

Infiltration / Inflow Assessment and Detection in Urban Sewer System

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Sammendrag

Infiltrasjon og innlekking (I/I) av fremmedvann til avløpsnett er ofte betydelig. Dette medfører økte kostnader for transport og rensing av avløpsvann. Fremmedvannet tar opp transportkapasitet og øker sannsynligheten for forurensningstap via overløp og oversvømmelser på terreng og i kjellere. Lokalisering og fjerning av fremmedvann er derfor prioritert i kommuners planer for oppgradering av avløpsnett.

Denne studien presenterer metoder for å lokalisere og kvantifisere I/I i avløpsanlegg, og diskuterer muligheter og begrensninger ved hver metode. Den konkluderer med at en kombinasjon av teknikkene er nødvendig for å oppnå tilstrekkelig kunnskap om årsaker og omfang av innlekking.

Abstract

Infiltration and inflow (I/I) of non-sewer water into the urban sewer system is a critical problem in the long term for sustainable urban water management and water infrastructural asset management, with serious environmental, social and economic impacts on cities and sewer systems. I/I of unwanted stormwater, groundwater and other extraneous sources in sewer systems decrease availability and increase the risk of hydraulic overloading of the wastewater network, which may lead to local flooding or sanitary sewer overflows. Furthermore, it has negative impacts on performance and efficiency of wastewater treatment plants and increases pumping costs, energy consumption and maintenance requirement.

There is no standard and specific operational procedure for investigating and detecting illicit connections and I/I in sewer systems. This study discusses commonly used and advanced methods of localizing and quantifying I/I level in sewer systems, and identifies advantages and limitations of each method. A combination of these techniques can provide sewer operators possibilities to compare different technologies and reducing assumptions and uncertainties in assessing and localizing I/I in the sewer system in a standardized way and support the decision-making in maintenance and rehabilitation plans with more accurate and reliable data about location and magnitude of I/I in the sewer system.

Key words: *Infiltration and inflow (I/I), urban water management, Sewer system, maintenance, rehabilitation*

Introduction

Urban sewer systems are one of the most significant and important water infrastructures in European cities and even all over the world. Water and wastewater networks are assumed as the lifelines of urban areas as they transport drinking water with high quality and safety to households and industries and collect polluted water for recycling and safe releasing into the environment (Rehan et al. 2014).

Functional efficiency and structural quality of sewer systems are the principal factors that ensure urban and industrial wastewater transportation to treatment plants without infiltration and exfiltration (Ellis & Bertrand-Krajewski 2010). Urban water and wastewater infrastructure assets are in the state of deterioration based on lack of sufficient municipal investments on their maintenance and rehabilitation (Rehan et al. 2014).

There are different types of sewer systems for transporting foul wastewater and stormwater. Most European cities rely on combined sewer systems (CSS), the most common way of draining wastewater and stormwater. Combined sewer overflows (CSO) may lead to environmental problems due to the discharge of untreated and polluted wastewater to receiving waters or other final recipients and trigger urban areas flooding in extreme rain events. On the other hand, stormwater separate systems have been introduced as one of the cost-effective solutions in many regions to disconnect impervious areas from CSS for reducing CSO emissions and hydraulic overloading of sewer systems (Langeveld et al. 2012). A major defect of separate sewer systems is the occurrence of faulty connections: unplanned sewer cross-connections that connect foul water outlets from residential or industrial sites to the stormwater system and/or stormwater outlets to the foul sewer system (Schilperoort et al. 2013). The volume of unwanted stormwater in foul sewer systems can be significant, resulting in a number of undesirable consequences on the performance of the wastewater system. Therefore, rehabilitation is required in the case of infiltration and illicit connection detection in the sewer systems.

