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The impact of infiltration and inflow on wastewater treatment plants

A case study in Sweden

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Summary

Literature regarding the concept of infiltration and inflow to sewer systems with special focus on how it affects the wastewater treatment and wastewater treatment plants were searched through online journals and databases, reports and interviews. The goal was to gain understanding of how the issue is handled in different regions and what the perception and knowledge of the issue is. We also wanted to find out how infiltration and inflow, and the effects of it, is regulated in different parts of the world to be able to understand what can be learnt and applied on the Swedish scenario. In order to better understand the Swedish condition, a comparison of flow data to some (self-selected) Swedish WWTPs was analyzed.

The issue: The amount of infiltration and inflow varies widely due to differences in climate, soil and town planning as well as the state and the principles of the sewers. However, figures on the actual amount of infiltration and inflow (as % of total flow) were scarce and are assumed to not be very representative. Some figures stated can be assumed to be too low, being at least partially due to great variation from year to year due to changes in weather, and a lack of common definitions and methods to calculate and present the data.

Terminology: Infiltration and Inflow, II are the most common words used for water in the sewers that is not real wastewater. However, the term "parasite water" is sometimes used, indicating the principle that the sewer capacity and WWTPs are meant for the actual wastewater and that infiltration and inflow should not really be there.

Infiltration and inflow is widely recognized as an issue for the environment as well as the economy of the operator of the sewer system and WWTPs.

Detection and quantification: At least 11 different methods used to detect or quantify infiltration and inflow were found. Most of them are based on flow rate data in sewers or at the WWTP. Some methods rely on tracers, such as components assumed to originate from wastewater (NH4, COD, etc.) and at least one is based on the composition of the water itself (stable water isotope method). The lower temperature of the inflow can be used to localize leaks. In addition, mathematical modelling approaches can be applied to quantify infiltration and inflow. The amount of infiltration inflow is most often quantified as share of the total flow or addition to the wastewater flow (%).

Solutions and mitigation: Different countries have different solutions, partly due to different climatic and other conditions, but also due to different legislation and perception of the issues of overflow, economics and practicalities of available solutions.

In Australia, the water and wastewater systems need to handle the extremes of both drought and flood and the main part of the population lives in widespread urban and suburban areas. Due to the long sewers connecting households, infiltration and inflow is potentially great even in separate systems. A lot of focus has been placed on water sensitive urban design "WSUD", which aims to reduce both the flood risk and the impact of drought, as well as reduce infiltration and inflow. However, the focus is also towards specifically on decreasing infiltration inflow, by improving the standards of the sewer systems themselves. The driver for this is reducing local combined or separate sewer overflows.

In the US the Clean Water Act together with the National Pollutant Discharge Elimination System (NPDES) regulates point-source discharges such as sewer overflows to meet water quality standards. Under the NPDES Permit Program facilities must secure a permit whenever discharges go directly to surface waters. In addition the combined sewer overflow (CSO) Control Policy requires municipalities to limit CSO discharges which includes constructing underground storage or increasing storage capacity to minimize sewer overflows and meet the Clean Water Act requirements.

New Zealand is close to the Australian and US perception, having recently released an Infiltration and Inflow control manual, based on existing manuals and guidelines from US and Australia.

In the Netherlands where the main part of the sewers is combined there is a movement towards an "improved separate system" where all but the first flush of stormwater is removed from the sewers and handled locally. Taking the first flush to the WWTPs would not be such an issue in the Netherlands, where the sewage sludge is incinerated.

Also in Germany, a large part of the sewers are still combined, although separate systems are politically preferred. There is a shift towards handling stormwater locally in redevelopment.

In Denmark, as in Sweden, there are no national guidelines on managing infiltration and inflow and the main focus is on practical issues, such as the condition of the receiving water body and bathing water quality standards.

Case study Sweden: Daily flow data from 12 medium to large WWTPs in Sweden was collected for the rainy years of 2011 and 2012. The data was analyzed and compared. The median dilution did not vary very much between the WWTPs, ranging from 130 to 230 % of the wastewater flow. However, during the shorter high flow periods the variation was a lot greater. At the ninety nine percentile level, the dilution a WWTP would be subject to for 1 % of the days of the year, the dilution varied from 350 % to nearly 800 % of the wastewater flow.

The other way of describing the flow was by relating it to the population served. When expressed in this way, the median flow to the WWTP was found to be between 250 to nearly 500 liters per person per day. However, the ninetynine percentile level ranged from 500 to above 1500 liters per person per day, giving the WWTPs substantially different hydraulic loadings to handle. When the hydraulic loads were compared with the capacity, it is not always the WWTPs with the highest peak flows that can handle the largest flows. Several WWTPs exceeded their hydraulic capacity around 1 % of the days during a rainy year, while one or two up to 10 % of the days.

Whereas dilution rate is a good measure when evaluating and comparing the performance of the sewer system, the population specific flow to the WWTP has advantages when comparing the situation between WWTPs. It relates the hydraulic burden of the flow to the service to society expressed as number of people served with wastewater treatment.

Sammanfattning på svenska

Syftet med arbetet var att förstå hur tillskottsvatten betraktas och hanteras internationellt, med fokus på påverkan på avloppsvattenrening och avloppsreningsverk. Vi ville också förstå om och hur tillskottsvatten och dess konsekvenser regleras i olika delar av världen och vilka lärdomar som kan vara av betydelse för Sverige. För att bättre förstå de svenska förutsättningarna har också en jämförelse av flödena till ett antal frivilliga svenska avloppsreningsverk genomförts.

Det visade sig **svårt att kvantifiera och jämföra** tillskottsvattenmängderna (som % av totala avloppsvattenflödet) baserat på den internationella litteraturen. De siffror som återfanns varierade stort och kan antas ha beräknats på olika sätt och utan enhetliga definitioner. Vi fann inget tydligt hänsynstagande till nederbördsberoende variationer mellan åren. En del av siffrorna kan därför antas vara för låga, särskilt om det är inverkan på investeringarna på avloppsreningsverket som man är intresserad av.

Angående **terminologin** så var *infiltration and inflow* (infiltration och inflöde), *I/I, II* eller variationer på detta tema de vanligaste uttrycken för tillskottsvatten. Termen *parasite water* (parasitvatten) används ibland och uttrycker tanken att tillskottsvattnet tar utrymme och kapacitet i ledningar och reningsverk från spillvattnet, som är det vatten som anläggningarna är avsedda för. Tillskottsvatten beskrivs allmänt som ett viktigt problem, såväl för miljön som för ekonomin för de som äger och driver ledningsnät och avloppsreningsverk.

Åtminstone tretton olika metoder för att **detektera och/eller kvantifiera tillskottsvatten** återfanns i litteraturen. De flesta baseras på flödesmätningar i ledningar eller till reningsverket. Spillvattenflödet eller basflödet definieras på olika sätt varefter mängden eller andelen tillskottsvatten beräknas. En del metoder baseras på analys av parametrar som representerar spillvattnet, varefter utspädningen och tillskottsvattenmängden kan beräknas. Internationellt beskrivs ofta metoder baserade på COD, men framgångsrik kvantifiering och spårning i Sverige har på senare år baserats på ammonium, kväve och/eller fosfor. Ammoniummetoden är tilltalande för spårning, eftersom det snabba resultatet från en ammoniumelektrod ger omedelbar information som den vidare spårningen kan baseras på. I något fall har isotopsammansättningen för själva vattnet använts för kvantifiering av tillskottsvatten. Framgången i detta är givetvis beroende av att källan för tillskottsvattnet är väsentligt annorlunda än källan för dricksvattnet. Matematisk modellering har framgångsrikt använts såväl för att kvantifiera tillskottsvattenmängderna som för att förstå mekanismerna bakom tillflödet. Tillskottsvattenmängderna uttrycks ofta som %, men procentsiffran kan antingen avse andel av det totala flödet eller tillskottsvattenmängden i förhållande till spillvattenmängden. Luleå Universitet (Dag och Nät) utvärderar en del av de nämnda metoderna inom ramen för Formasprojekt 2012-618.

Lösningar och strategier för tillskottsvattenfrågan varierar mellan regioner och länder beroende på bland annat klimat, ekonomi och andra förutsättningar, men också beroende på lagstiftningen och på hur man ser på bräddning av spillvatten och översvämningar.

I Australien, där en stor del av befolkningen bor i utbredda villaområden i några stora städer är ledningslängden per person hög och tillskottsvattenmängderna potentiellt höga även med duplikatsystem. VA-systemen måste också kunna hantera såväl extrema nederbördsmängder som torka. Man fokuserar mycket på att hantera dagvatten på ytan genom s.k. WSUD (Water Sensitive Urban Design) vars syfte är att minska risken för översvämning och torka såväl som att minska tillskottsvattenmängderna till avloppssystemen. Man arbetar också specifikt med att sänka tillskottsvattenmängder genom krav på täthet i nylagda ledningar. Drivkraften bakom detta är främst att minska lokala bräddningar från kombinerade eller separata system.

I USA regleras punktkällor till vatten, exempelvis från reningsverk och ledningsnät, genom ”Clean Water Act” och National Pollution Discharge System (NPDES). Anläggningsägare måste ha tillstånd enligt NPDES när utsläpp sker direkt till vatten. Dessutom finns en särskild bräddningspolicy, CSO Control Policy, enligt vilken samhällen är ålagda att begränsa bräddningar, exempelvis genom att införa lagringsvolymer i systemen för att klara kraven.

I Nya Zealand är inställningen lik den i USA och Australien. Nyligen har en manual för att begränsa tillskottsvattenmängderna presenterats. Den är baserad på manualer och riktlinjer från USA och Australien.

