TOWARDS BETTER MANAGEMENT OF COMBINED SEWER SYSTEMS. A METHODOLOGY BASED ON LOW-COST MONITORING

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DOCTORAL THESIS

Towards better management of combined sewer systems – a methodology based on low-cost monitoring

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El **Dr. Lluís Corominas Tabares**, investigador post-doc de l'Institut Català de Recerca de l'Aigua, i el **Prof. Manel Poch Espallargas**, catedràtic de la Universitat de Girona,

DECLAREM:

Que el treball titulat *Towards better management of combined sewer systems – a methodology based on low-cost monitoring*, que presenta l'Albert Montserrat Royuela per a l'obtenció del títol de doctor, ha estat realitzat sota la nostra direcció i el qual constitueix la seva Tesi per a optar al Grau de Doctor per la Universitat de Girona.

I, perquè així consti i tingui els efectes oportuns, signem aquest document.

Dr. Lluís Corominas Tabares

Prof. Manel Poch Espallargas

Girona, Abril de 2015

LIST OF PUBLICATIONS

This thesis has been written following the traditional monograph format, including the results in the form of articles, according to the regulatory basis of the University of Girona in regards to the Experimental Sciences and Sustainability PhD programme.

Accordingly, following are listed the scientific papers published in peer-reviewed journals, and which are an integral part of this thesis:

1. Montserrat, A., Gutierrez, O., Poch, M., Corominas, Ll. Field validation of a new low-cost method for determining occurrence and duration of combined sewer overflows. *Science of the Total Environment* 2013; 463-464, 904-912.

2. Montserrat, A., Bosch, Ll., Kiser, M.A., Poch, M., Corominas, Ll. Using data from monitoring combined sewer overflows to assess, improve, and maintain combined sewer systems. *Science of the Total Environment* 2015; 505, 1053-1061.

Edited versions of the papers 1 and 2 above are presented in Chapters 4.1 and 4.2 respectively, with permission of Elsevier Publishing (Appendix X).

Also, the contents shown in Chapter 4.3 of this thesis have been submitted in the following peer-reviewed journal to be considered for publication:

3. Montserrat, A., Hofer, T., Poch, M., Muschalla, D., Corominas, Ll. Using the duration of combined sewer overflow events for the calibration of sewer hydrodynamic models. Submitted to *Urban Water Journal* in April 2015.

ACRONYMS

Ci	Confidence interval
CSO	Combined sewer overflow
CSS	Combined sewer system
CWA	Clean Water Act
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
FWPCA	Federal Water Pollution Control Act
LTCP	Long-term control plan
NMC	Nine minimum controls
NPDES	National Pollutant Discharge Elimination System
NSGA	Nondominated sorting genetic algorithm
PE	Population equivalent
SRC	Standardized regression coefficient
SWMM	Storm water management model
UWWS	Urban wastewater system
UWWTD	Urban Wastewater Treatment Directive
WFD	Water Framework Directive
WWTP	Wastewater treatment plant

LIST OF FIGURES

LIST OF TABLES

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CONTENTS

ABSTRACT

In combined sewer systems (CSS) wastewater and stormwater flow through the same pipes. During severe rain episodes, the excess combined flow of untreated wastewater and stormwater is released out from the system through overflow structures, producing the combined sewer overflows (CSO). CSOs represent a threat for water quality of receiving water bodies and for human health, for what current (and future) legislation on the protection of water quality, are demanding more control on this transient discharges. This research focuses on developing a low-cost monitoring method to determine the occurrence and duration of CSOs, and making use of the obtained data to gain better understanding of the performance of CSSs.

The proposed method is based on using temperature sensors to monitor occurrence and duration of CSOs. It is assumed that different magnitudes of temperature exist between the atmospheric phase of the sewer and the overflowing mix of wastewater and stormwater. Thus, the abrupt temperature change produced during a rainfall episode is related to the occurrence of a CSO event. The inexpensive of modern temperature sensors is what defines the method as low-cost. The method was tested and validated in the CSS of La Garriga (Catalonia), monitoring the temperature in all the CSO structures for a period of 1 year. For the whole set of CSO events, occurrence and duration were successfully determined in 80% of cases. A discussion on the advantages, limitations and potential applications of the proposed method is provided.