Unwanted water in separate foul sewer systems is a well-known problem. Approximately 50% of the stormwater is discharged into the separate foul sewers and transported to the wastewater treatment plant (Peters et al. 2002; Langeveld et al. 2012). Moreover, under unfavorable conditions, the amount of groundwater infiltration into the deteriorated pipes can even exceed 50% of the total wastewater volume (Kracht & Gujer 2006). Infiltration and inflow (I/I) of unwanted stormwater, groundwater and other extraneous sources in the sewer system, are significantly unfavorable for the efficiency of the wastewater treatment plants and may overload the hydraulic load of the treatment

plants up to 100 % by infiltrated water (Ellis & Bertrand-Krajewski 2010). In addition, there is increasing evidence that in many cities, groundwater levels are controlled by the significant drainage effect of permeable sewer systems (Kracht & Gujer 2006). Generally, infiltration decreases the availability and increases the risk of pressurization of the wastewater network (Sægrov 2012). Practitioners often address this issue by calculating the “parasitic discharge” based on the assumption of minimum nighttime flow in the diurnal wastewater hydrograph is equal to the extraneous flows (Kracht & Gujer 2006).

I/I of non-sewer water into the urban sewer system is a critical issue in the long term for sustainable urban water management and water infrastructural asset management, which has serious environmental, social and economic impacts on cities and sewer systems. From the environmental point of view, the efficient curbing and removal of I/I of unwanted water into the sewer systems can reduce the hydraulic overload of sewer pipelines, which decreases the probability of local flooding and deterioration of urban infrastructures (Karpf & Krebs 2011), and its impacts on inhabitants’ life. It also reduces the probability of dissemination of sanitary sewer overflows in streets, urban areas and environment. Furthermore, from the economic point of view, it leads to lower maintenance requirements due to decreasing entry of sediments and decreases the cost and energy consumption in pumping stations and treatment plants because of removing unwanted feeding of foreign water (Schilperoort et al. 2013; Langeveld 2004). Therefore, for having the sustainable management of urban sewer systems, I/I of unwanted water into the urban sewer systems should be considered carefully and maintenance and rehabilitation plans should be implemented on these water infrastructural assets.

Efficient assessment and detection of I/I in urban sewer systems are important issues on

the long-term water infrastructure asset management, which have not been considered adequately and seriously in urban areas so far. The purpose of this study is to introduce and discuss commonly used and advanced methods of detection, localization, and quantification of I/I into the sewer systems, and identify advantages and limitations of each method. Some of these methods are going to be used in the Trondheim city in Norway for assessing the level of I/I into the foul sewer systems. This gives sewer operators the possibility to compare different technologies in assessing and localizing I/I in the sewer system in a standardized way and can support the decision-making on when and where to rehabilitate, depending on the selection criteria (hydraulic, social, environmental, economic, etc.).

Infiltration Detection and Measurement Methods

Infiltration is the entry of groundwater into the sewer system and service connections through defective pipes, pipe joints, connections, manhole walls, and so forth. In separate sewer systems, it is also very important to detect illicit and faulty connections, which result in infiltration and inflow of unwanted water into the pipeline network from different sources. Efficient removal of I/I into the sewer systems requires knowledge about the locations of I/I sources and illicit connections. There are several methods available for assessing and localizing the infiltration and inflow of

unwanted stormwater, groundwater, and other extraneous sources into the sewer system. Typically, the assessment of I/I in sewer systems is based on the conventional and rather inaccurate method of flow rate measurement, analysis of diurnal flow and load variation and balancing of water inputs and outputs (Ellis & Bertrand-Krajewski 2010, De Bénédictis & Bertrand-Krajewski 2004; Rutsch *et al.* 2005). Moreover, new measurement methods have been developed to assess I/I into sewer systems based on limited analytical effort and with little environmental risk.

These methods can be divided into two groups: quantitative methods for assessing the magnitude, volume and discharge of I/I, and qualitative methods for detecting the location of I/I sources. Each of these methods is based on some assumptions and has its own limitations and advantages. There is no unique and standard way of evaluation and localization of I/I in the sewer systems and a combination of these methods can be valuable for reducing assumptions and uncertainties and obtaining more independent, accurate and reliable data about location and magnitude of I/I in the sewer system. Finally, maintenance and rehabilitation can contribute to the improvement of the performance of sewer systems in the long term for sustainable urban water management. The systematic process for detection of unwanted water in specified catchments with different properties in Trondheim city is proposed in Figure 1.