I Nederländerna, där avloppssystemen i huvudsak är kombinerade, pågår en rörelse mot ”förbättrade separata system” där allt regnvatten utom det första från en yta ”first flush” hanteras lokalt på ytan. Att leda det första och mest förorenade dagvattnet till reningsverket bör inte utgöra ett kvalitetsproblem för slammet i Nederländerna eftersom slammet ändå förbränns där.

Även i Tyskland är en stor del av avloppssystemen kombinerade trots att separata system föredras politiskt. Vid nyutveckling av städer och samhällen hanteras numera ofta dagvattnet lokalt.

I Danmark, liksom i Sverige, finns det inga nationella riktlinjer för tillskottsvatten och fokus är i huvudsak på praktiska frågor, som tillståndet i recipienten och badvattenkvalitén.

För att bedöma läget i Sverige samlades dygnsflödesdata för de regniga åren 2011 och 2012 från tolv stora eller mellanstora reningsverk in och bearbetades. Spädningen varierade för reningsverken under de flesta av dygnen (median) från 130 till 230 % av spillvattenflödet. Under de korta perioderna som är avgörande för reningsverkets funktion var variationen betydligt större. Vid 99-percentilen, den utspädning som överskreds en procent av årets dagar, varierade utspädningen från 350 % till nästan 800 % av spillvattenflödet. Ett annat sätt att beskriva flödet är hur högt flöde som reningsverket tar emot per person och dygn. Uttryckt på det viset var medianflödet till reningsverken 250 till nästan 500 liter per person och dygn. Vid 99-percentilen varierade flödena från 500 till 1500 liter per person och dygn, vilket ställer väldigt olika krav på reningsverkens kapacitet för att hantera höga flöden. När de hydrauliska belastningarna jämfördes med kapaciteten för de biologiska reningsstegen är det tydligt att det inte alltid är reningsverken med de högsta flödena som också kan hantera mest vatten. Flera reningsverk hade flöden som överskred den biologiska kapaciteten en procent av årets dagar, medan några hade flöden som överskred kapaciteten upp till 10 % av dagarna under dessa regniga år.

Utspädningsgrad är ett bra sätt att kvantifiera tillskottsvattenmängder om det är ledningsnätets funktion som ska utvärderas. Flödet per ansluten person har fördelar när det handlar om att värdera den hydrauliska belastningen som ska hanteras på reningsverket. Det uttrycker den hydrauliska belastningen i förhållande till folkmängden som reningsverket är avsett att betjäna.

Contents

Background

The development of sewer systems started over a century ago for the main purpose of sanitation followed by environmental protection due to rapid urban growth (Bäckmann, 1985; EPA, 1971). However, until recently many of these systems have not received proper maintenance and upgrades and their poor performance has negative impacts on the environment. Particularly in combined sewer systems the inability of sewer pipes and wastewater treatment plants to handle large amount of water will likely result in overflows and direct releases of untreated wastewater into receiving waters (Field and Struzeski, 1972). These overflows are mainly caused by excessive infiltration and inflow of stormwater and groundwater, particularly after periods of rain and snowmelt.

The problem with infiltration and inflow which started many years back is widespread and affecting wastewater systems around the world (Weiss et al., 2002; Palowski, 2014; Tesik, 2015). This problem, if not alleviated, is expected to increase as the wastewater systems age and deteriorate. In addition to the water quality issue, infiltration and inflow cause property damage due to flooding or sewage backups into basement and streets and increase risks to public health (Bäckmann, 1985; Gustafsson et al., 2010).

The occurrence of infiltration and inflow has a significant impact on both economics and operation of wastewater treatment plants. Infiltration and inflow causes operational difficulties for the treatment facilities and increase costs due to energy demand, use of chemicals and labor costs (Ellis, 2001; Karpf and Krebs, 2011). Hence, high investment costs may be needed if treatment capacity and efficiency have to be met.

In the United States, the treatment and collection of wastewater accounts for up to 15% of the total infrastructural investment (NCPWI, 1998). In Sweden, wastewater management is also a vital part of the economy with 95% of domestic wastewater undergoes biological and chemical treatment processes (Naturvårdsverket Rapport, 2009).

Infiltration and inflow problems have been extensively studied in Germany, Norway, Netherlands, United Kingdom, USA, Canada, New Zealand and Australia. Guidelines related to management and control of infiltration and inflow have been developed in some cities while this issue is still under discussion and debate in northern Europe especially Sweden and Denmark.

Infiltration and inflow to the sewer systems is an issue in many countries and under different conditions. Actions for a sustainable management of the urban sewer systems are taken in order to protect public health and environmental resources.

Aim and limitations

The aim of this project is to evaluate the state-of-the-art of the impact of infiltration and inflow on wastewater treatment with focus on cities with Northern European climate. This covers issues related to combined sewer overflows (CSOs) and its environmental and social impacts. The case study was carried out by analysis of flow monitoring data from fully-functioning wastewater treatment plants in Sweden. The report does not cover flooding of local buildings and private properties. Neither are issues concerning the sources of infiltration and inflow covered in this study.

Methodology

A literature search was conducted to be able to gain knowledge about existing studies and practices related to management of infiltration and inflow in different cities giving special attention to cities with climatic conditions similar to those in Northern Europe.

A case study was focused on wastewater treatment plants in different cities of Sweden, based on the analysis of average daily flow measurements conducted for one-year periods of 2011 and 2012 respectively.

Interviews were conducted with key people in the wastewater and research industries in Sweden and abroad.

Results of literature review and interviews were presented under different topics specified in the report.

Terminology

Table 1 presents the definition of different terms referred to in this report.

Table 1. Terms and definitions

Terms	Definition	Reference
Infiltration	groundwater or water from below ground level (including seawater intrusion) that enters the sewer system through different sources such as leaking pipes and joints; this also contains some inflow water during wet weather period (rain-induced infiltration)	Weiss et al., 2002; EPA, 2014; Moors, 2015
Inflow	typically stormwater that enters the sewer system directly after storm events from roof and foundation drains and as a result of illegal or faulty connections and defective manholes	Weiss et al., 2002; EPA, 2014; Moors, 2015
Infiltration and inflow	total infiltration and inflow water where the sources are not distinguished	Bäckman, 1985
Combined sewer overflow	discharges of untreated wastewater and storm water from combined municipal sewer system due to poor hydraulic capacity during high flows or storm events	EPA, 2004; Schilperoort, 2004
Sanitary sewer overflows	discharges of untreated wastewater mostly as a result of pipe breakage, pump failure or poor maintenance	EPA, 2004¸ Schilperoort, 2004
Sanitary sewage	refers mainly to wastewater from domestic, commercial and industrial sources	EPA, 2004

Infiltration and inflow

What is infiltration and inflow and how are they quantified?

Infiltration and inflow is the intrusion of groundwater, stormwater or surface water into the sewer system through direct and intentional connections and/or leakages from defective pipes and manholes. Infiltration and inflow is also referred to in literature as parasite, unwanted, irrelevant or extraneous water. Infiltration and inflow to the sewer system may exhibit negative effects on the WWTP such as dilution of pollutant concentration in the wastewater resulting in increased pollutant load to the recipient water, reduction of sewer system and wastewater treatment capacity resulting in hydraulic overload of up to 100% and increase in operating costs (Ellis and Krajewski, 2010). Therefore, the intrusion of infiltration and inflow in the sewer systems is an economic issue as it needs to be transported and treated as real wastewater.

Infiltration and inflow differs a lot between WWTPs due to different factors such as the type and quality of the pipe, groundwater level and rainfall conditions (Ødegaard, 2016).

A number of methods have been developed and applied to quantify, detect or localize infiltration and inflow in sewer systems and they can be found in various publications (Weiss et al, 2002; Staufer et al., 2012; USEPA, 2014). There are two types of quantification methods: (1) the flow rate methods based on daily flow monitoring; and (2) the tracer methods based on natural tracer or pollutant load mass balance (see **Table2** for the description of the different methods). The conventional flow rate methods can be applied to quantify the amount of infiltration by measurements of wastewater flow during dry weather periods as average dry weather flow (EPA, 2014) or as total daily flow (Weiss et al, 2002; Ertl et al., 2008). Assuming most of the flows are due to groundwater, the rate of infiltration can also be quantified by taking the average of night time flows on dry weather days (WSAA, 2013; Water NZ, 2015). Usually the dry weather flow refers to periods of no rainfall and zero inflow or at maximum rainfall intensity of 0.3 mm (Staufer et al., 2012). For more accurate results, longer period of flow monitoring including rainfall intensity is recommended. On the other hand, inflow (rain derived or surface inflow) can be measured as the difference between the wastewater flow and infiltration flow data and the wet weather flow data taken from the beginning of the rain up to 4 hours after rainfall. During summer and spring, infiltration and inflow is estimated to be at maximum and high annual variation can be expected (Weiss et al., 2002).

The more recent tracer methods (**Table 2**) have been used to quantify infiltration based on mass balance analysis using a natural tracer such as water stable isotopes or pollutant load as COD, TSS or NH_4 concentration (De Benedittis and Bertrand-Krajewski, 2005; Kracht and Guyer, 2005; Bares et al., 2008; Kracht et al., 2008; Uggerby et al., 2013). In the isotope method, the wastewater flows were monitored together with the hydrogen and oxygen isotopes and compared to that of groundwater and drinking water. Results from studies have shown that during nighttime the wastewater is rich with isotopes and gets depleted during the day (Kracht et al., 2008). On the other hand, the chemical oxygen demand or COD is considered appropriate for this application since its concentration in infiltrating water can be assumed negligible. The COD method is simplified by employing an automated in-line device that measures COD spectrometrically. These tracer techniques have been evaluated in Switzerland in line with the European research project APUSS “Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems” (Kracht et al., 2008).