Low-cost monitoring would allow the simultaneous monitoring of several CSO structures, and hence the characterization of the system as a whole. The collected data from the CSS of La Garriga was used to develop a comprehensive methodology to evaluate the performance of CSSs. This methodology included: (1) assessing the capacity of a CSS using overflow duration and rain volume data; the rain volume at which each CSO structure starts to overflow(named *breaking point*) was determined. (2) Characterizing the performance of CSO structures with statistics; the averages with confidence intervals of some parameters were evaluated; also *ranking* curves were developed to provide information on the order in which the CSO structures overflow in relation to the other structures of the CSS. (3) Evaluating the compliance of a CSS with government guidelines, and (4) generating decision tree models to provide support to managers for making decisions about system maintenance. The obtained results can greatly support managers and engineers dealing with the improvement and maintenance of CSSs.

The information of CSO duration obtained with low-cost temperature sensors was used in the automatic calibration of a hydrodynamic sewer model, and the results were compared against a calibration using conventional flow measurements. A CSO structure from the CSS of the city of Graz (Austria) was regarded as case study, using a reference model previously calibrated against the flow discharge at the inflow channel. Different types of rain episodes and objective functions were evaluated, and a sensitivity analysis was conducted for the calibration parameters. The CSO volume, peak and duration were used to evaluate the goodness of the calibrations. The results revealed that using duration information can lead to similar results to the approach using flow data. For the small episodes the calibration with flow measurements led to better representation of the CSO volumes and peaks. For medium episodes the two approaches resulted within similar accuracies. The *duration approach* calibration achieved similar or better results on the CSO duration. Overall, both approaches resulted in significant better results than the reference model. In the case of the large episode, although similar errors in volume, peak and duration were obtained for the two approaches, none obtained better results than the reference model.

RESUM

En els sistemes de col·lectors unitaris (SCU) l'aigua residual i l'aigua pluvial és transportada conjuntament a través d'un sol sistema de col·lectors. Durant episodis de pluja intensos, l'excés d'aquest cabal combinat és descarregat fora del sistema a través d'unes estructures de sobreeiximent, produint el que s'anomena com descàrrega de sistemes unitaris (DSU). Aquestes DSUs representen una amenaça per la qualitat dels medis aquàtics receptors i per la salut humana, per el que les legislacions actuals (i futures) requereixen més control sobre aquestes descàrregues transitòries. La recerca presentada en aquesta tesi es centra en desenvolupar un mètode de baix cost per determinar la ocurrència i duració de les DSUs, i el tractament de les dades per aprofundir coneixement en el rendiment dels sistemes unitaris.

El mètode proposat es basa en l'ús de sensors de temperatura per detectar la ocurrència i duració de les DSUs. S'assumeix que les magnituds de temperatura entre la fase atmosfèrica del col·lector i l'aigua del sobreeiximent difereixen. Així, el canvi brusc de temperatura mesurat durant un episodi de pluja es relaciona amb la ocurrència d'un DSU. El baix cost dels actuals sensors de temperatura és el que defineix el mètode com a baix cost. El mètode es va implementar i validar en el SCU de La Garriga (Catalunya), mesurant la temperatura en totes les estructures de DSU del sistema durant un període d'un any. Per el conjunt de DSUs, la ocurrència i duració es va determinar amb èxit en un 80% de casos. Tanmateix es presenta una discussió sobre els avantatges, limitacions i aplicació potencial del mètode proposat.

Mètodes de monitorització de baix cost facilitaria el monitoratge de diverses estructures de DSU, i per tant la caracterització de tot el sistema en el seu conjunt. Les dades obtingudes del SCU de La Garriga es van utilitzar per desenvolupar una metodologia global per avaluar el rendiment dels SCUs. Aquesta metodologia va incloure: (1) avaluar la capacitat d'un SCU mitjançant dades de duració de DSU i volum de pluja; es va determinar el volum de pluja al qual l'estructura comença a sobreeixir (anomenat *punt de ruptura*). (2) Caracteritzar estadísticament el rendiment de les estructures de DSU en el seu conjunt; es van avaluar les mitjanes amb intervals de confiança d'alguns paràmetres; també, es van desenvolupar *corbes d'ordre* per donar informació sobre l'ordre en el qual les estructures sobreeixen en relació a les altres estructures del sistema. (3) Avaluar el compliment del SCU amb normatives estatals, i (4) generar models d'arbres de decisió per donar suport a gestors per prendre decisions sobre el manteniment del sistema. Els resultats obtinguts poden ser de gran ajuda per a gestors i enginyers que treballen amb la millora i manteniment de SCUs.