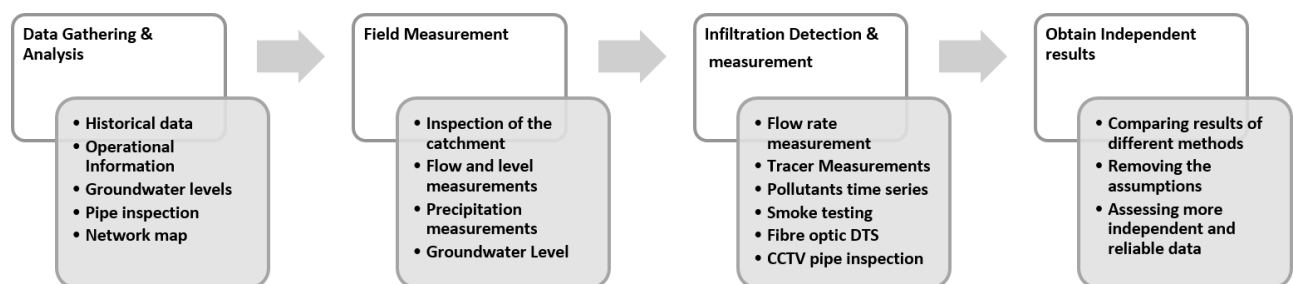


Figure 1. Systematic method for detecting unwanted water in sewer system

Quantitative methods

Flow rate method

The **flow rate measurement method** is one of the conventional methods of infiltration assessment in sewer systems. This method is based on the simple assumption of constant infiltration of groundwater in daily Dry Weather Flows (DWF). DWF is the mean daily sewage flow in a foul sewer system during a day and the day before of dry weather or less than 0.3 mm/day rainfall intensity because of avoiding contribution of stormwater inflow to flow measurement (excluding public or local holidays) (Karpf & Krebs 2011). Moreover, for excluding the contribution of snow-melt flow in DWF measurement, the day of DWF and three days before the air temperature should not be in the range of -2 to +2 °C (Karpf & Krebs 2011). Equation 1 is the basic method for calculating the I/I in the sewer system (SEPA 2014).

$$\text{DWF} = P * G + I + E \quad (\text{Eq. 1})$$

Where:

P= Population served

G = daily average water consumption per capita ($\frac{\text{Liters}}{\text{Person} * \text{day}}$) (typically 150-160 liters in Norway)

I = daily average I/I ($\frac{\text{Liters}}{\text{day}}$)

E = daily average industrial effluent flow ($\frac{\text{Liters}}{\text{day}}$)

Krapf and Krebs (2011) made some refinements in this basic method and developed a new approach for quantifying the components of I/I – infiltration from groundwater and Inflow from surface water – separately. The quantification of infiltration in this approach needs groundwater level and the level of wastewater in the pipes, whereas the inflow quantification refers to the permanent and temporary surface water flow, e.g. surface watercourses and flood events (Karpf & Krebs 2011).

Figure 2 illustrates the constant or base infiltration (BI) at the minimum nighttime flow, theoretical dry weather flow (DWF) and wastewater flow of a DWF week in the separate sewer network of Risvollan catchment in Trondheim. Risvollan is one of the study catchments in Trondheim, Norway with a good database and a measuring station to investigate hydrological parameters through the year. The amount of base infiltration in week 7, 2007 with 0 mm rainfall is 35.5% of total wastewater flow in the separate foul sewer of Risvollan catchment, which is a high volume in the dry weather conditions and is increased significantly in the wet weather conditions.