Other methods used to detect or localize I/I include smoke testing, dye testing, distributed temperature sensing (DTS) and closed circuit television (CCTV) method (Schilperoort, 2013; Beheshti et al., 2015).

In Europe, the use of Distributed Temperature Sensing (DTS) has been applied to localize sources of extraneous water or illicit storm water inflows into sewer systems (Hoes et al., 2009; Schilperoort et al., 2013; Uggerby et al., 2013; Walters, 2015). With the help of a fiber-optic cable installed in the sewer, this method records high resolution data of in-sewer temperatures at specific time and location over long monitoring periods. The detected abnormal temperature ranges or unexpected variations at specific location suggest the presence of illicit or unintended inflows (Hoes et al., 2009).

These approaches are based on some assumptions, each one having its own advantages and limitations as referred to in **Table 2**.

Table 2. Different methods used to detect or quantify the presence of infiltration and inflow

Methods	Type	Short description	Advantages (+) Disadvantages (-)	References
Triangle	Flow rate method	measures total daily flow (minimum 21 days) and rank in ascending order of magnitude, typical S-shaped curve	+ include both wet- and dry-weather days + simple and widely-used - large variation of results	Weiss et al, 2002
Moving-minimum	Flow rate method	measures total daily flow and determine temporal variation of I/I	+ simple and widely-used - large variation of results	Weiss et al, 2002; Ertl et al., 2008
Dry weather flow	Flow rate method	measures flow hydrograph on dry weather days	+ simple and widely-used - neglect days with storm inflow - inaccurate results	EPA, 2014
Minimum night time flow	Flow rate method	measures night time flow, assuming most flow due to groundwater	- mainly based on hydrograph - applicable only to residential flow	WSAA, 2013; Water NZ, 2015
Density average	Flow rate method			Ertl et al., 2002
Stable water isotope	Tracer method	uses direct natural tracer such as stable isotope composition of local drinking water (proxy for sewage) and local groundwater (proxy for infiltrating water)	+ allows direct calculation of infiltration ratios + robustly produce accurate results + suitable for routine applications on catchment or sub-catchment scale - requires comprehensive hydrologic and hydrogeological study - costly - certain boundary conditions have to be satisfied, ex. only one source of wastewater and one source of infiltration water	Kracht et al., 2008; Ellis and Krajewski 2010; Schilperoort, 2004
Pollutant time-series	Tracer method	measures infiltrating waters based on time series of wastewater flow, pollutant concentration is measured at a single point in the sewer system using automatic in-line device with a high temporal resolution	+ uses automatically operating in-line device + robustly produce accurate results - costly - requires a minimum amount of wastewater for the device to operate	Kracht et al., 2008
Ammonium concentration	Tracer method	Analyze ammonium concentration of grab samples and relate to expected concentration in undiluted sanitary wastewater. Too much II is assumed when ammonium concentration is	+quick and simple +uses natural tracer in wastewater -Equipment for analyzing ammonium in field	Uusijärvi, 2013

Methods	Type	Short description	Advantages (+) Disadvantages (-)	References
		below a set value, for instance 20 mg N/l.		
Nitrogen and Phosphorus concentration.	Tracer method	Analyze total nitrogen and phosphorus concentration of composite samples and relate to concentration in sanitary wastewater.	+ II can be accurately quantified -Time consuming sampling and analysis. - Equipment for sampling	Mattsson et al. 2016
Distributed Temperature Sensing (DTS)	Detection/ localization method	locate sources of I/I using fiber-optic cable installed in the sewer to record high resolution in-sewer temperatures at specific time and location	+ this technique is based on a proven technology + easy to use and does not require access to private properties + allows detection of foul water discharges to storm sewer and vice versa + accurate measurements with high spatial and temporal resolution - more advanced equipment is needed - costly - time-consuming	Hoes et al., 2009; Pazhepurackel, 2009; Schilperoort et al., 2013; Uggerby et al., 2013; Walters, 2015
Stevens-Schutzbach	Empirical method	measures groundwater infiltration or base infiltration using empirical relationship between average daily sanitary flow and minimum daily flow	+ good estimate of based infiltration + verified as most accurate empirical method - applicable only to residential flow	Mitchell et al., 2007
Minimum flow factor	Empirical method	uses average daily flow to determine minimum daily flow in relationship to basin size, based on published minimum flow factors		Mitchell et al., 2007
Mathematical modelling approaches			- labor intensive - requires loads of data and longer monitoring period	Karpf and Krebs, 2011

Infiltration and inflow can be reported in various ways, such as based on the number of inhabitants connected (in liters per person per day), the size of the sewer system (in liters per millimeter of pipe diameter per kilometer length per day) or as the ratio of peak wet weather flow to average dry weather flow (Donohue and Associates, 2012).

According to some studies, majority of the cases related to infiltration follows an 80/20-rule, which means that 80% of the problem originates from 20% of the area (CIRIA, 1996; Stevens, 2012). This ratio could be used to estimate the initial cost of the I/I study. In addition, the amount of infiltration may vary widely with a range between 10 and 1,000 liters per day per millimeter pipe diameter per kilometer of pipe length (Metcalf & Eddy Inc., 1991).

The EPA suggested a threshold infiltration rate of 140 liters/per mm diameter per kilometer length per day while in excess of that amount further removal is required (EPA, 2014). As most of the sewer systems are operating as separate systems, the WWTPs are not configured to treat high flows especially during storm events. Therefore, there has been a great deal of work related to I/I and reduction of inflow in many cities.

Issues of infiltration and inflow

Sources

Infiltration comes from surrounding soil that enters the sewer system through cracked pipe walls and displaced joints and continues in a steady but slower rate even after a rainfall event (**Figure 1**).
Infiltration is mostly groundwater, however, when sewer system or pumping stations are located nearby shorelines, intrusion of seawater is possible. In many places groundwater infiltration is often severe wherever sewer systems lie below the water tables. Infiltration is easier to quantify than inflow.

Inflow enters the sanitary sewer system directly after storm events from different sources such as roof run offs, sumps, yard drains and foundation drains, through defective manholes and storm sewer cross-connections (EPA, 2008). During and immediately after storm events inflow water can contribute as much as 70 to 80% of the I/I load in large WWTPs while in smaller plants it can contribute up to 95%. Nevertheless, its total contribution to the annual flow is quite low (Pearlman, 2007; Field and Struzeski, 1972). As sanitary sewers are normally constructed below storm sewers, cross-leakages in separate systems is an unavoidable risk (Bäckman, 1985).

Several parameters influence the occurrence and magnitude of infiltration and inflow such as the geohydrological conditions (i.e. soil characteristic, groundwater table), construction of the sewer trench, sewer pipe material, workmanship, age of the sewer system, maintenance procedure and connected impermeable surfaces (Bäckman, 1985; GSDS, 2005; EPA, 2008).

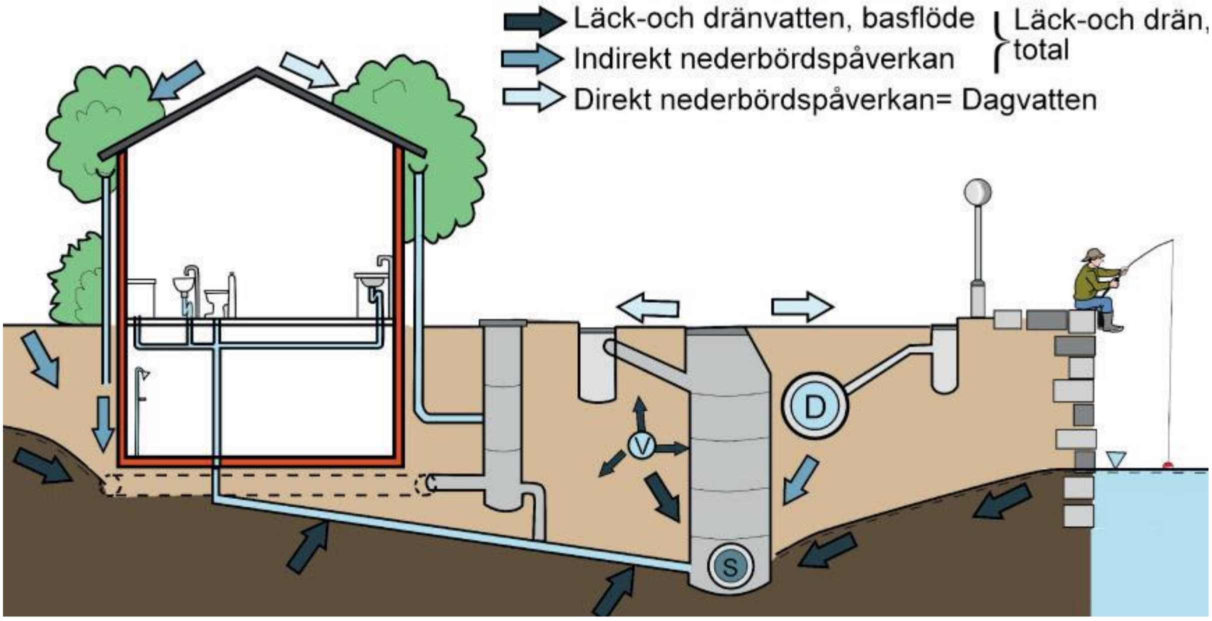

Figure 1. Possible sources of infiltration and inflow (Bäckmann et al., 1997; Svenskt Vatten Utveckling Rapport Nr 2014–11)

Systems

Most urbanized areas are served with two different types of sewer systems, combined system and separate system. In combined sewer systems both wastewater and stormwater (also referred to as rainfall or surface run off) are transported in a single pipe to the wastewater treatment facility, whereas in separate systems the wastewater and stormwater are conveyed separately with only wastewater undergoing treatment before discharged into surface waters (EPA, 2004; Weiss and Brombach, 2007; Schilperoort, 2004). Although separate sewer systems can be considered beneficial, still many combined systems are in use today, especially in older cities around the world. This is partly due to the high investment costs needed to transform combined sewer systems into separate sewer systems. For completely new urban development separate sewer systems are often preferred.

