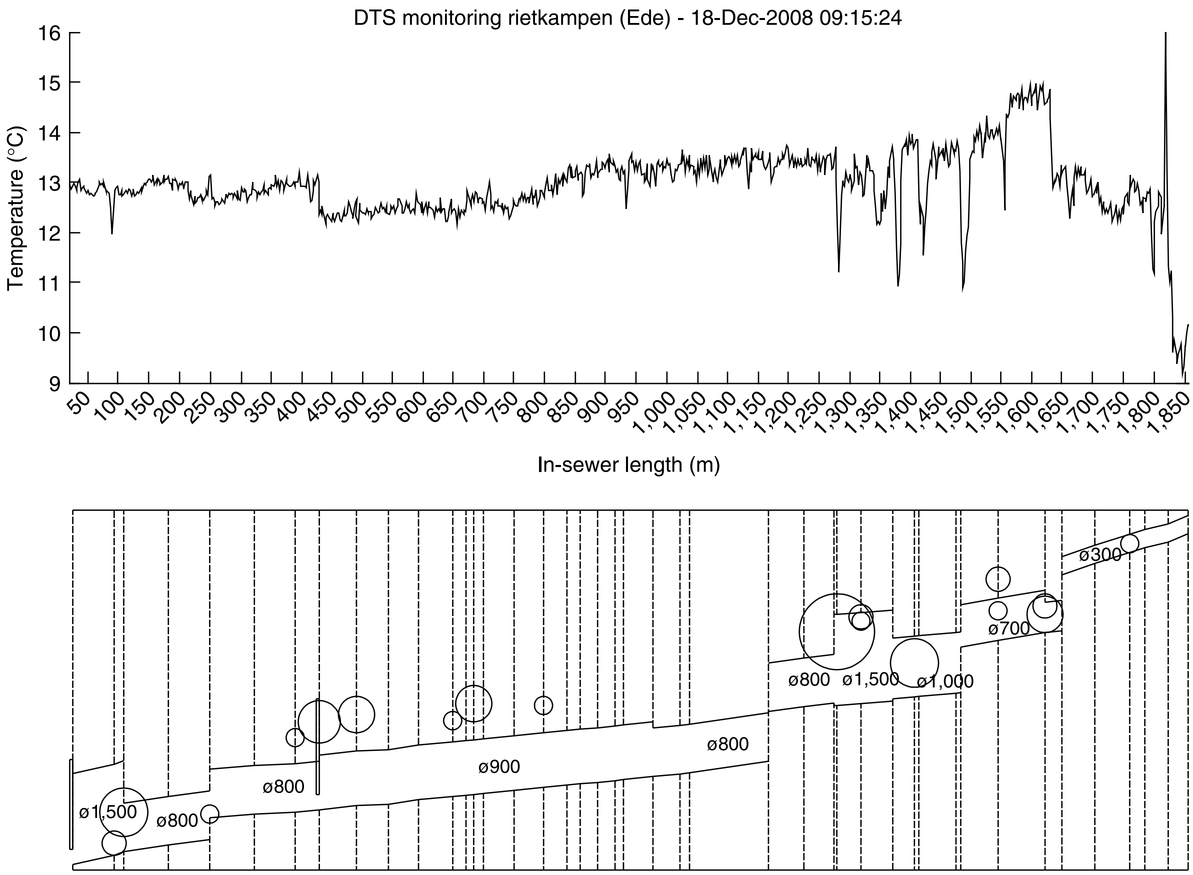


**Figure 3** | (upper graph) DTS monitoring results for 18 December 2008 09h15. Dashed vertical lines represent 50 m sewer lengths; (lower graph). Longitudinal profile of the studied sewer length. Dashed vertical lines represent the locations of manholes with any side-connections indicated by circles. The two graphs vertically correspond.

A DTS monitoring campaign took place 15–23 December 2008. Programmed temporal and spatial resolutions were 30 seconds and 2 meters, respectively. All presented results have a precision of approximately 0.15°C.