La informació de duració de DSU obtinguda amb sensors de temperatura de baix cost es va utilitzar en la calibració automàtica d'un model hidrodinàmic de col·lectors, i els resultats es van comparar amb una calibració utilitzant dades convencionals de cabal. El cas estudi fou una estructura de DSU del SCU de la ciutat de Graz (Àustria), utilitzant un model de referència prèviament calibrat amb dades de cabal al col·lector principal. Es van avaluar diferents tipus d'episodis de pluja i funcions objectiu, i es va realitzar una anàlisi de sensibilitat per als paràmetres de calibració. El volum, pic i duració de DSU es van utilitzar com a criteris per avaluar la bondat de la calibració. Els resultats van revelar que utilitzant informació de duració es pot arribar a obtenir resultats similars al de l'enfocament amb dades de cabal. Per els episodis petits la calibració amb cabal va donar una millor representació dels volums i pics de les DSUs. Per els episodis mitjans les dues calibracions van donar precisions similars. La calibració amb dades de duració va aconseguir resultats similars o millors en la duració de les DSUs. En general, els models calibrats van presentar millores significatives en comparació al model de referència. Per l'episodi gran, no obstant, tot i que es van aconseguir errors similars en volum, pic i duració per les dues calibracions, no es van obtenir millors resultats que el model de referència.

RESUMEN

En los sistemas de colectores unitarios (SCU) las aguas residuales y pluviales son transportadas a través de un solo sistema de colectores. Durante episodios de lluvia intensos, el exceso de este caudal combinado es descargado fuera del sistema a través de aliviaderos, produciendo lo que se conoce como descarga de sistemas unitarios (DSU). Estas DSUs representan una amenaza para la calidad de los medios acuáticos receptores y para la salud humana, por lo que las legislaciones actuales (y futuras) requieren más control sobre estas descargas transitorias. La investigación presentada en esta tesis se centra en el desarrollo de un método de bajo coste para determinar la ocurrencia y duración de las DSUs, y el tratamiento de los datos para profundizar conocimiento en el rendimiento de los sistemas unitarios.

El método propuesto se basa en el uso de sensores de temperatura para detectar la ocurrencia y duración de las DSUs. Se asume que las magnitudes de temperatura entre la fase atmosférica del colector y el agua de la descarga difieren. Así, el cambio brusco de temperatura medido durante un episodio de lluvia se relaciona con la ocurrencia de una DSU. El bajo coste de los actuales sensores de temperatura es lo que define el método como de bajo coste. El método se implementó y validó en el SCU de La Garriga (Cataluña), monitorizando la temperatura en todas las estructuras de DSU del sistema durante un período de un año. Para el conjunto de DSUs, la ocurrencia y duración se determinó con éxito en un 80% de casos. Asimismo se presenta una discusión sobre las ventajas, limitaciones y aplicación potencial del método propuesto.

Métodos de monitorización de bajo coste facilitan la monitorización de diversas estructuras de DSU, i per tanto la caracterización de todo el sistema en su conjunto. Los datos obtenidos del SCU de La Garriga se utilizaron para desarrollar una metodología global para evaluar el rendimiento de los SCUs. Esta metodología incluyó: (1) Evaluación de la capacidad de un SCU mediante datos de duración de DSU y volumen de lluvia; se determinó el volumen de lluvia en el cual la estructura empieza a aliviar (nombrado *punto de ruptura*). (2) Caracterización estadística del rendimiento de las estructuras de DSU en su conjunto; se evaluaron las medias con intervalos de confianza de algunos parámetros; también, se desarrollaron unas *curvas de orden* para dar información sobre el orden en el cual las estructuras alivian en relación a las demás estructuras del sistema. (3) Evaluación del cumplimiento del SCU con normativas estatales, y (4) generación de modelos basados en árboles de decisión para dar soporte a los gestores para tomar decisiones sobre el mantenimiento del sistema. Los resultados obtenidos pueden ser de gran ayuda para gestores e ingenieros que trabajan con la mejora y mantenimiento de SCUs.

