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Article

Quantification Assessment of Extraneous Water Infiltration and Inflow by Analysis of the Thermal Behavior of the Sewer Network

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Abstract: Infiltration and inflow (I/I) of unwanted water in separate urban sewer networks are critical issues for sustainable urban water management. Accurate quantification of unwanted water I/I from individual sources into a sewer system is an essential task for assessing the status of the sewer network and conducting rehabilitation measures. The study aim was to quantify extraneous water I/I into a sanitary sewer network by a temperature-based method, i.e., fiber-optic distributed temperature sensing (DTS), which was applied for the first time in a separate sewer network of a catchment in Trondheim, Norway. The DTS technology is a relatively new technology for sewer monitoring, developed over the past decade. It is based on continual temperature measurement along a fiber-optic cable installed in the sewer network. The feasibility of this method has been tested in both experimental discharges and for the rainfall-derived I/I. The results achieved from the monitoring campaign established the promising applicability of the DTS technique in the quantification analysis. Furthermore, the application of this method in quantifying real-life, rainfall-derived I/I into the sewer system was demonstrated and verified during wet weather conditions.

Keywords: distributed temperature sensing (DTS); extraneous water infiltration and inflow (I/I); rainfall-derived infiltration and inflow; sewer system; stormwater management; sustainable urban water management

1. Introduction

Urban sewer systems are one of the most important city lifelines, conveying wastewater and stormwater to treatment plants. Representing a high asset value [1], urban sewer systems in most cities all over the world are undergoing deterioration due to aging [2]. Thus, accurate monitoring, maintenance and rehabilitation are necessary for their preservation. However, their underground location makes it difficult to monitor and understand their status. Infiltration and inflow (I/I) of unwanted water into separate sewer networks are significant challenges in urban sewer systems. Answering questions about location and magnitude of unwanted water intrusion is essential for understanding the sewer network performance for sustainable urban water management.

I/I of unwanted water into separate sewer networks have negative outcomes on social, environmental and economic aspects of sustainable urban wastewater management, as well as on chemical and energy resources. These undesirable phenomena trigger overloading of sewer networks and wastewater treatment plants. Moreover, I/I increase the risk of local flooding and sanitary sewer overflow in urban areas, while escalating pumping operation time. All of these consequences are followed by diminished performance of sewer systems and amplified costs, energy consumption, maintenance and operation, and negative urban and environmental issues [3–6].

In general, I/I from extraneous and illicit water are equal to ~50% of the wastewater volume [3,7]. Extraneous water refers to I/I from rain-induced infiltration, direct stormwater inflow, groundwater infiltration, drain water, leakages from the drinking water network and other extraneous sources in separate sewer systems [5,8,9], which may include illicit and faulty cross-connections between stormwater outlets and the wastewater system [6,8]. In some cities, extraneous water can even exceed the wastewater volume [4]. Therefore, it is important to perform rehabilitation measures to manage and control this issue.

There are various conventional and innovative techniques available for I/I measurement in sewer systems, such as the flow-rate measurement and tracer methods [3,4]. The flow-rate measurement is a method based on analyzing the water balance and diurnal flow rate in dry weather conditions and assigning the minimum nighttime flow as the I/I-related flow [3,5,10]. However, this method can be inaccurate due to sewer overflow in overloaded systems [5]. Furthermore, the assumption of having no flow during nighttime, the omission of sewer network exfiltration, and instrumental errors during flow measurement—especially in shallow wastewater flows—makes the flow-rate measurement method unreliable. Tracer methods, e.g., pollutant indices, the stable isotopes method, and chemical tracers, are other I/I measurement methods in sewer systems. The pollutant indices methods are based on analyzing the in-sewer pollutant time series, such as chemical oxygen demand, total nitrogen and total phosphorus, for evaluating the I/I volume [5,11]. Alternatively, stable isotopes of water molecules ($\delta^{18}O$ and $\delta^{2}H$) can be used as natural tracers for assessing the I/I into the sewer networks [3,10]. These tracer-based methods can provide accurate I/I assessments but require intensive field measurement and laboratory analysis, especially in large catchments [5].

In contrast to the conventional methods, adaptive and innovative I/I detection and measurement techniques like distributed temperature sensing (DTS) may have higher accuracy with fewer environmental risks. The DTS technology is a monitoring technique developed in the 1980s in the UK for testing telecommunication cables [12,13]. The technique is based on analyzing system behavior by measuring the temperature along spans of fiber-optic cables over time [14]. The DTS method has become a broadly applicable technique in different fields, i.e., leakage control in dams and the oil industry, fire control, and pipeline monitoring [15,16]. Furthermore, DTS has various applications in the field of water, such as stream hydrology [17–19], limnology [20], groundwater science [21–23], and urban sewer systems research [7,8,24]. The application of DTS in full-scale sewer systems has been developed since 2009, when Pazhepurackel (2009) and Schilperoort and Clemens (2009) tested this technology in combined sewers [24,25]. Moreover, this method was applied successfully in separate storm sewers for detecting illicit connections from sanitary sewers [7,8,26]. Schilperoort (2011) has reported the successful application of fiber-optic DTS cables in separate sanitary sewer systems for localizing the extraneous water I/I from stormwater inflow, groundwater infiltration and illicit connections [27]. Among different I/I detection methods that has been previously studied by Beheshti et al. (2015) [3], the DTS technology was chosen to be the main focus in the present study.

Over the last decade, the detection of I/I in sewer systems has attracted a lot of attention, while there are few studies on the I/I quantification issue. I/I quantification is a valuable tool for assessing the condition of the sewer network. The aim of this study was to scrutinize and quantify the extraneous water I/I entering the separate sewer systems from individual I/I sources by analyzing the thermal behavior of the wastewater. Therefore, the feasibility of the DTS for I/I quantification was investigated for the first time in a full-scale separate sewer system in Trondheim, Norway. For this reason, experimental artificial inflows with different temperatures and discharges were applied to the measurement campaign. Moreover, to demonstrate the feasibility of this method in the full-scale system, rainfall-derived I/I quantification was applied during wet weather conditions. The results can be used for evaluating the severity of individual I/I sources in each pipe section and decreasing I/I into the sewer system with rehabilitation.

2. Methodology

2.1. Distributed Temperature Sensing (DTS) Technology

Fiber-optic distributed temperature sensing (DTS) is a technology for sewer monitoring, i.e., detecting illicit connections and extraneous water I/I in sewer systems, that has been used over the past decade. The principle of this method is monitoring the thermal changes in the sewer system by temperature measurement up to several kilometers in continuous time along a fiber-optic cable. This method is a combination of installed fiber-optic cables in the sewer network and a control unit that consists of a laser instrument, an optoelectronic sensor and a computer. Figure 1 illustrates the standard layout of the DTS monitoring technique in a sewer network. The laser instrument emits laser pulses continuously into the fiber-optic cable, the optoelectronic sensor reads the backscattered light, and the computer is responsible for interpreting the receiving values to readable data [8,13,24]. Imperfections along the glass fibers reflect the laser light. The reflection spot of the laser light can be localized as [8,28]:

$$L = c\Delta T/2n \quad (1)$$

where

L: the laser light reflection location;
ΔT: laser light reflection duration from the initial time that laser pulses into the cable;
c: the laser light speed in the fiber (~2/3 of the light speed in vacuum);
n: the reflective index of optical fiber.