As shown in **Table 3**, both systems have its own advantages and disadvantages.

Table 3. Comparison of separate and combined systems*

Advantages	Disadvantages
Separate sewer system	
Low risk of overflow and flooding Low health risk Reuse of stormwater Low energy and labor costs at treatment plant	High capital and maintenance cost Risk of faulty connections Risk of pollution from untreated stormwater ex. heavy metals from roofs and surface run offs
Combined sewer system	
Minimum operation and maintenance cost Pollutants from stormwater can be treated	Large volume of water to be treated High risk of overflows Release of polluted wastewater during overflow Lower pollutant removal at WWTPs

*References: 1) Schilperoort, 2004; 2) Weiss and Brombach, 2007; 3) Laden, 2010; 4) Beheshti et al., 2015

Rebuilding all combined systems into completely separated sewer systems might be a challenge in the near future due to the possible increased risks from direct discharges of stormwater into local receiving waters. This may demand construction of extra storage basins not only for hydraulic purpose but also to capture and retain pollutants from stormwater and minimize unnecessary pollution of receiving waters.

In Denmark, decentralization of stormwater and centralization of wastewater treatment has been implemented, by converting combined sewer systems into separate networks. This increases treatment capacity, reduces combined sewer overflows and enables the release of "clean" stormwater into natural recipient water bodies (Thorndahl et al., 2015). However, despite constructing new separate systems only a part can be considered as "truly" separate systems since the majority are still connected to the existing combined sewer system. Thus, the present sewerage system in Denmark consists of a minor percentage of "truly" separate systems and a major percentage of combined sewer systems (Schaarup-Jensen et al., 2011). On the other hand, there have been ongoing efforts in some municipalities to change the old combined system into separate sewer systems but this can take many years to accomplish due to the complexity of the infrastructure and high investments needed (Lautsen,2016).

In Sweden, the use of combined sewer systems was common until the mid-1950s. Since then separate systems were developed but until now 20-25% of urban areas are still operating with combined sewer systems. In Germany, around 50% of the population is served by combined sewer system which is still the most preferred system while separate system is considered more as a political preference (Weiss and Brombach, 2007; Brombach et al., 2005). In Netherlands, combined systems constitute 72% of all Dutch gravity drainage systems (Schilperoort, 2004). However, nowadays the improved separate system is the most desired choice especially in modern residential areas in the Netherlands (Schilperoort, 2004). This improved separate system is a new drainage system in which the first part of the stormwater called the "first flush" which is most contaminated is directed to the wastewater pipe to be treated at the treatment plant (Larsen et al., 1998; EPA, 1999; Schiperoort, 2004).

In Canada, the construction of new combined sewer systems has been prohibited since mid-1970s, and there are no present jurisdiction allowing new combined sewers or combined sewer extensions. Yet, a number of older municipalities are still at least partially served by combined systems (HMM, 2012).

Compared to other countries, separated stormwater and wastewater systems are very common in Australia (NRMMC, 2004).

Problems

The occurrence of infiltration and inflow can negatively affect both the economics and operation of the entire sewer network and wastewater treatment facilities especially if biological processes are involved. Excessive infiltration and inflow reduce both the sewer hydraulic performance and the wastewater treatment efficiency. Consequently, this brings significant increase in operation costs due to extra energy requirement for pumping, addition of chemicals and extra labor costs (Ellis, 2001; Karpf and Krebs, 2011). When pumping stations are located near coast lines, the intrusion of seawater adds to infiltration flow creating high risk of odor problems and corrosion of sewer lines due to hydrogen sulfide and sulfuric acid (GSDS, 2005). Due to climate change, the rising of sea level can be expected and this can have detrimental effects on the sewer systems in the coming years, in addition to predicted increase in precipitation intensity. In addition, the burden of infiltration and inflow is high for aging and deteriorating sewer infrastructures (Tafuri and Selvakumar, 2002).

During wet weather periods, high amounts of inflow and infiltration enter the sanitary sewer and cause surcharging of the pipes giving rise to sanitary sewer overflows and pollution of receiving water (Adams and Papa, 2000). Discharges of untreated wastewater and stormwater are known to contain high concentrations of organic compounds, heavy metals, pathogenic microorganisms and other environmental pollutants (Gasperi et al., 2009; Birch et al., 2011; Gasperi et al., 2010; Passerat et al., 2011). In addition to water quality issue, these unwanted discharges have corresponding social costs in the form of property damages due to flooding or sewage backups in basements and streets, increasing risks to public health (Bäckmann, 1985; Gustafsson et al., 2010).

The impact of climate change should also be considered as it influences the performance and condition of sewer systems by increasing risk of pipe defects, storm overflows, pollutant and odor problem, saltwater intrusion as attributed by several sources such as increased variations in weather, rainfall intensity, temperatures and sea level rise (King County, 2011; Moors, 2015).

In the USA, between 23,000 and 70,000 sanitary sewer overflows (SSOs) has been reported to occur yearly, with a total volume of up to 40 billion liters, 60% of which comes from leakages. Discharges of untreated wastewater and stormwater due to combined sewer overflows have been estimated to be roughly 3,200 billion liters annually. This phenomenon, in addition to sewer leakages contaminating recreational waters, has contributed to major waterborne disease outbreaks in the U.S. (Tibbetts, 2005). The occurrence of sewer overflows has been a major threat to drinking water quality (Golden, 1996).

In Australia, the average annual contribution of stormwater pollutants such as nutrients and suspended solids to Sydney Harbor has been estimated to be 63.5 tons, 475 tons and 343,000 tons of total-N, total-P and TSS (total suspended solids), respectively, and is expected to increase up to three times during wet season (Birch et al., 2010).

Perception of the problem

Infiltration and inflow is a big part of urban wastewater management issues recognized globally. Increasing attention has been paid and more and more studies are being conducted to investigate the important sources and plausible solutions to control or reduce its occurrence and quantity. It is clear that insufficient maintenance of sewer systems contribute significantly to infiltration and inflow. It is often difficult to evaluate the magnitude of the problem due to lack of reliable data and information and finances to deal with the existing sewer network and the consequences downstream of the treatment plant. Despite awareness of the problem, rehabilitation of existing systems is not prioritized not only due to financial constraints but also due to lack of political involvement and support on the issue.

Due to the complexity of the problem, it is not only the responsibility of the municipality or the water management sector but also the private property owners as they are significant contributors to the problem.

Solutions

To help mitigate the problem, newly developed and modern sewers and WWTPs in developed cities are nowadays built with extra capacity to manage stormwater. Stormwater management is an important component in urbanized areas. In many cities, the stormwater is reused for watering gardens, recreational fields and golf courses, as an environmentally friendly alternative. The reuse of stormwater for such purposes also reduces the utilization of drinking water. In addition, green infrastructure practices such as rain gardens, permeable pavements or *in situ* infiltration system to mimic the process of retaining water in a natural way are being employed. These systems not only produce cleaned and filtered water but also reduce the volume of stormwater that enters the sewer system (Dietz, 2007; Woodcock et al., 2013). Green infrastructure has been practiced in many cities and different terms are used in literature. In the US, it is called “low-impact development technologies”, “water sensitive urban design (WSUD)” in Australia and Canada and in the UK “sustainable urban drainage systems (SUDS)” (GDSDS, 2005). In Sydney (Australia), the WSUD program is highly supported by the communities.

Another water conservation technique called the grey infrastructure has been employed to increase sewer and wastewater treatment capacity through construction of larger diameter pipes and underground storage to temporarily store stormwater (Moors, 2015).

Minimizing the potential for overflows through source control or prevention practices is often effective and economical and these can be made possible through adequate sewer maintenance, reuse and/or recycling of wastewater and stormwater and reduction of surface run off (Kok, 2004; ARMCANZ and ANZECC, 2004; Moors, 2015). These strategies could be integrated by municipalities as a vital component to the water or wastewater management plans.

In many cities, separate sewer systems have been implemented in response to problems encountered with combined sewer overflows, insufficient wastewater treatment capacity during high flows, and sewer backups. However, even on dry weather days the incident of sewer overflows cannot be avoided when there is pumping failures or pipe blockages. Consequently, the ecological effect of sewer overflows during dry periods is more severe as the wastewater is more polluted and undiluted in comparison to wet weather overflows (Winder, 2003). In addition the environmental impact of sewer overflows depends largely on the quality of the discharge and the receiving environment (Winder, 2003).

More stringent regulations on wastewater effluent quality including infiltration and inflow released as overflows and bypasses are needed in order to maintain excellent quality of the water bodies. In the US, point source discharges such as sanitary sewer overflows are prohibited under the Clean Water Act and require secondary treatment, limits on oxygen-demanding pollutants and suspended solids, as well as disinfection to be able to meet its water quality standards. On the other hand, no secondary treatment is required for CSOs. However, a CSO Control Policy has been issued and required municipalities to minimize or prevent CSO discharges such as by constructing underground storage separating wastewater and stormwater. Blending or bypassing has been allowed to manage peak flows, followed by effluent disinfection before discharged into water bodies (Tibbetts, 2005). However, a bipartisan legislation which amended the Clean Water Act prohibited bypassing in municipal treatment plants except when there is “no feasible alternative to the bypass”.