## RESULTS AND DISCUSSION

### Monitoring results

Figure 3 shows DTS monitoring results for 18 December 2008 09:15:24. Data for these results have been recorded in the 30 seconds prior to the registration time stamp. The graph consists of 925 individual temperature measurements, one for each two meter section along the 1,850 m cable. Temperatures in the downstream 2/3 part of the cable range between 12°C and 14°C; temperatures in the upstream 1/3 part of the cable can be well outside this range. Sharp temperature drops (as e.g. around $x = 1{,}280$ m and $x = 1{,}490$ m) to values of 11°C to 12°C are due to the cable being lifted (just) above wastewater level. This can be caused by an invert level difference where the cable 'travels' from one level to the other via the shortest route hovering over the wastewater, instead of following the z-shaped course of the wastewater. Also, in some cases at sharp bends in the sewer line the cable was pulled too taut during installation, causing the cable to move up the circular concrete pipes to the widest part of the pipe and hence being lifted from the wastewater. At these locations in-sewer air temperatures rather than wastewater temperatures are recorded.

Sharp temperature increases in the upstream section of the cable (e.g. at $x = 1{,}818$ m and between $x = 1{,}560$ m and $x = 1{,}630$ m) are due to discharges from house-connections. Temperatures up to 35°C have been recorded. Logically corresponding to domestic use, these increases occur

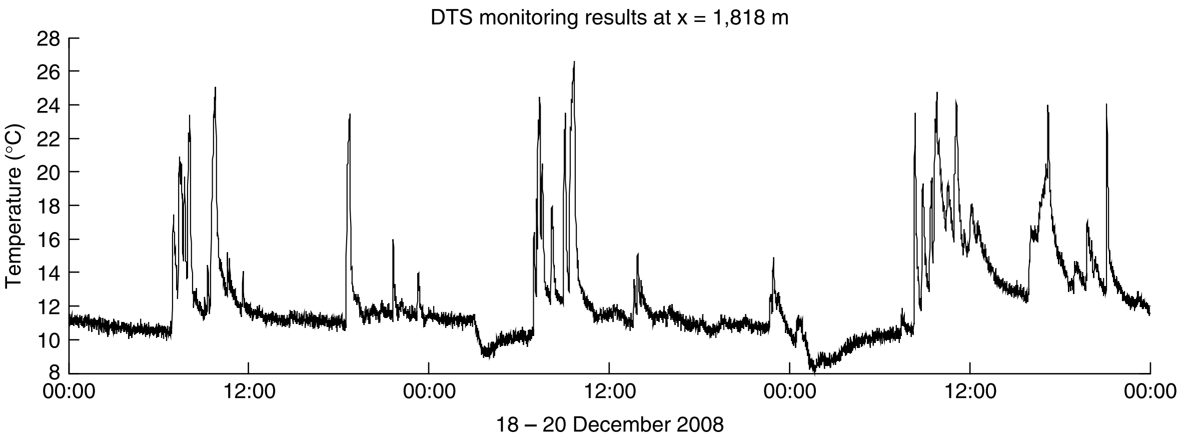


**Figure 4** | DTS monitoring results for 18–20 December 2008 at location $x = 1{,}818$ m.

mainly during morning and evening hours whereas hardly any warm water discharges are observed during the night, see Figure 4. The lowest temperatures in the early hours of 19 and 20 December in Figure 4 are due to the same phenomenon that causes the low temperatures over the last 30 meters of cable in Figure 3: no wastewater present in the sewer. Again, at these moments and locations in-sewer air temperatures rather than wastewater temperatures are recorded. Values for air temperatures in empty sewers are lower than for sewers where the cable is situated just above the wastewater. In the latter situation in-sewer air temperatures are influenced by the relatively warm wastewater.

Plotting monitoring results of a 24-hour dry weather period in the same graph yields Figure 5. Temperature variations over a day decrease in downstream direction. In the upper 400 meter of the cable flow is limited, allowing the cable to register individual discharges. Between $x = 1{,}450$ m and $x = 1{,}250$ m household connections are present, but the amount of energy in individual discharges has often become too limited compared to the energy content of the main flow to be noticed by the DTS system. Undisturbed flow between $x = 1{,}250$ m and $x = 850$ m reduces (1) the temperature variation over a day from $\pm 2$°C to $\pm 1$°C due to dispersion of energy and (2) the average temperature due to energy loss during transport.