It should be noted that the laser light reflects back from the location L to the detector and, therefore, the total length of its travel would be 2 L. Furthermore, the spatial accuracy of the reflection spot is $c\Delta T$.

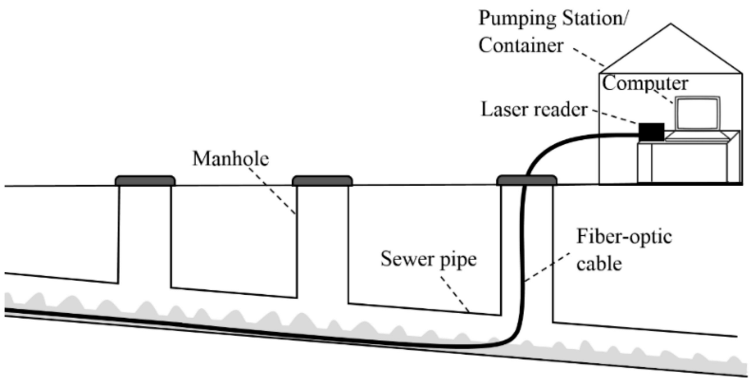

Figure 1. Standard layout of the distributed temperature sensing (DTS) technique in a sewer network and the control unit stored outside the sewer system in a pumping station.

By passing the laser light through the fiber, several mechanisms, such as physical features of the surrounding cable, affect the specifications of the light transmission, and different scatterings with various wavelength and intensity form. This can be interpreted by computer software into physical parameters like temperature for each location along the cable. The most important scatterings are "Raman" and "Rayleigh", which can be used to plot temperature against distance. Raman light consists of two broadband components, Stokes and anti-Stokes, respectively, at longer and shorter wavelengths than the main source laser light [8]. The temperature of each single reflection location is derived from the ratio of thermal-dependent anti-Stokes and thermal-independent Stokes intensities [8,29]. The Rayleigh backscatters have the same wavelength as the laser source and provide information about the reflection location by known light speed and measured travel time [24,29]. The corresponding location of L on the measurement campaign can be defined by using hot water or freeze spray on different locations.

Typically, the DTS system can measure the temperature with time and spatial resolution of 18–60 s and 0.5–2 m, respectively, along the fiber-optic cable functioning as a linear sensor. It is applicable to have cables anywhere in the network to gain information about the thermal behavior of the sewer system and detect the problematic parts of it. Any changes in the temperature of in-sewer water are recorded, and the exact place of the I/I source can be determined. This method can be used in I/I detection in sewer systems, as long as the infiltrated water has a different temperature than in-sewer water [6,8].

The DTS system can be calibrated by putting the fiber-optic cable in a medium with known temperature, e.g., an ice-bath, before installation. For calibration of the cable after installation, the same procedure can be done by reference measurement of more than two calibration sections with a length of at least 10 times the length of the spatial sampling interval coiled cable, which are far from each other [13,17]. In this method, the accuracy of calibration of a DTS system by standard thermometer measurement can yield up to ±0.1 °C [8,27]. Since the signal attenuation process in the fiber-optic cables is in theory completely log-linear, two temperature-offset measurement may be adequate for the calibration process in normal conditions [27]. It is also necessary to do temperature-offset measurements by standard individual thermometers in more than two separated locations along the cable when there are splices and connectors in the cable for calibrating raw DTS data with slope and offset parameters [27]. The long-term installation of fiber-optic cables in the sewer network, however, can trigger a drift in measured temperature, which is typically below 1 °C and can increase up to several degrees centigrade [13]. In this case, dynamic calibration during the entire installation period with the aforementioned methods is needed to correct the offset and control the drift [13]. All these calibration methods were considered in the present study to secure the precision and accuracy of the results.

2.2. Infiltration and Inflow Quantification

DTS technology can be used to characterize I/I entering the sewer system; i.e., quantifying the extraneous water volume entering the sewer system. Schilperoort (2011) proposed a theoretical approach for quantifying discharges [27]. This approach is based on the assumption of temperature and volume differences between extraneous water I/I (T_2, V_2) and the in-sewer water (T_1, V_1), which results in a new temperature and volume (T_3, V_3) in the mixed flow, assuming instantaneous mixing (Figure 2). The inflow share, which is the ratio of the volume of I/I (V_2) and the upstream in-sewer water (V_1), is calculated by Equation (2) [27]. This equation is derived from the conservation laws for energy ($V_1T_1 + V_2T_2 = V_3T_3$) and mass ($V_1 + V_2 = V_3$), as well as the in-sewer wastewater temperature change ($\Delta T = T_3 - T_1$).

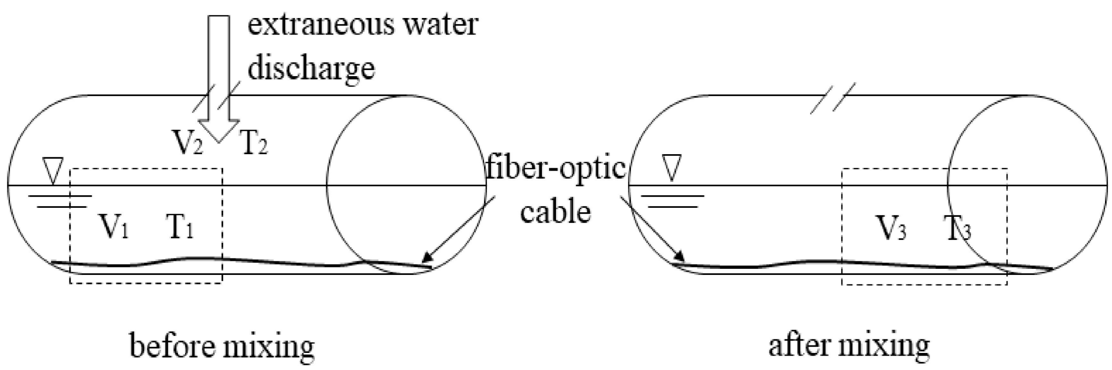

Figure 2. Extraneous water I/I with volume V_2 and temperature T_2 into the separate sewer network with volume V_1 and temperature T_1 resulting in a mixed flow with a new volume V_3 and temperature T_3.

$$\frac{V_2}{V_1} = \frac{\Delta T}{(T_2 - T_1) - \Delta T} \quad (2)$$

The volume (V) in Equation (2) can be replaced with discharge ($Q = \frac{V}{t}$), when 't' is the duration of the I/I mixing process, which is equal for both in-sewer and extraneous flows ($t = t_1 = t_2$). Therefore $\frac{V_2}{V_1} = \frac{Q_2 t_2}{Q_1 t_1} = \frac{Q_2}{Q_1}$ and Equation (2) can be rewritten as:

$$\frac{Q_2}{Q_1} = \frac{\Delta T}{(T_2 - T_1) - \Delta T} \quad (3)$$

The inflow share, or relative contribution of I/I to the sewer network ($\frac{V_2}{V_1}$), can be estimated based on the temperatures of I/I (T_2) and in-sewer water (T_1 and T_3). Moreover, for estimating the absolute contribution, it is necessary to measure the upstream or downstream flow. The accuracy of ΔT is dependent on the thermal precision of the DTS instrument, the defined measurement resolution, and the distance between the measurement site and the instrument [13,27].