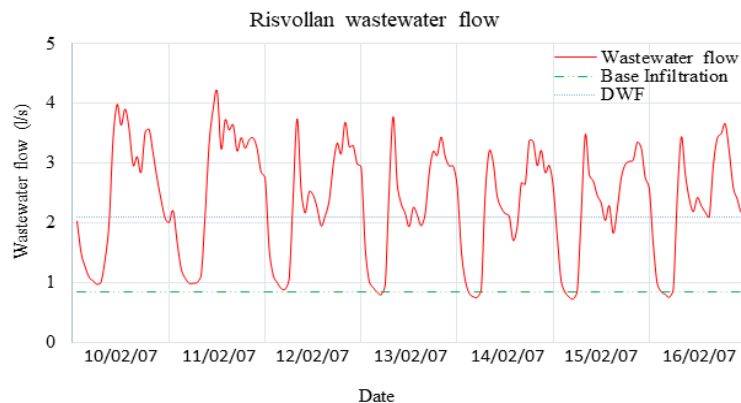


Figure 2. Wastewater flow, theoretical dry weather flow and base infiltration in the separate sewer of Risvollan catchment, Trondheim

Tracer methods

Tracer techniques have proven to be one of the most powerful tools to characterize water residence time, flow and pollutant transport in hydrological systems (Koeniger et al. 2009). The ideal tracer should have the following features (Pitt et al. 1993):

- A significant difference in concentration between possible pollutant sources
- Small variations in concentrations within each likely pollutant source category
- A conservative behavior (no significant concentration changes due to physical, chemical or biological processes)
- Ease of measurement with adequate detection limits, good sensitivity, and repeatability.

Stable isotopes method

The stable isotopes method is a tracer method and relies on different isotopic signatures of main water from a distant hydrological source and infiltrating water from groundwater and local precipitation, as a direct natural tracer (Ellis & Bertrand-Krajewski 2010). Stable isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$ of water) provide a reliable tool to quantify the infiltration of foreign water in sewer system (Kracht et al. 2007). Figure 3 illustrates daily wastewater isotopic characterization graph and hydrograph of

wastewater flow contributors: ‘foul sewage’ and ‘infiltration’.

In this method, the infiltration fraction is calculated by equation 2, which is based on the concentration of different isotopes as tracers (Ellis & Bertrand-Krajewski 2010).

$$X_{\text{infiltration}}(t) = \frac{C_{\text{foul sewage}}(t) - C_{\text{spillwater}}(t)}{C_{\text{foul sewage}}(t) - C_{\text{infiltration}}(t)} \quad (\text{Eq. 2})$$

The stable isotopes composition of the foul sewage and local groundwater are assumed as tracers for foul sewage and infiltration respectively. Then infiltration flow can be calculated by equation 3 (Ellis & Bertrand-Krajewski 2010).

$$Q_{\text{infiltration}}(t) = X_{\text{infiltration}}(t) * Q_{\text{wastewater}}(t) \quad (\text{Eq. 3})$$

Pollutant time series method

The pollutants time series method quantifies infiltration fraction by analyzing time-series of pollutant concentrations and wastewater flows. Automatically operating in-line devices are applied in this method to obtain time-series of pollutant concentrations with a high temporal resolution. Based on the time-series of the wastewater flows, a modelled time-series of pollutant concentration is calculated, and by fitting this model series to the measured data, a set of parameters, which define $Q_{\text{infiltration}}$, can be estimated (Ellis & Bertrand-Krajewski 2010).

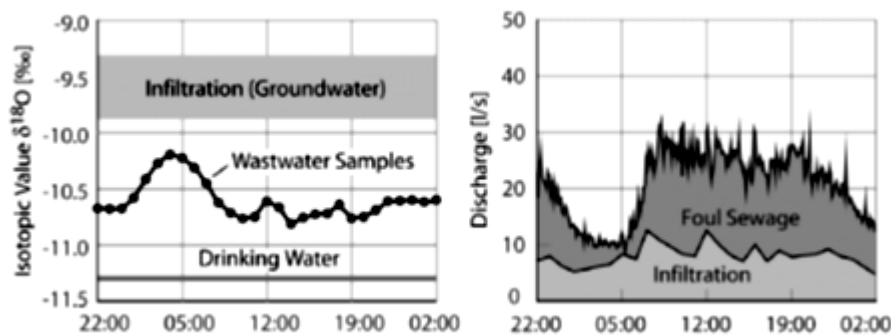


Figure 3. Isotopic characterization and disintegration of a daily wastewater hydrograph into “foul sewage” and “infiltration” (Kracht & Gujer 2006; Ellis & Bertrand-Krajewski 2010)