## Flow ratio calculations using DTS results

The temperature increase at $x = 430$ m that can be observed in both Figures 3 and 5 is due to the inflow of relatively

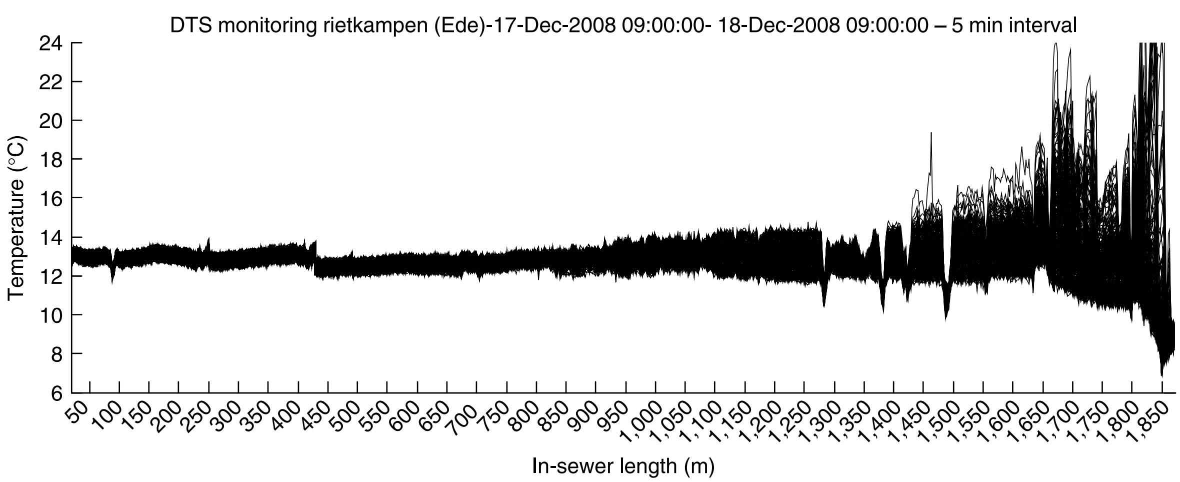


**Figure 5** | DTS monitoring results for 17 December 2008 09h00–18 December 2008 09h00. A total of 288 plots (24 hours, every 5 minutes) have been plotted in one graph.

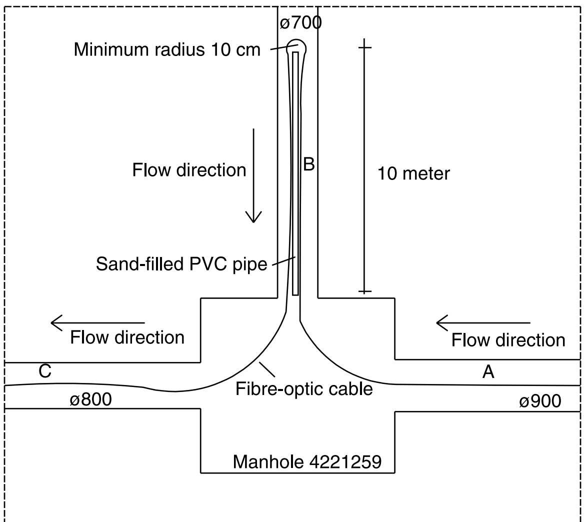


**Figure 6** | Lay-out of cable loop that allows monitoring wastewater temperatures in the main collector sewer (locations A and C) and in a contributary sewer (location B).

warm water from a side-connection (ø700 mm diameter). Temperatures of wastewater in the contributary before discharging to the collector sewer have been monitored by the DTS system thanks to a loop in the cable. At the manhole, instead of continuing directly into the next part of the collector sewer, the cable has been inserted into the contributary in a loop of approximately 10 meters, see Figure 6. The cable has been attached to a ø32 mm sand-filled PVC pipe that holds the cable in place.

This cable configuration allows simultaneous monitoring of wastewater temperatures at three locations: in the main collector both upstream (location A) and downstream (location C) of the side-connection and in the contributary sewer pipe (location B). Figure 7 shows monitoring results for these locations for a 2-day period. In general, wastewater temperatures directly downstream the manhole are $\pm 1$°C higher than temperatures directly upstream the manhole. Wastewater temperatures from the contributary sewer are on average several degrees higher than in the main collector.