Australia has undertaken significant work on the issue of infiltration and inflow in sewer systems and developed strategic framework on infiltration and inflow management which includes policy, guidelines and current management practices. In 2013, WSAA (Water Services Association of Australia) released a guideline called “Good Practice Guideline for the Management of Wastewater System Infiltration and Inflow” which made a conclusion based on Melbourne Water study that rehabilitation of at least 40% of the total piped system within a catchment is needed to produce a measurable reduction in rainfall-derived inflow and infiltration (RDII) (MWH, 2008).

A national legislation in New Zealand called Local Government Act (LGA) includes provisions providing water agencies the right to perform certain actions related to infiltration and inflow management such as source detection and rehabilitation. The provisions include powers of entry to perform investigation and rehabilitation work, construction of works on private land to rehabilitate sewers and/or disconnect illegal inflow sources (Water NZ, 2015). In addition, bylaws have been adopted by local authority to facilitate the infiltration and inflow projects. For example, a wastewater bylaw prohibits the discharge of storm water from private property into the sewer system. New Zealand also developed an

Infiltration and Inflow Control Manual which is based on existing manuals and guidelines from Australia and USA, with particular reference to the recently published WSAA Good Practice Guidelines.

In Denmark, there are no national guidelines on infiltration and inflow management, however, each municipality is governed by its own regulation related to overflows, such as, for example, some municipality allow a yearly discharge of 0.5% overflow without treatment (la Cour Jansen, 2016). In addition, before any release of overflow a permit is required to assure that the quantity of the overflow is within acceptable limit for the receiving water body (Lautsen, 2016). The treatment plants should be dimensioned based on the recipient water requirement such as fulfilling the bathing water quality standard in Copenhagen area. Furthermore, the design of new sewer systems should be based on a 10-year period of storm. Recently, under *The Cloudburst Management Plan* additional measures are considered in order to handle and direct stormwater to the sea via roads, canals, urban waterways and underground tunnels (Haghighatafshar, 2014). Environmental impacts of such systems are yet to be investigated.

Table 4 presents a summary of existing guidelines and regulations related to infiltration and inflow and overflows in different countries.

Table 4. Guidelines and regulations related to infiltration and inflow

Country	Title	Short description	Reference
USA	National Pollution Discharge Elimination System (NPDES)	NPDES permit program addresses water pollution by regulating point sources that discharge pollutants directly to receiving water	EPA
USA	Prevention and Correction of Excessive Infiltration and Inflow into Sewer Systems - Manual of Practice	Guide to local officials to determine the magnitude and location of infiltration and inflow, economic evaluation of excessive infiltration and inflow and corrective actions	APWA, 1971
USA	Combined sewer overflow (CSO) Control Policy	Limit CSO discharges such as constructing underground storage to meet the Clean Water Act requirements	EPA, 1994
USA	Guide for Estimating Infiltration and Inflow	Provide information on estimating infiltration and inflow volume in the collection system and for responding to NPDES permit reporting requirements.	EPA, 2014
USA	Reducing Peak Wet Weather Flows through I/I Reduction	Guideline document for I/I management	WERF, 2003
USA	Existing Sewer Evaluation and Rehabilitation	Guideline document for sewer evaluation and rehabilitation programs	WEF, 2009
Australia	Good Practice Guidelines for Management of Wastewater System Inflow and infiltration	guideline document for I/I management programmes across Australia	WSAA, 2013
New Zealand	Inflow and infiltration control manual	Guideline document for I/I management	NZ Water and Wastes Association, 2015
New Zealand	Local Government Act (LGA)	provides water agencies the right to perform certain actions related to infiltration and inflow management such as source detection and rehabilitation	LGA, 2002
Canada	Best practices guide: Management of inflow and infiltration in new urban developments	Guideline document for I/I management	Kesik, 2015
Denmark	The Cloudburst Management Plan	Includes methods measures to handle and direct stormwater during extreme rainfall	The City of Copenhagen, 2012

How much or how big is the problem?

Global experience

The issue of sewer infiltration and inflow is widespread and many cities around the world are facing severe environmental consequences. There has been a great deal of studies related to infiltration and inflow as a result of more stringent regulations on water quality standards. However, the lack of investments in sewer maintenance and rehabilitation is a limiting factor that will likely result in continuous deterioration of the urban sewer infrastructures, increasing events of sewer overflows due to excessive infiltration and inflow (Rehan et al., 2014).

In Europe, most of the municipalities are served with combined sewer systems and serious problems related to overflows have been encountered as a result of excessive infiltration and inflow (Bäckman, 2016).

Worldwide, the rate of infiltration and inflow varies to a great extent due to the complexity of the sewer system and the many factors influencing its magnitude. Wide variations can be expected between WWTPs and municipalities due to different factors such as the condition of the sewer infrastructure, rainfall intensity, soil conditions and the groundwater level. This problem is expected to increase as more and more severe precipitation is predicted to occur in the future (Haghighatafshar, 2014). **Table 5** shows the estimated average contribution of infiltration and inflow to sewer systems based on different quantification methods.

Table 5. Estimated average contribution of infiltration and inflow to sewer system reported in literature

Country	% I/I share	Reference
Germany (Baden-Württemberg)	35	Weiss et al, 2002
Netherlands	38	Schilperoort, 2004
Norway (14 different cities)	67	Ødegaard, 2016
Austria (32 WWTPs)	25-50	Ertl et al., 2008
Sweden	50	Svensson and Gustavsson, 1996; Gustavsson and Svensson, 1996
UK	45	White et al., 1997; Ainger et al., 1998
Scotland (Edinburgh)	60	GDSDS, 2005
Ireland (Dublin)	10-75	GDSDS, 2005
Switzerland	35-65	Kracht and Gujer, 2005
Canada	8	Holeton et al., 2011; Environment Canada, 2010
Czech Republic	45	Bares et al., 2008
USA	55-65	Pearlman, 2007

The methods of quantifying infiltration remain controversial due to considerable uncertainties associated with underlying assumptions which may be crucial when planning a sewer rehabilitation program. In addition, small cities and low-income municipalities are generally limited with resources for sewerage infrastructure development and technicalities.

North European climate

Norway

A lot of work has been done in Norway related to infiltration and inflow. Based on a recent survey conducted on 14 Norwegian cities, infiltration and inflow accounted for in average 67% of the total flow at the treatment plant (Ødegaard, 2016). Consequently, the release of nutrients via overflows (in kg/yr) was found to be higher than the wastewater treatment plant discharges. As with wastewater, the overflow is regulated in Norway. Therefore prior to discharge, treatment of the overflow is required such as chemical treatment using coagulant and microsand followed by a lamella separator, to remove solids, phosphorus and organic matter. This treatment is important since both wastewater and overflow quality must be measured and reported. In addition, treatment of the overflow to reduce the phosphorus content for the receiving water has been considered a cheaper alternative than extending the capacity of the treatment plant. Norway has done some maintenance at the sewer network such as replacement of 0.1 % of the pipe system but it only covers part of the damaged sewer (Ødegaard, 2016).

Denmark

There are a lot of efforts going on in Denmark in order to find solutions to infiltration and inflow problems in the sewer systems. In some municipalities such as Aarhus, problems in the separate sewer systems are more severe due to high number of illicit connections and leakages from damaged or untight sewer pipes as the most common cause of basement flooding and overflow in pumping stations to the water bodies (Lautsen, 2016). The municipalities are trying hard to investigate the problems such as looking for illicit connections and getting a solution as soon as possible and at the same time the sewer systems are getting rehabilitated through retrofitting and relining. In addition, large storage basins and equalization tanks are in operation in order to handle sewer overflows especially during storm events and until the WWTP is able to treat the overflows. Treatment of sewer overflows is important in Denmark in order to maintain good quality water in rivers, lakes and harbors.

Netherlands

Infiltration and inflow is a serious problem in the Netherlands wherein some catchments studied as high as 80% infiltration and inflow has been recorded. The investment cost necessary to compensate the additional pollution caused by infiltration and inflow has been estimated to be €15/pollution equivalent according to STOWA (Foundation for Applied Water Research in Netherlands). This covers cost to build storage basins and upgrade pumping facilities and treatment plants. Thus, annual investment of roughly €330 million is required to be able to manage approximately 22 million *pollution equivalents* caused by infiltration and inflow (Schilperoort, 2014).

Germany

Result of the study conducted in Baden-Württemberg, south of Germany showed an average infiltration and inflow of 35% in addition to 35% of stormwater are entering the WWTPs from combined sewer systems. Therefore, this accounts to about 70 % of non-sewage water passing through the treatment plant (Weiss et al., 2002).

In a countrywide survey conducted in Germany, an average infiltration of 30% was estimated whereas about 10% of the German WWTPs are expected to experience more than 50% infiltration flow (Statistisches Bundesamt 2003; ATV-DVWK Arbeitsgruppe Fremdwasser 2003).

As part of the pollution control strategy combined sewer overflow (CSO) tanks are employed in Germany and recently there are approximately 20,000 CSO tanks in operation in Germany. However, it has been found that some CSO tanks were still full of combined sewage even some weeks after the storm events.

According to the German Association for Water, Wastewater and Waste (DWA) around 20% of the German public sewer systems needs to undergo short to mid-term rehabilitation for an equivalent cost estimate of about €62 billion ($70 billion) (Berger and Lohaus 2005).

Ireland

Infiltration studies in Ireland have been quite limited despite awareness of this issue. The Greater Dublin Strategic Drainage Study (GDSDS) conducted for 3 years an initial evaluation of infiltration through flow measurement and modelling of different catchments. Results revealed that infiltration flow varied widely among catchments, from 10 % to 75 % of dry weather flow. In a WWTP with 4 catchments, a total infiltration flow of 2011 liters per second was observed. In some sewers, the tidal level was found to influence the infiltration rate, increasing the flow as the tide level rises. In addition, high rates of groundwater infiltration were also observed in some catchments during middle of autumn and middle of spring. Sewer rehabilitation or stormwater diversion has been proposed for sewers that exhibited substantially high infiltration rate (GDSDS, 2005).