The method may be applied at the outlet of any sub-catchment where a continuous discharge of wastewater can be assured. However, a minimum amount of wastewater flow is required for the operation of the measuring devices, which may be critical during minimum nighttime flow. It is assumed that infiltrated water contains negligible concentrations of contaminants. Furthermore, the main types of industrial effluents should be excluded, as this may hinder a regular data analysis.

Qualitative methods

Smoke Testing

Smoke testing is an engineering surveying method to locate, identify and classify the potential sources of infiltration and inflow from stormwater outlets into separate foul sewers. This method involves pumping large volumes of a vegetable-based, non-toxic, odorless smoke into sewer network through a manhole (Figure 4). The smoke is generated by a smoke generator engine and travels through the sewer network. Smoke tends to escape through places like openings and vents of the sewer system in the testing area and they may point out to the infiltration/inflow sources in the system (City of Toledo 2011; Hoes *et al.* 2009). This method has the ability to find some of the infiltration/inflow places, and for having more accurate results the network should be

monitored with a CCTV television camera (Schwindamann 2008).

Dye Testing

Dye testing is a tracing method for detecting the path of the flow with tracking dye and determining illicit connections existing in sewer systems. In this method, a fluorescent non-toxic dye is added to a water source, which is suspected as a source of infiltration and inflow into the sewer system. In another way, a period of heavy rainfall is simulated by flooding the stormwater system with pumped water from a large tank. Dyes of different colors are applied to different places. The sewer system is monitored simultaneously by a television camera (CCTV) and infiltration of stormwater is confirmed by finding dye in the sewer system.

The alternative way is to have field staff detecting plumbing fixtures and placing the dye into them. The dye is flushed through the system with running water. When the first dye is observed at the downstream of the tested facility, alternative dye colors are added in the upstream to test multiple fixtures simultaneously. The dye test is repeated until it is confirmed in the sewer or in a storm sewer, or surface water. An illicit connection will be detected in the case of finding the dye in a location other than a sewer system.

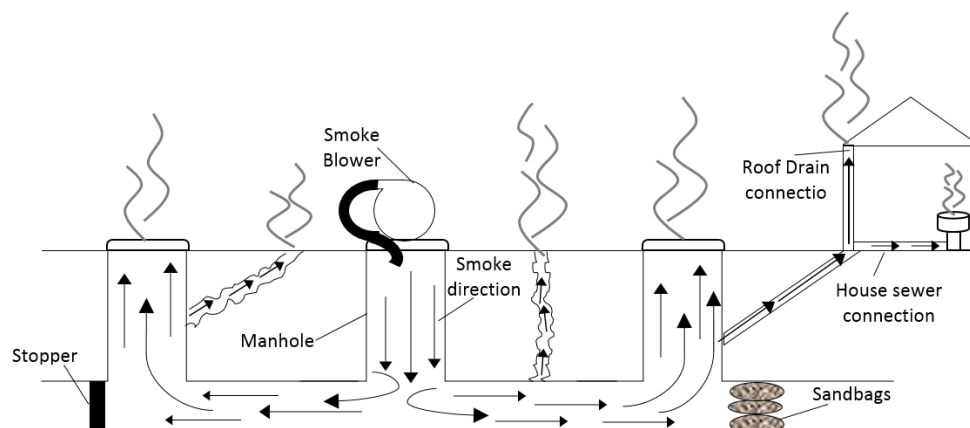


Figure 4. Smoke Testing process for finding potential sources of infiltration and inflow into a foul sewer system