Characterizing unwanted water I/I is a challenging task when I/I flow is low relative to the wastewater flow. This may result in the fiber optic cable being submerged completely under water. In this situation, instantaneous mixing cannot happen between the extraneous discharges and the in-sewer water layer above the cable, making it difficult to accurately measure the temperature changes and the location of I/I sources [27]. To avoid this problem in the present study, the analysis was carried out in a separate sanitary sewer, which was not submerged.

2.3. Case System Description

The DTS measurement campaign was conducted in the separate sanitary sewer system of Lykkjbekken catchment in Trondheim, Norway. The catchment was a rural area and located near Jonsvatnet Lake, the main water source of the city (63°22′46″ N 10°32′35″ E–63°21′47″ N 10°29′16″ E). The sewer network of this catchment consisted of small PVC pipes with 160 mm internal diameter, which were rehabilitated and inspected by closed-circuit television (CCTV) camera. The fiber-optic DTS cable was installed in the Lykkjbekken sewer network over a length of around 4.8 km in a three-month monitoring campaign (23 August 2015–20 November 2015). The DTS instrument was a Yokogawa's DTS ×3000 unit, which was stored outside the sewer network in the pumping station and connected to one end of the cable on the downstream side of the sewer pipeline. The temperature with the resolution of 0.01 °C was recorded with time and spatial resolution of 18 s for each 50 cm of the cable. Figure 3a illustrates a schematic overview of the DTS monitoring campaign inside the sewer network of Lykkjbekken catchment.

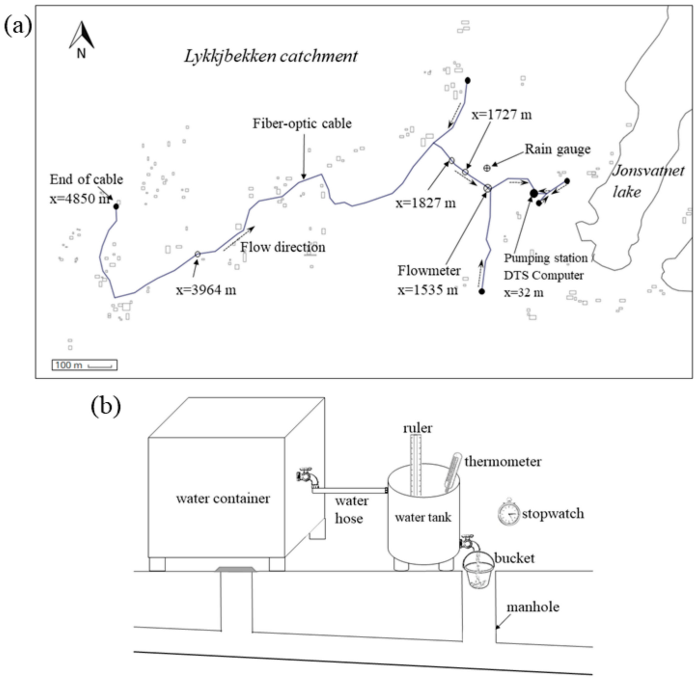

Figure 3. Schematic overview of the (**a**) DTS cable installation in the separate sewer network of Lykkjbekken catchment; and (**b**) experimental setup of the artificial inflow into the sewer network.

2.4. Experimental Setup

To test the feasibility of DTS technology in quantifying the volume of extraneous water I/I into the sewer system, a number of experimental artificial discharges with different temperatures, flows, and velocities were spilled into the sewer network of Lykkjbekken catchment (Table 1). The test locations were x = 1727 m and x = 1827 m on the fiber-optic cable (Figure 3a).

Table 1. Artificial discharge characteristics in the sewer network of Lykkjbekken, Trondheim.

Date	Test Number	Test Location (m)	Time (hh:mm)		Temperature (°C)	Discharge (L/s)	Inflow Share (%)
			Start	End			
28 Aug. 2015	1	1727	09:42	09:47	34	0.079	5.8%
28 Aug. 2015	2	1727	09:53	09:59	33	0.13	9.8%
28 Aug. 2015	3	1827	10:24	10:28	31	0.188	26%
28 Aug. 2015	4	1827	10:35	10:40	32	0.356	51.8%
28 Aug. 2015	5	1827	11:49	11:54	20	0.060	4.7%
28 Aug. 2015	6	1827	11:58	12:02	20	0.338	61.3%
28 Aug. 2015	7	1827	12:05	12:08	20	1.69	389%
28 Aug. 2015	8	1827	12:13	12:17	20	0.18	12.6%
28 Aug. 2015	9	1727	12:30	12:32	20	0.46	7.18%
28 Aug. 2015	10	1727	12:34	12:39	20	0.208	12.13%
28 Aug. 2015	11	1727	12:42	12:45	20	0.41	90.2%
28 Aug. 2015	12	1727	12:47	12:53	20	0.05	4.47%
28 Aug. 2015	13	1727	12:53	12:58	20	0.09	5.67%
23 Oct. 2015	14	1727	08:35	11:55	13	0.07	9.27%
23 Oct. 2015	15	1727	12:25	13:05	11	0.067	5.76%
23 Oct. 2015	16	1727	13:05	13:25	11	0.056	18.5%
23 Oct. 2015	17	1727	13:25	15:38	11	0.059	12.6%
23 Oct. 2015	18	1827	13:42	13:48	11	0.0016	0.47%
6 Nov. 2015	19	1727	08:47	12:10	1	0.056	8.18%
6 Nov. 2015	20	1727	12:15	14:30	9.5	0.056	103%

The experimental setup for artificial discharges was quite simple and consisted of a water tank with a valve, water containers with different water temperatures, water hose, thermometer, stopwatch, ruler and a bucket (Figure 3b). The tank was connected to the water container by a water hose. A thermometer controlled the temperature of the water and the ruler controlled the water level inside the tank to be able to maintain a steady water level, while there was an inflow into the tank from the container and an outflow from the tank to the manhole. The discharge and velocity of the artificial inflow were calculated by the time needed to fill the bucket with a defined volume, and by adjusting the tank valve, different discharges were provided.

2.5. Precipitation and Flow Measurement

Precipitation and flow measurements are key parameters in I/I studies. Precipitation is an important variable in hydrological rainfall-runoff studies and has a direct impact on the surface runoff and the groundwater discharge. From the I/I point of view, this variable is a dominant element on the quality and quantity of in-sewer water parameters [27]. However, the wastewater flow measurement is a challenging task, and the current flowmeters in the market do not respond well, especially to low flows, therefore their results in shallow flows can be inaccurate. In addition, the presence of debris in wastewater and sedimentation problems on the flowmeter sensors are additional challenges in flow measurement in wastewater networks with shallow flows.