Canada

The release of untreated bypasses and overflows as a result of infiltration and inflow is still a serious ongoing issue in Canada. In Ontario, the reported amount of untreated bypasses between 1991 and 2007 was estimated at 2.2 to 10.8 million cubic meters in total (Environmental Commissioner of Ontario, 2003). In addition to combined sewer overflows which are widespread in older urban areas, these bypasses downstream at the treatment plant are localized releases usually occurring over a longer period and threatening the environmental quality of the waterways. In Quebec province alone, more than 30,000 overflow events have been recorded in 2008 with a total duration of over 300,000 hours (Holeton, 2011). Associated with climate change, there has been significant increase in overflows with rainfall events. However, there is still limited information regarding the frequency and CSO discharges in many provinces in Canada. In order to reduce CSOs, the new sewer systems in Canada are mostly built as separate systems while the old combined sewer infrastructures are getting upgraded. In addition, many cities across Canada have adopted technological solutions to divert and treat CSOs using end-of-pipe methods to maintain good overflow quality (Toronto Water, 2007, Li et al., 2004).

Australia

The high frequency of storms in Sydney makes wet weather overflows a major environmental issue for Sydney Water. Thus to tackle the problem on sewer infiltration and overflows, Sydney Water has implemented new low infiltration sewerage (LIS) system (Harris, 2014). This new technology is believed to limit the amount of rain entering the sewer system to not more than 2% with the improved design, construction, quality and maintenance. This eventually leads to reduction in maintenance costs and occurrence of wet weather overflows and enhancement of wastewater treatment capacity. The LIS system are built with either polyvinylchloride, polypropylene or glass reinforced plastic pipes and rubberized ring joints or solvent weld joints (Harris, 2014). This system is designed to handle only up to three times peak dry weather flow therefore the pipe diameter is smaller than usual. Assessment of this technology includes collection of wastewater flow data and rainfall data for comparison to determine the extent of wet weather infiltration. Preliminary results reported based on 1 rainfall event and 2 weeks of monitoring revealed the effectiveness of the LIS system to substantially reduce sewer infiltration.

USA

In the USA, a lot of effort has been undertaken for the purpose of eliminating or reducing extensive infiltration and inflow and a great deal of literature is available related to infiltration and inflow projects in many cities. According to American Society of Civil Engineers (2005), the EPA estimated wastewater infrastructure needs of nearly €350 billion to replace and upgrade existing systems in the United States over the next 20 years including renewal of wastewater treatment. To decrease the amount of CSOs alone by 85% over the 20-year period, the EPA estimated the cost to be about €45 billion ($50.6 billion) (Tibbets, 2005). This results in higher sewer rates to be able to raise funds to maintain and improve sewer infrastructures.

District of Columbia – Combined sewer system long term control plan

The District of Columbia, of which about 1/3 of urban surface is served with combined sewer system, used to discharged combined sewer overflows during period of heavy precipitation into nearby rivers and creek. To control CSOs, the District of Columbia Water and Sewer Authority (WASA) has made an assessment on the impact of CSO on recipient water and developed a CSO “Long Term Control Plan (LTCP)” to meet water quality standard as required under the USEPA National Pollutant Discharge Elimination System (NPDES) Permit. Different technologies were considered and evaluated for its capacity to reduce the amount of CSO and the pollutants involved. These were focused on source control, inflow control, sewer system optimization, sewer separation, storage technologies, treatment, and receiving water improvement. The control measures applied are based on the need of a particular receiving water body. The control measures considered include construction of extra storage and conveyance facility, construction of new pipeline, separation of combined sewer overflows, rehabilitation of pumping stations, construction of new pumping stations and upgrading of WWTPs. At the WWTP, improvements include addition of new clarifiers and nitrogen removal process. The WWTP is expected to capture and treat 99% of CSO based on yearly average with the LTCP implementation. Implementation of the control plan over a 40-year period gives residential user a 150% increase in annual wastewater cost in 15-years.

Milwaukee County - Cost estimate for infiltration and inflow reduction

An alternative method was considered to estimate the potential benefit and cost of infiltration and inflow reduction at the Milwaukee Metropolitan Sewerage District (MMSD) based on previous infiltration and inflow reduction demonstration and pilot projects. Sewersheds with the highest amount of infiltration and inflow were the target of the reduction program. A unit cost was calculated based on unit of flow normalized by the sewershed area (in gallons per acre per day or liters per second per hectare) with reference from a 5-year peak hour flow within pre-rehabilitation and post-rehabilitation stage (Perry et al., 2007).

Cost estimation was done at the sewershed scale regardless whether the affected sewers were publicly or privately owned. The cost analysis was based on performance outcomes from several infiltration and inflow demonstration and rehabilitation projects and not on a specific reduction technology. The reduction procedure was conducted at different levels, starting from the sewershed with the highest level of infiltration and inflow rate per unit area and employing this level as the pre-rehabilitation rate to continue to the next level, and so on, until the lowest level is attained. The cost was calculated as the cumulative sum of cost for each level of rehabilitation. This resulted in an estimated total capital cost of about €530 million ($600 million), to reach a desired peak flow reduction of 19% or to reduce the infiltration and inflow rate to approximately 1.1 liter per second per hectare (10,000 gallons per acre per day) (Perry et al., 2007).

The average annual maintenance cost to keep a constant level of infiltration and inflow was roughly estimated for all service areas with and without rehabilitation, assuming a 7% increase in infiltration and inflow per decade. The approximate maintenance cost required for a period of 20 years is €355 million ($400 million), which is about 0.4% of the MMSD total asset value (Perry et al., 2007).

Case study in Swedish WWTPs

The purpose of the case study was to investigate simple methods to quantify the effect of high flows contributed by infiltration and inflow on wastewater treatment and suggest useful indicators to benchmark the performance of a WWTP. These indicators will support WWTP operators in understanding the impact of flow in the operation of the WWTP and the future investments. Most of the data was collected within the scope of a master's thesis (Molander, 2015) and has been presented at the NORDIWA conference in Bergen (Mattsson et al., 2015). More data has since been added from additional municipalities. All data was generously supplied by the municipalities included in the study.

In the case study, a number of Swedish WWTPs were investigated to be able to quantify the extent of infiltration and inflow using different key indicators. The WWTPs selected varied widely in terms of geographical locations, treatment capacity and number of populations served (**Table 5**). Average daily flow measurements for 1-year period as well as site-specific data of each WWTP were collected. The Years 2011 and 2012 were considered as characterized by high rainfall intensity and high flows to the treatment plant. The selection of data in **Table 5** was based on the year with the highest flow to each WWTP. For WWTP D (Syvab), in which the capacity varies between summer and winter, the winter capacity was chosen based on the assumption that the lower, winter capacity, is limiting.

The wastewater flow data was processed to generate different indicators based on average flow per person (in liters per person per day, l/p/d), dilution of flow, daily flow per volume capacity of the WWTP, and percentage of wastewater bypassing biological treatment as illustrated in tables and figures. The data are also expressed as percentiles (50 or median, 90, 99).

Results and discussions

All WWTPs investigated are operated as activated sludge systems mostly with nitrogen removal with activated sludge tank depths between 3 and 6 meters. A few of the WWTPs have nitrogen removal that takes place in the biofilm systems. As shown in **Table 6** the physical population is used instead of population equivalent, for the following reasons: 1) industries generating organic matter that influences industrial equivalents, when based on BOD equivalents, do not necessarily influence flow significantly, 2) relating to the actual population is considered simpler, and 3) at WWTPs with limits on nitrogen removal (such as most of those included in this study), a reasonable amount of extra BOD may be an advantage and a better indicator of extra load may be based on the industrial nitrogen load.

In **Table 7**, the relative capacity is calculated by taking the ratio of hydraulic capacity and the volume of the secondary treatment (in l/l/d).

Table 6. Basic WWTP data

			Biological reactors		Biological reactors + clarifiers	
WWTP	Population (p)	Capacity (l/p/d)	m^2	m^3	m^2	m^3
Gryaab 2011(A)	666 441	908	8810	78500	29910	150700
Bromma 2012 (B)	320 500	809	5000	24000	10600	50000
Henriksdal 2012 (C)	782 600	607	18900	204000	29900	262000
Syvab 2011 winter (D)	290 412	494	4762	22600	17002	68200
Käppala 2012 (E)	454 909	950	17551	122003	30051	187123
Sjölunda 2011 (F)	291 200	1484	8550	34770	14620	57140
Gässlösa 2011 (G)	82 600	1569	2280	12280	3480	17080
Umeva 2012 (H)	93 364	925	909	3180	3294	9870
Göviken 2012 (I)	50 800	1180	1100	3300	5600	16800
Västerås 2012 (J)	130 333	884	2310	12600	4920	21810
Kalmar 2011 (K)	55880	468	990	3960	2590	9860
Sundet 2011 (L)	61598	1164	1500	7500	3000	14250

Table 7. Secondary treatment volume and hydraulic capacity per unit volume

WWTP	Secondary treatment volume (l x 10^3)	Hydraulic capacity (l/d x 10^3)	Hydraulic Capacity per unit volume (l/l/d)
A	150700	604800	4.0
B	50000	259200	5.2
C	262000	475200	1.8
D	68200	143424	2.1
E	187123	432000	2.3
F	57140	432000	7.6
G	17080	129600	7.6
H	9870	86400	8.8
I	16800	59962	3.6
J	21810	115197	5.3
K	9860	26160	2.7
L	14250	71700	5.0

There are different ways to assess the condition and performance of a wastewater treatment facility such as by considering the discharged pollutant load, toxicity of the wastewater and the frequency of bypasses and overflows. However, for the purpose of this case study, the dilution of wastewater is considered as a common indicator of the impact of urban run off as infiltration and inflow. As shown in **Table 8** and **Figure 2**, majority of the WWTPs are experiencing an average dilution of 2, indicating that on annual basis the total volume of infiltration and inflow is in the same order of magnitude as the real wastewater (domestic and industrial) referred to as debited wastewater in this report. However, it can be seen that the extent of dilution varies a lot within a year and most of the days it can be lower than the average. This is expected as can be seen in the fluctuation of the wastewater flow presented in **Figure 3**.