DTS method

Fibre-optic Distributed Temperature Sensing (DTS) is a widely-used technique measuring temperature with a high resolution and high frequency along cables with lengths up to many kilometers (Vosse et al. 2013). The method is based on proven technology, which for decades has been used in the industries of oil drilling, fracture control in pipeline systems, industrial process control and leakage detection in dams and hydrology (Schilperoort et al. 2013; Johansson 1997). This technique has also proven to be a powerful tool to detect and locate infiltration and illicit connections in stormwater sewers (Haan de et al. 2011; Langeveld et al. 2012). The application of fibre-optic DTS in sewer systems has been developed since 2010 (Vases et al. 2013). DTS enables the monitoring of the performance of house connections and detection of foul sewage inflows to storm sewers and vice versa (Schilperoort et al. 2013). Stormwater inflow can only be detected as long as the temperature of this inflow differs from the in-sewer temperatures. In addition, the in-sewer propagation of storm and wastewater can be monitored, enabling a detailed view on advection (Schilperoort et al. 2013). The installation of a fibre-optic cable in a combined sewer system has also proven feasible (Langeveld et al. 2012).

Figure 5 gives an overview of the DTS monitoring results in a foul sewer on 28 April 2011 in the Netherlands. The horizontal axis indicates the length along the fibre optic cable in the sewer system and the vertical axis indicates the time of monitoring. The figure illustrates the measured temperature values of each point along the cable per minute in a time-span of 2 hours. The temperature variation after 04:30 is due to a storm event. The flow direction in this figure is from right to left and the exact places of stormwater inflows into the sewer system are demonstrated in this figure (Schilperoort et al. 2013).

DTS method can also be in the classification of quantified methods. This method can quantify I/I in the sewer system by assuming that I/I has a different temperature and volume (T_2, V_2) from the in-sewer water in the sewer system (T_1, V_1) (Figure 6). The mixture has a new temperature and volume (T_3, V_3). By the help of the laws of conservation of energy ($V_1T_1 + V_2T_2 = V_3T_3$), conservation of mass ($V_1 + V_2 = V_3$), and in-sewer temperature changes ($\Delta T = T_3 - T_1$), the volumetric ratio of I/I (V_2) and in-sewer water before infiltration (V_1) will be derived (Schilperoort 2011).

$$\frac{V_2}{V_1} = \frac{\Delta T}{(T_2 - T_1) - \Delta T} \quad (\text{Eq. 4})$$

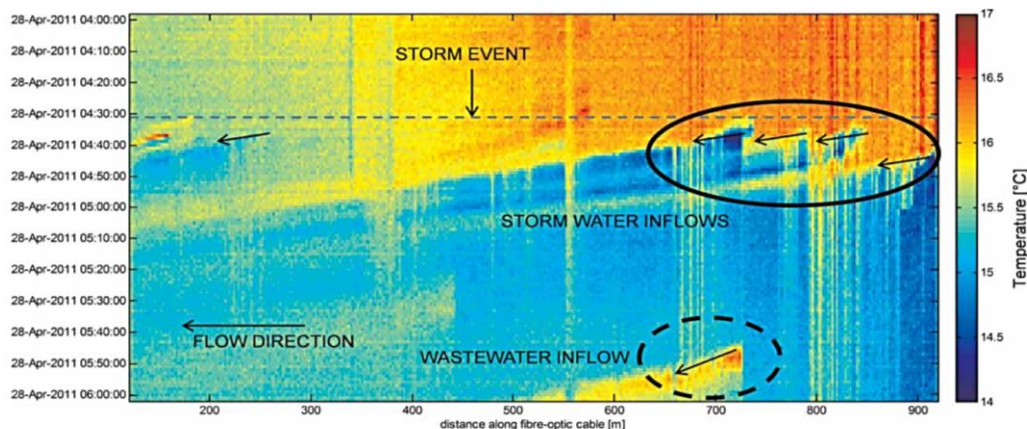


Figure 5. DTS monitoring results in a foul sewer (Schilperoort et al. 2013)