In this study, rainfall and wastewater flow were monitored by installing a rain gauge and a flowmeter in Lykkjbekken catchment, see Figure 3a. For the precipitation measurement, a tipping bucket rain gauge with a standard resolution of 0.2 mm was applied. Moreover, an ultrasonic Doppler flowmeter was installed downstream of the artificial discharge point to measure the in-sewer flow in order to check the accuracy of the DTS method in quantifying the extraneous water.

The artificial discharges were added at two and three manholes upstream of the flowmeter at x = 1535 m. There were no household connections between these points to have an accurate flow measurement and avoid the contribution of any wastewater spills. Furthermore, the results from CCTV inspection and DTS monitoring did not show any I/I contribution from groundwater or other sources in that part of the network.

2.6. Infiltration and Inflow (I/I) Temperature

To use the DTS method for quantification of rainfall-derived inflows, it is important to have the temperature of runoff. The heat balance has a great impact on the temperature of runoff and stream water and is connected to the meteorological circumstances, such as air temperature [30]. Several studies have successfully modeled the stream temperature based on a linear and non-linear relationship with air temperature [30–33]. The stream-air temperature relationship uses an S-shaped logistic function, with temperature between 0–20 °C following a linear regression and temperatures outside of this range following a non-linear relationship. The non-linear behavior is due to the influence of snowmelt and groundwater at low temperatures and evaporative cooling and enhanced back radiation at high temperatures [32]. The temperature of surface runoff and lateral soil flow from rain has a linear regression with air temperature, which is close to the ambient air temperature and can be approximated to the average daily temperature [31]. However, the runoff from snowmelt has a temperature just above the freezing point and can be set to 0.1 °C [31,34]. On the other hand, surfaces heated in excess of the ambient air due to solar radiation [14] may initially transfer some heat to the runoff at the start of rain events. Therefore, nighttime inflows can be considered to eliminate the influence of short-wave solar radiation and improve quantification accuracy.

Groundwater temperature varies seasonally. To accurately quantify groundwater infiltration, groundwater temperatures should be measured using a well in the catchment. Annually, however, groundwater temperatures are assumed to be 1–2 °C higher than the average air temperature [35]. To quantify I/I from unwanted sources with unknown temperature, e.g., from illicit connections or groundwater, an accurate temperature can be measured using a sensor or looping the fiber-optic cable.

The temperature sensor should be installed at the location of an I/I source after its detection, and I/I quantification can then be performed accurately. However, installation of these sensors in the sewer is not easy. Moreover, differentiating the temperature of wastewater from I/I in submerged sewers is difficult and may make I/I temperature measurements inaccurate. Alternatively, it is possible to measure the temperature of I/I from illicit and faulty connections, by looping the DTS cable in the I/I location before entering to the sewer, and then continuing the cable to the next part of the network [24].

3. Results and Discussion

3.1. Artificial Discharge I/I Assessment

In this study, the applicability of the DTS technology was examined for quantification of the extraneous water I/I into the sewer system. Therefore, different artificial discharges were applied to analyze the wastewater thermal behavior from the I/I aspect. The DTS cable recorded water temperature upstream and downstream of the artificial discharges with known temperature, volume, and flow. As a result, the inflow share, which is the volumetric proportion of I/I to the sewer network in comparison with the upstream flow, was estimated by the equations of conservation of mass and energy (Equations (2) and (3)). Table 1 in the experimental setup presents the characteristics and results of the artificial discharge tests conducted in the Lykkjbekken catchment.

For I/I quantification, it is important to calibrate the fiber-optic cable accurately to achieve precise results. In the present study, due to the presence of some fusion splices, the cable was calibrated with reference measurements at six calibration sections along the cable using standard thermometer sensors. Figure 4 demonstrates the calibration of the DTS measurement in the Lykkjbekken catchment. The temperature-offsets verify the log-linearity of the signal attenuation process. The sedimentation of debris and wet wipes on fiber-optic cables, however, may reduce the sensitivity and accuracy of temperature measurements during low flow and long-term installation and can also increase the risk of sewer blockage. To avoid this problem in the present study, the maintenance of the sewer network was conducted by pipeline flushing during the DTS monitoring campaign.

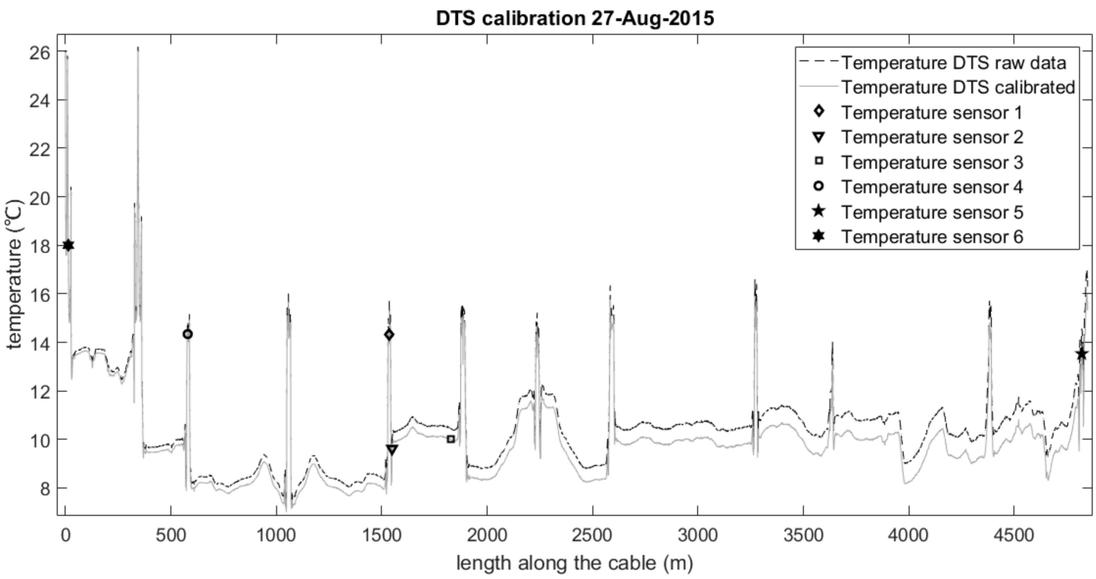

Figure 4. DTS calibration by six standard thermometers along the installed fiber-optic cable.

Figures 5–7 demonstrate the results of some artificial discharge tests with different temperatures and flows. In these figures, the upstream and downstream temperatures of infiltration point and the calculated infiltration share by Equation (3) are presented. According to the pumping data, water consumption curve, and flowmeter data, the average daily flow in the network was 0.5 L/s.