Table 8. Percentage (%) dilution of incoming wastewater

WWTP	Average	Median	90 percentile	99 percentile
A	282	234	479	760
B	224	207	288	471
C	182	166	240	399
D	172	167	206	276
E	186	170	257	412
F	157	139	209	363
G	226	198	330	515
H	212	190	307	445
I	211	188	275	578
J	216	192	300	442
K	154	130	220	352
L	179	168	230	379

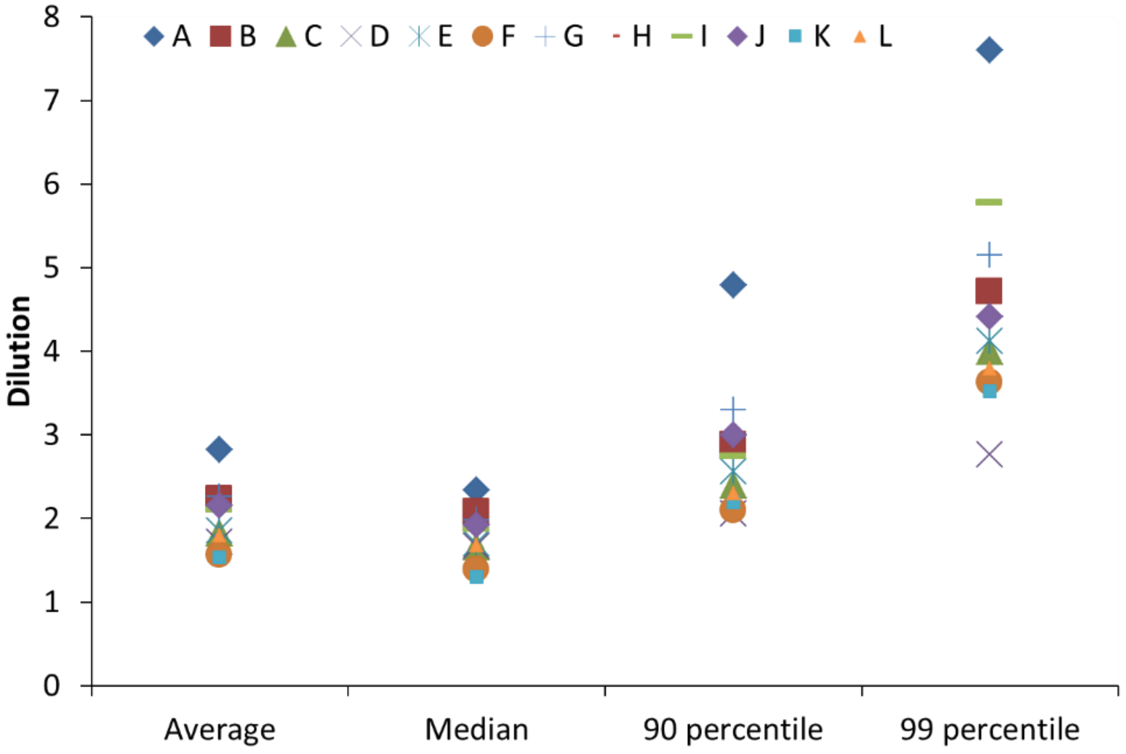

Figure 2. Dilution of wastewater flow at the WWTPs

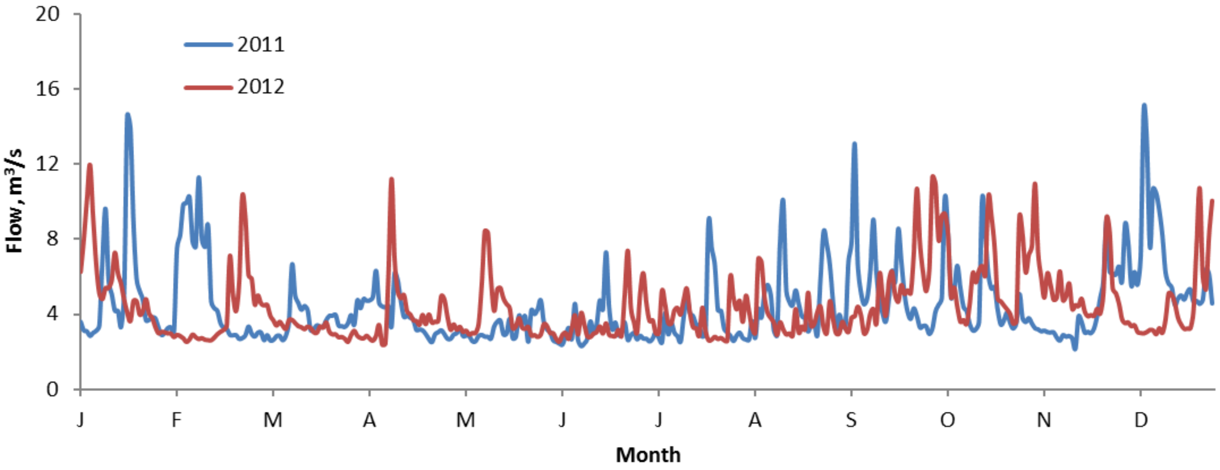

Figure 3. WWTP (A) average daily wastewater flow during a 2-year monitoring period

The dilution of the wastewater (**Table 9**) and the flow per capita shown in **Figure 4**, which showed to be independent on the WWTP size, are indicators that described how much extra flow the WWTP needs to handle. It is important to have reliable estimates of wastewater flow or debited wastewater and this is mostly based on domestic potable water consumption by assuming that almost all of the metered water is converted to wastewater (Jacobson, 2006). If possible, the water coming from private wells, leakages from water distribution system as well as other significant use of water such as for cooling, gardening or irrigation may be taken into account. The wastewater flow is an important parameter during planning and actual design of a wastewater treatment system (Jacobson, 2006).

Table 9. Flow to WWTP and wastewater flow (l/p/d)

WWTP	Debited wastewater	Average	Median	90 percentile	99 percentile	99 percentile/median	99 percentile/Debited
A	204	575	478	977	1549	3.2	7.6
B	199	443	410	570	933	2.3	4.7
C	198	361	329	475	791	2.4	4.0
D	242	417	404	499	669	1.7	2.8
E	194	361	330	498	799	2.4	4.1
F	254	398	354	532	921	2.6	3.6
G	235	533	466	776	1212	2.6	5.1
H	200	424	381	614	889	2.3	4.4
I	200*	421	376	550	1156	3.1	5.8
J	200*	431	384	601	883	2.3	4.4
K	200*	279	263	353	517	2.0	2.6
L	200*	359	336	460	759	2.3	3.8
Average	211	419	376	582	939	2.5	4.5

*No data available; 200 l/p/d is used as a standard value.

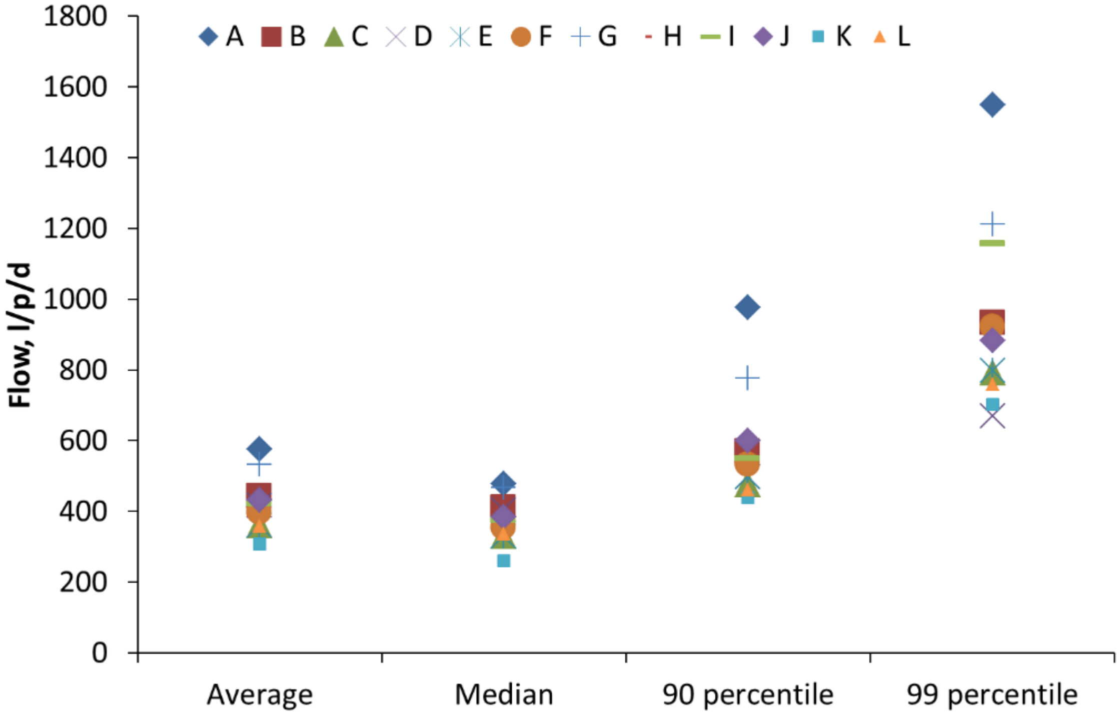

Figure 4. Wastewater flow per capita

In order to describe the step effect caused by excessive flow, it is important to relate the flow per capita to the WWTP secondary (biological) treatment capacity as shown in **Figure 5 and Figure 6**. Most of the treatment plants have a secondary treatment capacity well above the median flow while there is a wide margin at the 90 percentile of the flow. For both WWTP A and D, the 90 percentile of flow is close to the capacity indicating that treatment capacity is exceeded for about 10% of the time on a yearly basis. In addition, the 99 percentile of flow at these treatment plants together with 3 other WWTPs (B, C and K) is well above the capacity. These findings imply that the potential of the flow to bypass secondary treatment on less than 1% of the days is a challenge. Moreover, it can be considered that the overflows upstream of the WWTP have contributed to the low probability of exceeding secondary treatment capacity.