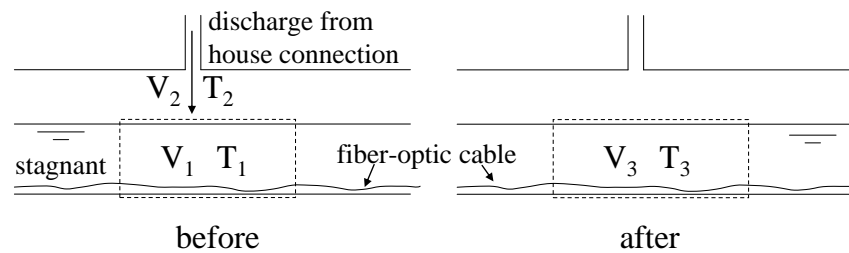


Figure 6. Different temperature and volume of in-sewer water before and after ($T_1, V_1; T_3, V_3$) mixing with I/I (T_2, V_2) (Schilperoot 2011)

CCTV for Inspection of sewer network

Pipe inspection is crucial for the choice of the rehabilitation method, for instance, full replacement or a no-dig solution (Sægrov 2012). Pipe inspection by Closed Circuit Television (CCTV) is a traditional and useful tool to detect and localize pipe defects and their types, misconnections and illicit connections, and I/I sources in the sewer systems (Tuomari & Thompson 2003). However, the probability of finding the faulty connections from households to storm sewers by this method is low because of not having continuous discharges from these misconnections (Hoes *et al.*, 2009). Nevertheless, this method can give important information about the severity and position of I/I sources and together with other tools provide a good basis for rehabilitation.

Comparison & Discussion

Various methods can be used currently for localization and quantification of I/I into the sewer system. The advantages and limitations of the presented infiltration/inflow assessment methods are summarized in Table 1. A combination of using these techniques can provide the possibility to compare different technologies and reducing assumptions and uncertainties in assessing and localizing I/I in the sewer system in a standardized way and support the decision-makers in maintenance and rehabilitation plans with

more independent, accurate and reliable data.

In Trondheim city, a combination of these methods is planned to apply for quantification and qualification of I/I in separate sewer systems. Analyzing the gained results from different methods will help in reducing the uncertainties and assumptions and obtaining more accurate and reliable data and knowledge about the sewer system. This approach can be outlined in different steps for I/I control in Trondheim:

1. Flow measurement in sub-catchment (overview of situation)
2. Tracer methods in several locations for determining local sites of infiltration
3. DTS method to detect I/I sources
4. CCTV inspection and smoke testing to identify problems in detail

Conclusions

I/I of stormwater and groundwater into the sewer system is a serious concern in the long term. The purpose of this paper is to present and discuss different qualitative and quantitative methods in assessing and detecting I/I into the sewer system in the long term by rehabilitation plans. Each of these methods is based on some assumptions and has its own limitations and advantages. There is no unique and standard way of evaluation and localization of I/I in the sewer systems and a combination of

Table 1. Advantages and limitations of different methods in assessing infiltration and inflow in sewer systems