Furthermore, considering the physical characteristics of the network, i.e., material, slope, and diameter by using Manning's equation, the corresponding velocity for the average daily flow in both test locations was around 0.65 m/s. The travel distance for the flow from the I/I experimental location was around 12 m per 18 s (the time span of DTS measurement). Therefore, to analyze the DTS data in x = 1727 m and x = 1827 m, the upstream of x = 1733 m and 1833 m, and the downstream of x = 1721 m and 1821 m were considered, respectively, to compare the temperature of downstream with the upstream of the previous time-step.

As can be concluded from the graphs in Figure 5, the temperature differences between upstream and downstream have a significant role in calculations of the inflow share. The artificial flows can have the same temperature and discharge while the inflow shares and calculated in-sewer flows can vary based on wastewater temperature fluctuations caused by upstream spills from households. In Figure 5, the 2 min inflow of 0.46 L/s and 20 °C had an average share of 7.18% (test number 9), while the average share for 3 min inflow of 0.41 L/s and 20 °C was 90.2% (test number 11), which was due to the different upstream temperatures and flows.

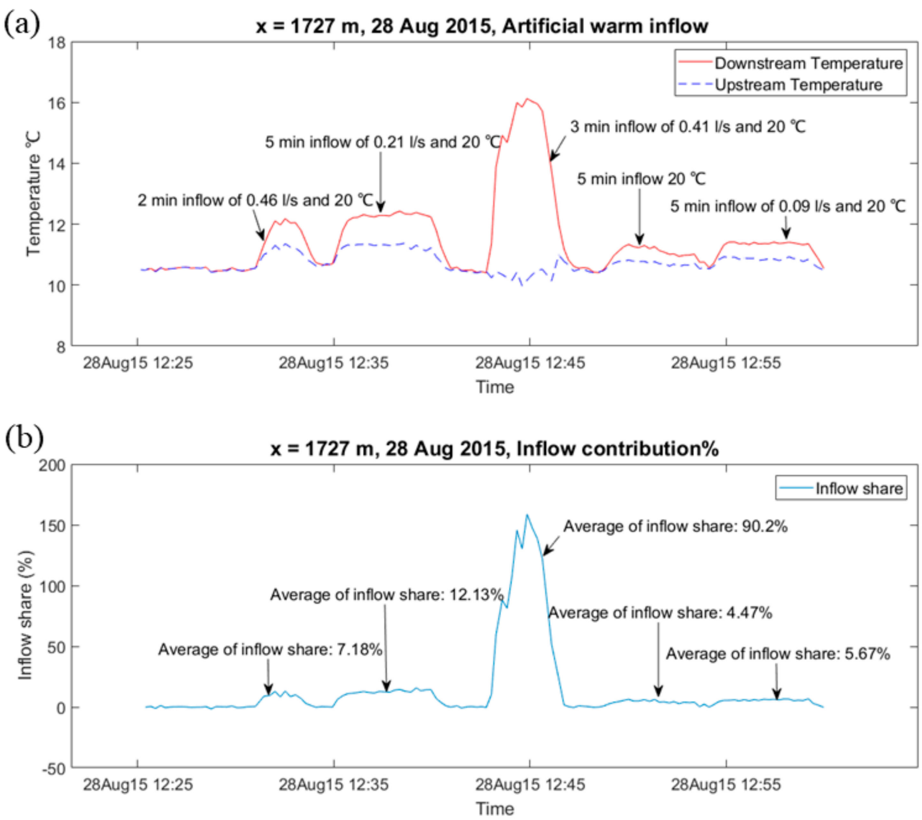

Figure 5. (**a**) Upstream and downstream temperatures on 28 August 2015 around warm artificial discharge in location x = 1727 m; (**b**) percentage of inflow share in comparison with the upstream flow.

The thermal behavior of the sewer system against cold water I/I was examined in this study as well. Figure 6 shows the thermal analysis of the system in cold I/I tests at x = 1727 m by demonstrating the detailed temperatures of upstream and downstream of the injection point and the calculated inflow shares in comparison with the upstream flows. The average inflow share during 3 hours and 23 minutes of 0.05 L/s inflow and 1 °C was around 8.18% of the flow, while it varied between 3–15% during this time span. The reason can be explained by the wastewater flow and temperature fluctuations due to the upstream domestic spills.

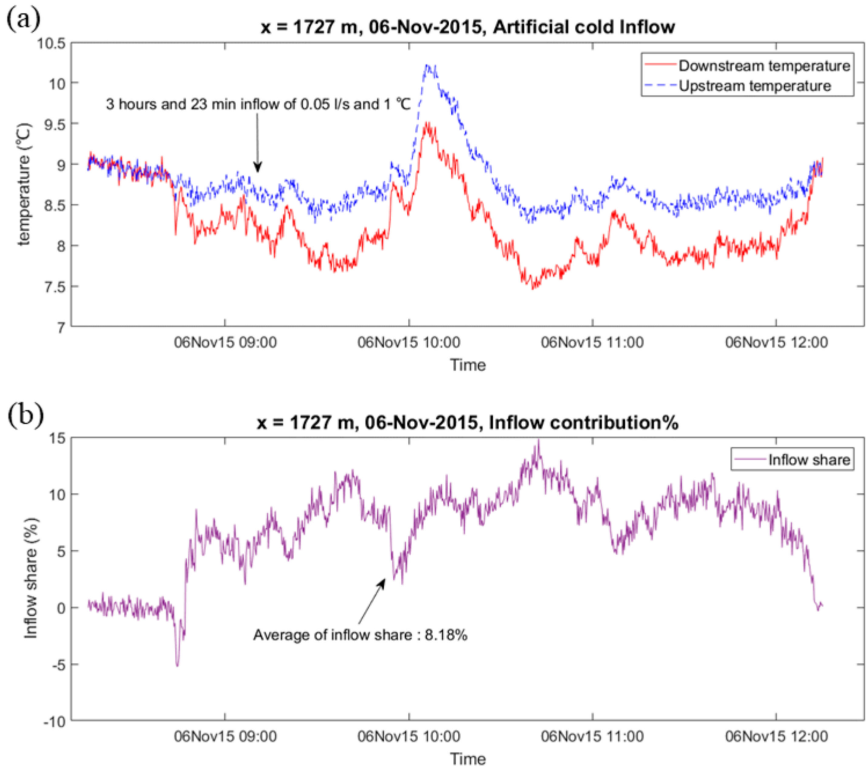

Figure 6. (**a**) Upstream and downstream temperatures on 6 November 2015 around cold artificial discharge in location x = 1727 m; (**b**) percentage of inflow share in comparison with the upstream flow.