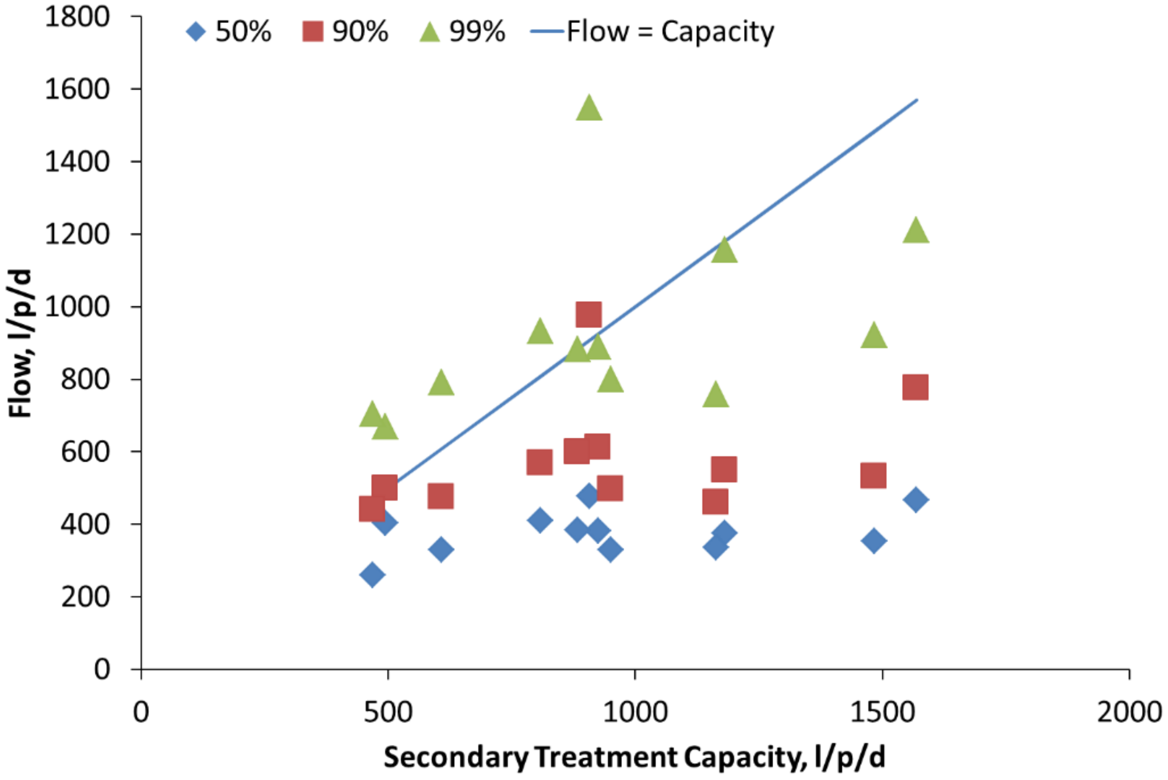

Figure 5. Wastewater flow per capita versus secondary treatment capacity

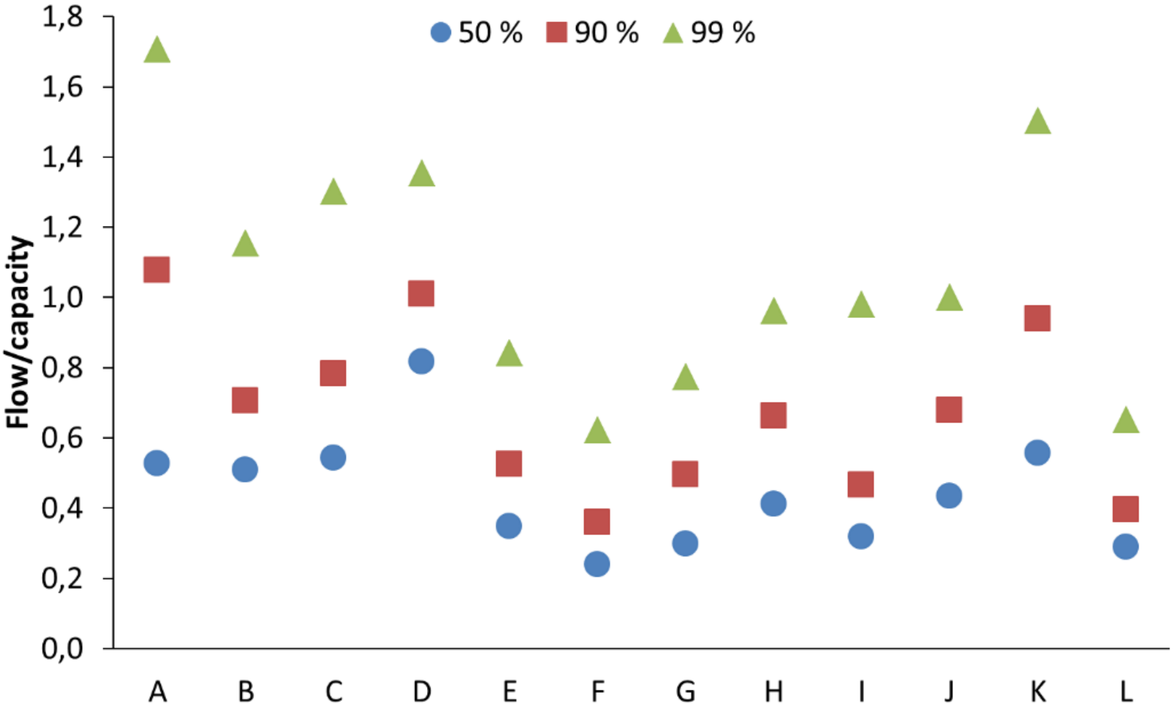

Figure 6. Ratio of wastewater flow and secondary treatment capacity

In **Table 10**, the capacity needed to bypass less than 1, 5 or 10% of the annual flow is estimated based on the amount of water bypassed assuming a secondary treatment capacity (between 90 and 99%) for WWTPs A (with often high flows) and E (typical flow).

As shown in the table, if the WWTP is operating at 99% capacity (bypassing 1% of the flow), 4% of the wastewater (between 99 and 95%) requires almost 30% of the WWTP capacity whereas if only 90% is treated (bypassing 10% of the flow), around 40% less capacity is needed. This calculation shows that a reduction in high flow conditions will result in lower investment costs for both WWTPs and that reducing bypass, for example from 5% to 1% of the annual flow, by extending the capacity of the treatment plant will incur a relatively high investment costs.

On the other hand, it is important to operate the treatment plant at a maximum capacity to prevent or reduce the occurrence of untreated overflows especially when there are no overflow retention basins available.

Table 10. Estimated secondary treatment capacity to treat x% of wastewater (in liters per person per day)

WWTP	Capacity (l/p/d)			% of the capacity	
	90 percentile	95 percentile	99 percentile	99-95	99-90
A	731	947	1316	28	44
E	374	463	655	29	43

Looking at the data in this case study, it is obvious that the wastewater flow is putting severe pressure on the WWTPs indicating economic and environmental consequences where sewer maintenance and rehabilitation or upgrading of WWTPs could be considered. But before that, a cost-benefit analysis could be needed.

Conclusions and recommendations

Infiltration and inflow is an issue recognized in many modern cities around the world to cause negative impacts on the economics and operation of wastewater treatment plants. In many cases mitigation of infiltration inflow is combined with other goals, such as flood prevention and drought prevention. The strength of these drivers influences the work done on mitigating infiltration inflow.

Quantification can be done in several ways; of which most are focused on finding sources in order to mitigate. The dilution rate of the wastewater is often used to estimate the amount of infiltration and inflow. For quantifying the hydraulic impact on the WWTP specific hydraulic loading (l/p/d) has advantages and is also an easy figure to communicate to other stakeholders involved in the mitigation process.

In Sweden, the hydraulic loading of the WWTPs varies greatly and is not always in accordance with the hydraulic capacities of the WWTPs. The case study was based on wastewater flow data from 12 voluntary WWTPs. It cannot be assumed to describe an average situation, or describe regional differences.

However, it is obvious that infiltration and inflow has a great impact on the removal rates at the WWTPs and on the effluent loadings. This dependency increases with tighter restrictions. Therefore, the management of infiltration and inflow likely results in an increasing impact on the aquatic environment as well as the economy of the wastewater system, specifically the WWTPs.

In order to gain better understanding it would be useful to quantify the situation with a wider base of data from representative municipalities.

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