Wanner *et al.* (2004) show that -in undisturbed flow-wastewater temperature reductions due to energy exchange with its surroundings over lengths of 1 km are of the order of 0.1°C. Hence, over short distances (10 m in each direction) wastewater energy loss to its surroundings is negligible. As a result, at any moment the energy contained by the wastewater directly downstream the manhole should be the sum of energy contained by wastewater directly upstream the manhole plus any energy in the contributary flow. In other words, wastewater temperatures at location C should be the flow-proportional average of wastewater temperatures at A and B. Using conservation of flow and energy two unknown flows (e.g. $Q_A$ and $Q_B$) can be expressed as a percentage of a known flow (e.g. $Q_C$) using the measured temperature values:

$$Q_A = \frac{(T_C - T_B)}{(T_A - T_B)} Q_C \quad \text{and} \quad Q_B = \frac{(T_A - T_C)}{(T_A - T_B)} Q_C$$

Applying these equations on the data of 17 and 18 December (Figure 7) yields relative flow contributions of 10–40% for $Q_A$ and 60–90% for $Q_B$ to the total flow $Q_C$. However of a plausible order of magnitude, these percentages have not yet been verified with separate flow measurements. The reliability and accuracy of calculated percentages is subject of further research. An important factor is the representativeness of the DTS temperature measurement for energy content calculation of a flow. Also, situations that annul the conservation of flow and energy between locations A, B and C (such as backwater effects after a storm event) require further study.

Possibly, a DTS monitoring system using cable loop configurations can ‘transfer’ information on flow quantities further up- or downstream a catchment area. This is particularly interesting if a catchment area is equipped with a relatively reliable form of flow monitoring such as an ultrasonic full-pipe measurement at for instance a downstream pumping station. Installing a DTS system starting at this pumping station and including a cable loop configuration at every junction, the relative contribution of every (often free-flow) contributary could be determined. If the accuracy of the determined contributions is superior to the accuracy of free-flow monitoring results with for instance electro-magnetic or ultrasonic sensors, DTS monitoring can have an added value for in-sewer flow monitoring.

## Monitoring of in-sewer propagation of stormwater

The influence of a (small) storm event on in-sewer temperatures can be seen in Figure 8. The horizontal axis

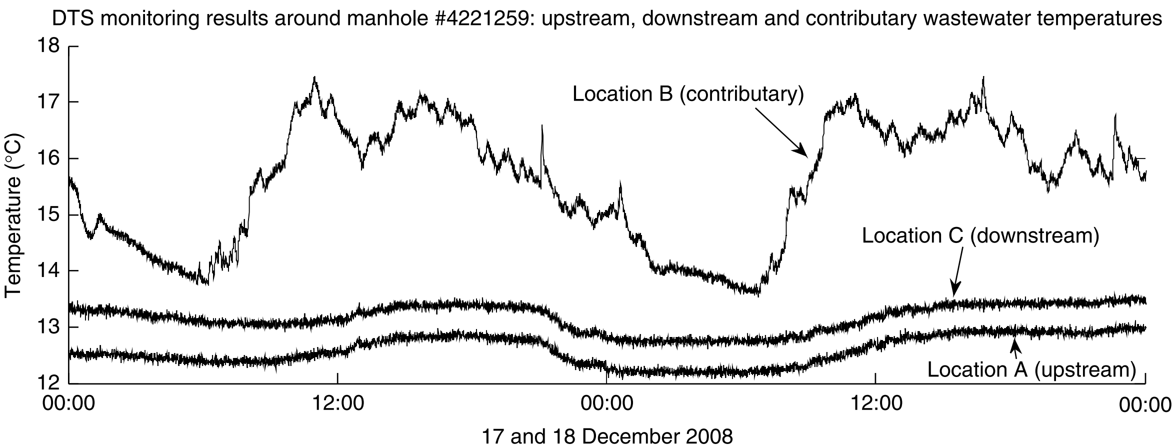


**Figure 7** | DTS monitoring results for 17 and 18 December 2008 in the direct vicinity of manhole #4221259: upstream (location A), downstream (location C) and contributary (location B) wastewater temperatures.

represents the length along the cable from $x = 20$ m where the cable enters the sewer to $x = 1{,}850$ m at the end of the cable; the vertical axis represents a time-span of six hours: Friday 19 December 2008 00h00–06h00. The figure consists of $925 \times 720$ pixels (respectively 1,850 m divided by a 2 m spatial resolution and 6 hours divided by a 30 seconds temporal resolution) that each represent a measured temperature value. Each pixel is colored in accordance with the color bar next to the graph spanning 11°C to 18°C.