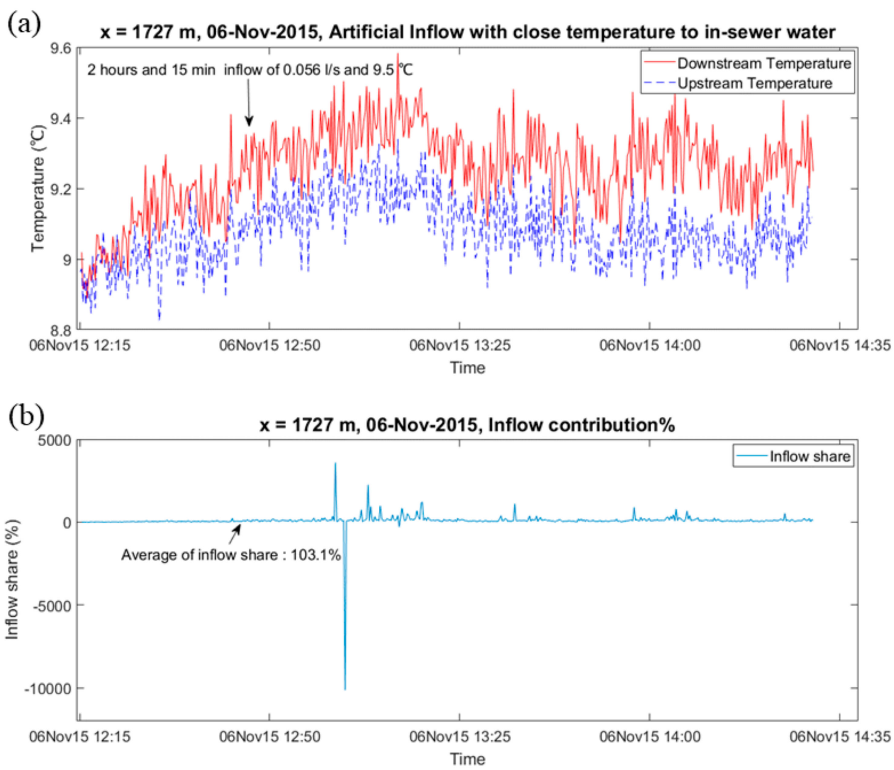

Figure 7. (**a**) Upstream and downstream temperatures on 6 November 2015 around artificial discharge with close temperature of in-sewer water in x = 1727 m; (**b**) percentage of inflow share in comparison with the upstream flow.

In the next experiments, the thermal behavior of the wastewater was studied under the artificial inflows with the temperature close to the wastewater temperature. As demonstrated in Figure 7, it is hard to find out the correct amount of I/I when the temperature of the inflow is close to the temperature of the wastewater, due to the fact that the numerator and denominator of Equations (2) and (3) become close to zero.

For verifying the application of the thermal method in I/I quantification, the flow data downstream of the artificial inflow point (measured by an ultrasonic Doppler flowmeter) was exploited. Figure 8 demonstrates the measured flow by the flowmeter and the calculated flow by the DTS method (Equation (3)) versus time.

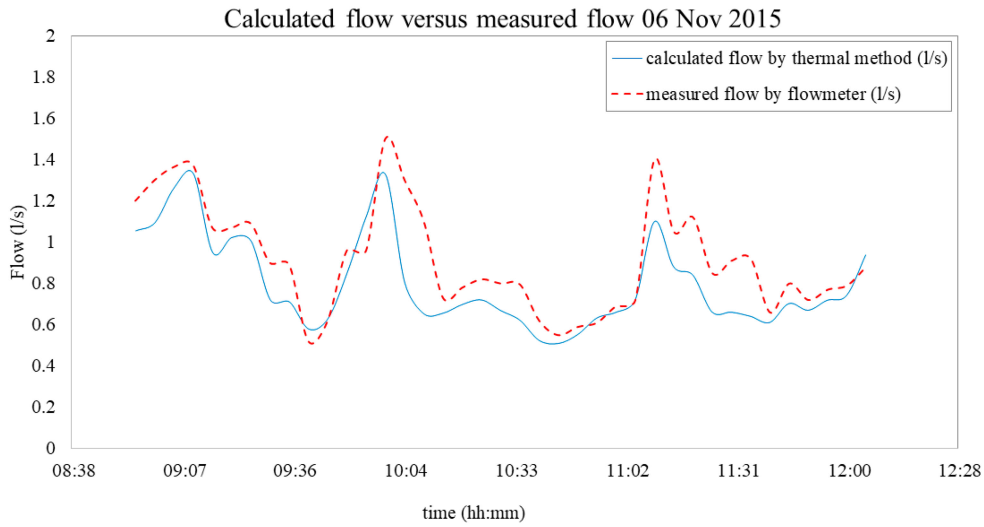

Figure 8. Measured flow by the flowmeter and calculated flow by DTS method versus time on 6 November 2015 at x = 1727 m.

By comparing the calculated wastewater flow with the measured flow by the flowmeter in Figure 8, both datasets demonstrated the same tendency and good correlation (72%) with each other. The relative error of ultrasonic flow data from the calculated flow by the thermal method was 11.96%, which can be due to the instrumental measurement errors of the flowmeter. In practice, the uncertainty and relative error in wastewater flow measurement by Doppler ultrasonic flowmeters can vary and even exceed 6–12%, which arises from different parameters, such as beam width, beam angle, and inherent instrumental errors [36]. Moreover, application of flowmeters in low and shallow flows can have high uncertainty and inaccuracy, which is also the case in the present study. Therefore, the deviation of flowmeter data from the calculated flow in Figure 8 is in the acceptable range, verifying the accuracy of the results for the thermal-based flow measurement. Nevertheless, a specific laboratory calibration is needed to assess the accuracy of these types of flowmeters, which was out of the scope of this study.

3.2. Low Infiltration Artificial Discharge

The capability of the DTS in finding out the low I/I was analyzed by an artificial injection with a low discharge of 0.0016 L/s and a temperature of 11 °C into the sewer network of Lykkjbekken (Figure 9).

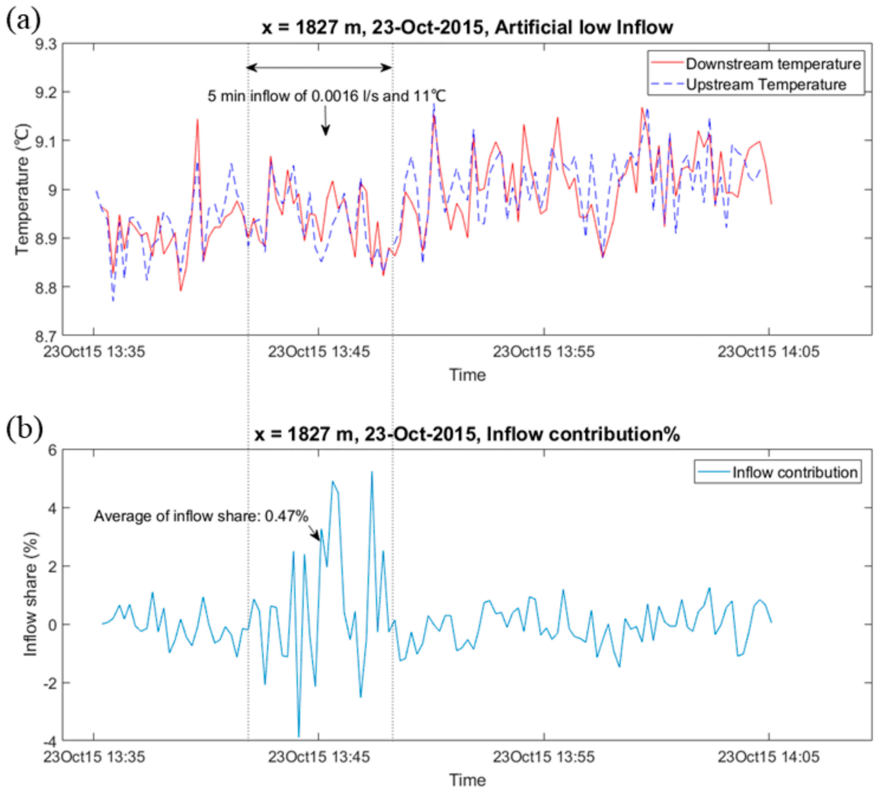

Figure 9. (**a**) Upstream and downstream temperatures on 23 October 2015 around artificial low discharge in x = 1827 m; (**b**) percentage of inflow share in comparison with the upstream flow.