Classification	Method	Advantages	Limitation
Quantitative methods	Flow rate measurement	Simple method	Based on simplified assumptions
		Widely-used method	Inaccurate results
	Stable isotopes method	Do not introduce radioactive or chemical contaminants into the environment (Koeniger et al. 2009)	Drinking water and groundwater should have homogenous but distinct isotopic signatures (Ellis & Bertrand-Krajewski 2010)
		Cause less disturbance and environmental impact than tritium, salts or dye tracers (Koeniger et al. 2009)	Components of drinking water and groundwater sources should interact (Ellis & Bertrand-Krajewski 2010)
			Inhomogeneity of the local groundwater or other origins of parasitic waters is crucial (Ellis & Bertrand-Krajewski 2010)
			Comprehensive hydrologic and hydrogeological investigation (Ellis & Bertrand-Krajewski 2010)
	Pollutant time series method	Definable, accessible for sampling, and precise statistically describable 'infiltration main source' (Ellis & Bertrand-Krajewski 2010)	
		Flexible infiltration measurements (Ellis & Bertrand-Krajewski 2010)	Preparation of the experimental team (Ellis & Bertrand-Krajewski 2010)
		Automatically-operating in-line devices for obtaining pollutant concentration (Ellis & Bertrand-Krajewski 2010)	Local boundary conditions at the investigation site (flow condition, accessibility) (Ellis & Bertrand-Krajewski 2010)
		Wide practical applicability with considering natural storage and interflow phenomena (Ellis & Bertrand-Krajewski 2010)	In the case of using submersible UV-VIS spectrometer, bias-, and drift-free operation is required (Ellis & Bertrand-Krajewski 2010)
Qualitative methods	Smoke Testing	Simplifying measurements in rainy seasons, when infiltration increases due to elevated groundwater (Ellis & Bertrand-Krajewski 2010)	Time-consuming and expert-oriented measurement
		Inexpensive method	Not a very accurate method (Schwindamann 2008).
		relatively easy method	Don't find all the infiltration points (Schwindamann 2008)
		Environment-friendly method	A television camera is needed for monitoring the network (Schwindamann 2008).
	Dye Testing	No need to restricted space entry	
		Inexpensive method	Difficult to see dye in high-flow or turbid conditions
		Relatively easy method	Time-consuming in low flows
		Points to a specific source	Entering a facility is necessary
	DTS Method	No need to restricted space entry	Rather labour-intensive
			Require entrance onto private premises
Source of unwanted water localized exactly (Langeveld et al., 2012; Schilperoort et al. 2009)		High initial cost of the DTS device	
Takes place in the public part of the system and without the residents of the area involved (Schilperoort et al. 2009)		Expert-oriented method in non-automated process (Vosse et al. 2013)	
Safer results compared to more traditional research (Langeveld et al. 2012; Schilperoort et al., 2009)		Almost new technique with low experience in sewer systems	
Large areas –up to several hundred- can be examined and monitored simultaneously		Results are by nature not-easily-reproducible (Vosse et al. 2013)	
Use of single instrument in an easy and safe location		Performance of stormwater separating manifolds varies over time & making them unreliable (Langeveld et al. 2012)	
CCTV method	set-up is easy in use and nearly free of maintenance	Time-consuming method	
	Effective technique	Expensive	
	Inspection of active taps	Ineffective if inactive taps convey illicit discharges (Tuomari & Thompson 2003)	
	Provide observations record	time-consuming to interpret results (Tuomari & Thompson 2003)	
	Only way for pipe inspection between manholes	Conducted in water-filled or obstructed sewers	

these methods can be valuable for reducing assumptions and uncertainties and obtaining more independent, accurate and reliable data about location and magnitude of I/I in the sewer system. A combination of quantitative and qualitative methods will be utilized in localizing and assessing of I/I in the foul sewer systems of Trondheim, Norway. This gives sewer operators the possibility to compare different technologies in assessing infiltration/inflow in the sewer system in a standardized, qualified and quantified way. Use of these I/I assessment methods can support the decision-makers on when and where to rehabilitate, depending on the selection criteria. The application of different methods for evaluating infiltration in sewer systems depends on available data and resources. It should also be considered that an uncertainty assessment should be carried out when various methods are used. Comprehensive and detailed understanding of the locations of any excess water inflow or the illicit connections is necessary for the efficient restriction and removal of infiltration/inflow in the sewer systems. Some infiltration/inflow assessment methods, e.g. tracer method, can be quite labor-intensive and may require entrance onto private premises, while inflows are often only detected by chance. DTS method, smoke testing, and CCTV inspection are the qualitative methods, which are planned to apply in separate foul sewer network of Trondheim. Detecting infiltration/inflow into sewer system by fibre-optic DTS method is a rather new technique in sewer systems. DTS technique is a strong technique for detecting illicit connections to storm sewers, and detecting stormwater entering foul sewers based on previous experiments and researches. Furthermore, the continuous monitoring in time and space makes the DTS a powerful method for investigating flows with different temperatures. Pipe inspection by CCTV is also a useful tool in the case of

detecting defects, their features and locations by video camera inspection.

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