Between 00h00 and 03h00 individual discharges from house-connections can be distinguished at the upstream part of the cable. The location, duration and propagation of the discharges can be derived from the shape of the 'warm water plumes'. Between 03h00 and 04h00 a small storm event produces approximately 2 mm of rain. A near immediate response with lower wastewater temperature values can be observed for the most upstream 300 m of the cable. Between $x = 850$ m and $x = 1{,}550$ m wastewater temperatures do not seem to be immediately influenced by inflowing stormwater, but only later when a cold water front travels downstream at a velocity of about 0.38 m/s. Below $x = 850$ m no reaction to the storm event can be observed. Possibly, the volume of stormwater entering the sewer system is too limited to significantly influence the temperature of the increasing amount of flow.

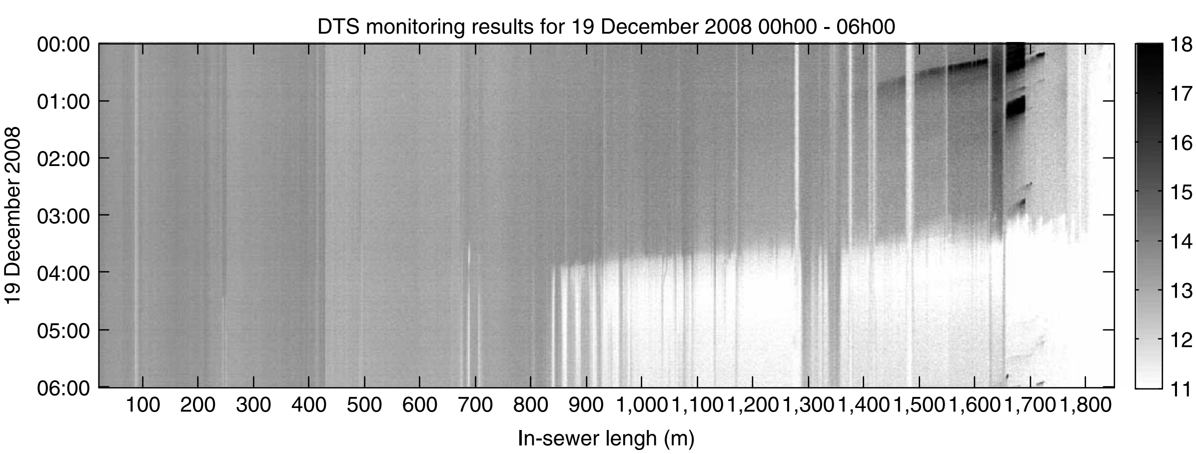


**Figure 8** | The influence of a storm event on DTS monitoring results on 19 December 2008 00h00–06h00.

## CONCLUSIONS

Fibre-optic distributed temperature sensing is a powerful tool to study several in-sewer processes that influence wastewater temperatures. The installation of a fibre-optic cable in a combined sewer system has proven feasible. The use of a single instrument that performs the measurements and logs the data in an easy accessible and safe location and that can simultaneously monitor up to several hundreds of monitoring locations makes the DTS set-up easy to use and nearly free of maintenance.

Data from a one-week monitoring campaign in an 1,850 m combined sewer system shows the level of detail with which in-sewer processes can be studied. Individual discharges from house-connections can be tracked in time and space. With a dedicated cable configuration the confluence of wastewater flows can be observed with a potential to derive the relative contributions of contributary flows to a total flow. Also, the inflow and in-sewer propagation of stormwater can be monitored. More data collecting (for instance during large storm events) and subsequent data interpretation are ongoing to further develop the potential of DTS monitoring for in-sewer process observation.

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