In Figure 9, the quantification analysis of the low-flow injection was investigated by analyzing the temperature data upstream and downstream of the injection point. The calculations demonstrated that the average inflow share was around 0.47% of the upstream flow, and the calculated wastewater flow by Equation (3) was around 0.36 L/s. These calculated numbers were reasonable for the wastewater network of the Lykkjbekken catchment. Considering the error of flow measurement by ultrasonic flowmeters (6–12%), the calculated results were in good agreement with the downstream flow data from the water consumption curve and the flowmeter (0.41 L/s). However, in low-flow injections, the temperature changes are not significantly larger than the measurement noises, and therefore makes it difficult to identify these types of flows in DTS monitoring graphs.

3.3. Rainfall-Derived I/I Assessment

To demonstrate the application of the DTS method in the quantification of rainfall-derived I/I, the location x = 3964 m was considered, which confronted notable I/I of extraneous water in rain events. The real-life I/I calculation in the present study was based on the assumption of having the same temperature for nighttime surface runoff as the surrounding temperature, and there was not any snow in the catchment. Moreover, the household spills reduced drastically during nighttime, resulting in more accurate rainfall-derived I/I assessment during wet weather conditions. Therefore, to assess the real-life I/I, the upstream and downstream temperatures of the location x = 3964 m were analyzed during the storm events at midnight of 11 November 2015 (Figure 10) and 28 August 2015 (Figure 11).

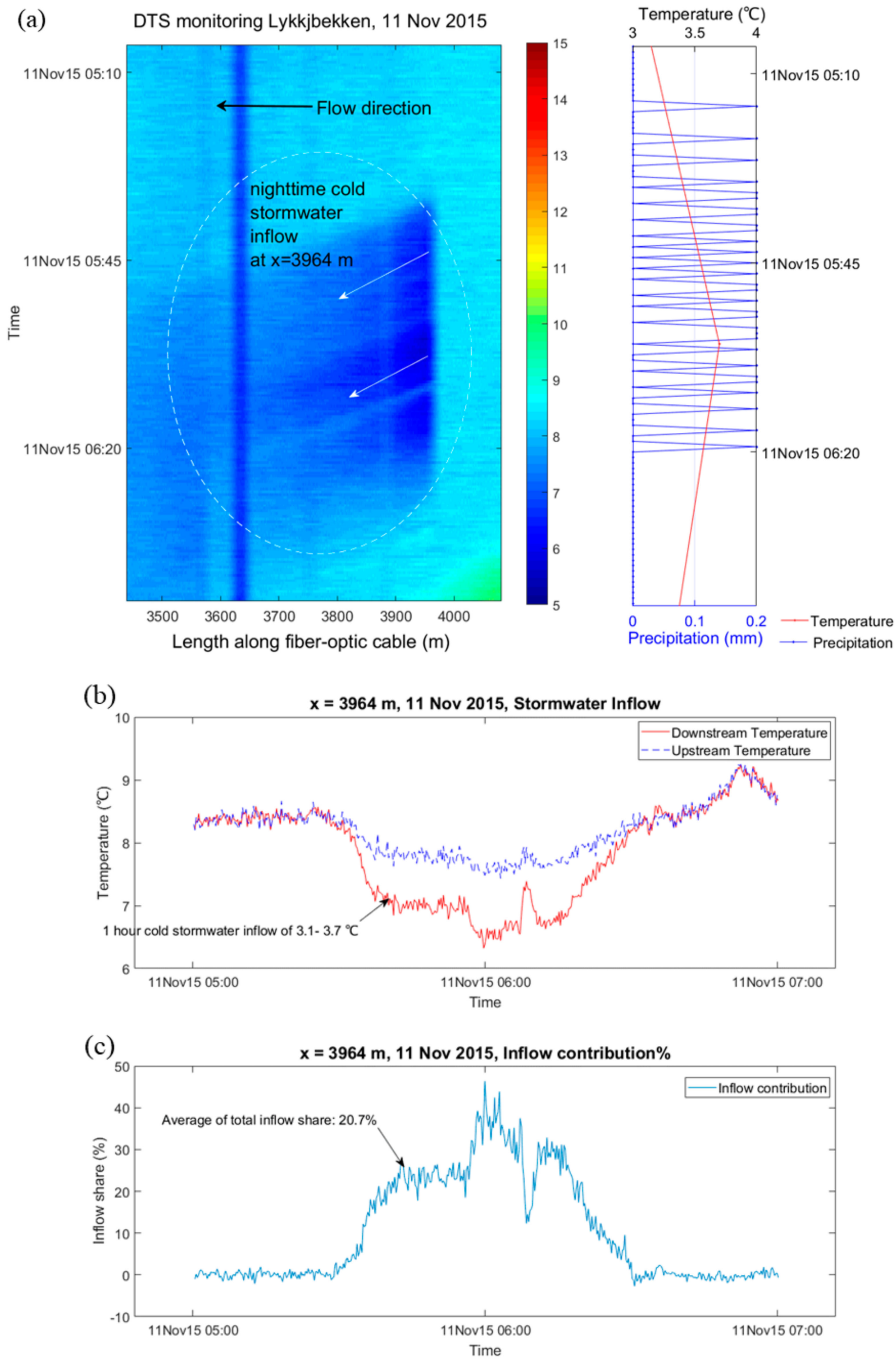

Figure 10. (**a**) DTS monitoring results around the rainfall-derived I/I point of x = 3964 m in storm event of 11 November 2015; (**b**) the upstream and downstream temperatures around real stormwater infiltration at x = 3694 m; (**c**) percentage of I/I share in comparison with the upstream flow.

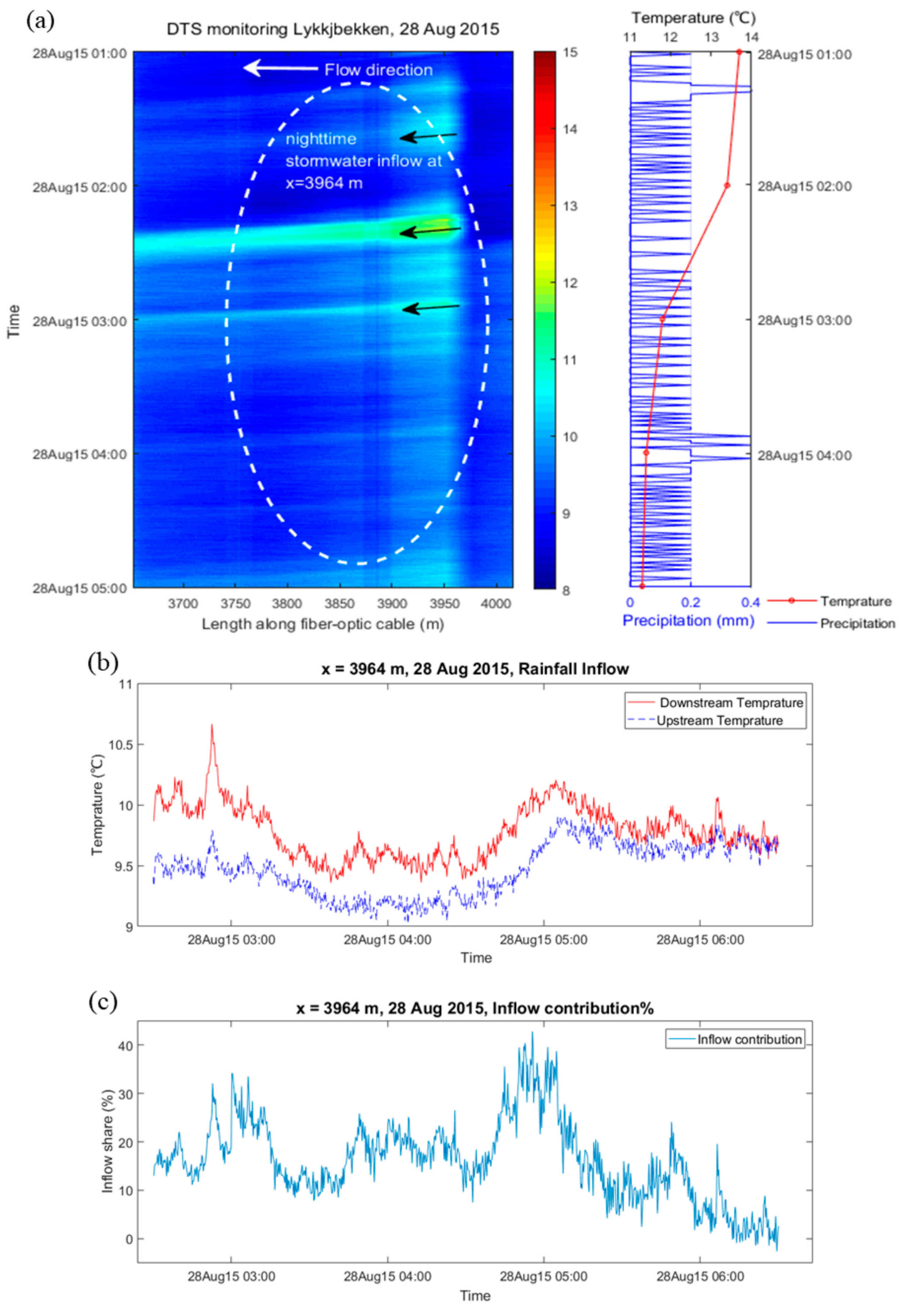

Figure 11. (**a**) DTS monitoring results around the rainfall-derived I/I point of x = 3964 m in storm event of 28 August, 2015; (**b**) the upstream and downstream temperatures around real stormwater infiltration at x = 3694 m; (**c**) percentage of I/I share in comparison with the upstream flow.

Figures 10a and 11a demonstrate the DTS monitoring results in the heat-map format and illustrate the continuous thermal behavior of the sewer system along the fiber-optic cable installed in the sewer pipeline section. In the DTS monitoring heat-map, the horizontal axis shows the location of the cable along the sewer network and the vertical axis presents the time, while each pixel on the figure represents an in-sewer temperature for a specific time and location. The exact location of extraneous water I/I can be detected by analyzing temperature changes caused by different spills from various sources into the sewer network.

As can be seen in Figure 10a, the DTS results indicate a decrease in downstream temperatures of x = 3964 m in comparison with the upstream location, after starting the rain event at 05:15 on 11 November 2015 with an intensity of 6 mm/hour. The I/I was related to inflow of relatively cold stormwater at that location in a cold night (3 °C) from the misconnected roof and yard drains. With using upstream and downstream temperatures recorded by the DTS (Figure 10b), and assuming the stormwater temperature to be equal to the air temperature, the relative contribution of inflow with respect to upstream volume was derived according to Equation (2) (Figure 10c). The dominated temperature of wastewater before inflow was around 8.2 °C and stormwater inflow with a temperature equal to the surrounding temperature (around 3.1–3.7 °C) decreased the temperature of the wastewater significantly. In this case, the calculated inflow share was between 14–42% with a mean value of 20.7% during this rainfall.

Figure 11 shows a warm stormwater inflow into the sewer network in the midnight of 28 August 2015 with air temperature of 11–13 °C, which was warmer than the wastewater temperature (8–9 °C). Using the same assumptions, which were described above for the rainfall of 11 October 2015, the inflow share in this case was between 4–42% with an average of 18.3% (Figure 11c). The rainfall-derived I/I calculations in different rainfalls in location x = 3694 m showed the severity of the I/I source and pointed to the immediate need for rehabilitation or spot-repair of that location. Moreover, the temperature differences between rainfall-derived I/I in both warm and cold nights highlighted the direct influence of the surrounding temperature on the temperature of the rainfall-derived I/I and the importance of the air temperature measurement in rainfall-derived I/I assessments.

4. Conclusions

In the present study, the application of the DTS technique for accurate quantification of extraneous water ingress and infiltration from individual I/I sources in the separate sewer networks was considered and analyzed in a catchment in Trondheim, Norway. I/I measurements were carried out by analyzing the thermal behavior of in-sewer water and utilizing an equation based on the conservation of energy and mass (Equation (2)). For this purpose, both experimental artificial discharges and real-life rainfall-derived I/I during wet conditions were assessed.

In experimental flows, artificial discharges with different temperatures and flows were applied to check the feasibility of the DTS method in quantifying I/I contributions in the sewer network. These results verified the applicability of the method in quantification goals, except when I/I water temperature was the same as in-sewer water. Moreover, in low-flow I/I, the difference between the temperature changes and measurement noises were not significant, making I/I detection difficult with DTS monitoring. In addition, this method demonstrated robustness and practicability in I/I measurement during wet conditions. Analyzing the thermal behavior of the in-sewer water during storm events revealed that the temperature of the rainfall-derived I/I in sewer networks was dependent on ambient air temperature. Therefore, monitoring the air temperature in this type of study was very important and should always be considered.

The results of this study identified the condition of the sewer network by determining the severity of individual I/I sources in the sewer network. I/I assessment is a demanding task in sewer rehabilitation and can support the urban water decision-makers and sewer operators in prioritizing and spot-repairing problematic parts of the network. These types of measures are valuable for sewer-infrastructure asset management as well as sustainable urban water management.

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