La información de duración de DSU obtenida con sensores de temperatura de bajo coste se utilizó en la calibración automática de un modelo hidrodinámico de colectores, y los resultados se compararon con una calibración utilizando datos de caudal. Se evaluó una estructura de DSU del SCU de la ciudad de Graz (Austria), utilizando un modelo de referencia previamente calibrado con datos de caudal en el colector principal. Se evaluaron diferentes tipos de episodios de lluvia y funciones objetivo, y se realizó un análisis de sensibilidad para los parámetros de calibración. El volumen, pico y duración de DSU fueron los criterios para evaluar la bondad de la calibración. Los resultados revelaron que mediante información de duración se puede llegar a obtener resultados similares al del enfoque con datos de caudal. Para los episodios pequeños la calibración con caudal dio una mejor representación de los volúmenes y picos de las DSUs. Para los episodios medianos las dos calibraciones dieron precisiones similares. La calibración con datos de duración consiguió resultados similares o mejores en la duración de las DSUs. En general, los modelos calibrados presentaron mejoras significativas en comparación al modelo de referencia. Para el episodio grande, sin embargo, aunque se consiguieron errores similares en volumen, pico y duración en las dos calibraciones, no se produjo mejora respecto al modelo de referencia.

CHAPTER 1

INTRODUCTION[1]

[1] This section includes some paragraphs extracted from Montserrat et al. (2013) and Montserrat et al. (2015).

1.1 Historical background

The concern about wastewater generated by humans began with the transition from the nomadic lifestyle, typical of the first hunter-gatherers human communities, to permanent human settlements which led to a growing concentration of the population in towns and cities. Thus, the construction of infrastructure for wastewater disposal (and stormwater too) is not recent, while it dates back to early historic times, when significant breakthroughs in urban drainage and sanitation were made by ancient civilizations such as the Mesopotamian, the Egyptian or the Greek (Lofrano et al., 2010). Archaeological studies made during the 20th century provided ample evidence on the sewerage and stormwater drainage systems developed in Ancient Greece 4,000 years ago (e.g. Angelakis et al., 2005).

The Romans, outstanding managers and engineers, perfected the building of sewer and stormwater pipes, and conducted its development with the purpose to serve not only the richest but all the citizens (Lofrano et al., 2010). The most famous roman sewer, the “Cloaca Maxima” (the great sewer), was originally constructed to evacuate the marsh on which the Roman Forum was being built (Sura, 2010), to finally discharge into the Tiber river. With a height of 3.3 m and a width of 4.5 m in its largest section (Malacrino, 2010), and a final length of 1,600 m (Aldrete, 2009), it is considered the largest ancient sewer in the world, and the fact that some parts are still in use today testimony the quality and solidity of the work.

With the fall of the Roman Empire in the 3rd century, it came the dark ages of sanitation (Lofrano et al., 2010), which lasted from the Middle Ages to the 19th century. During this period there was a generally deep sanitation regression and most of the health standards brought by the ancient cultures were lost (Hilgenkamp, 2011). In fact, the city streets themselves acted as sewers, and even expressions like “*Look out below!*” became popular (Johnson, 2007), referring to the way in which waste (solid and liquid) were typically disposed, by throwing them out the window directly into the streets of European cities such as Paris or London. This situation (lack of both hygiene and wastewater management) contributed to extend the great epidemics that significantly reduced an important part of the population in Europe throughout the Middle Ages.

The first part of the 19^{th} century was marked by a population explosion in Western Europe, especially in the United Kingdom, which grew from 8.5 million in 1700 to over 21 million in 1820 (Maddison, 2001). The overcrowding situation in cities, combined with increased industry, made the existing sewer systems totally obsolete, unable to drain the consequential increase of generated wastewater. As a result, this period also saw major cholera epidemics in the towns and cities of Europe and North America, while great discussions about the spreading of this disease took place (Cooper, 2007). A key contribution was made by the English Dr. John Snow who, in his 1849 essay “On the Mode of Communication of Cholera”, directly related the cases of people infected with cholera to the areas in which the drinking water supply was contaminated by vomits and feces from cholera patients. Hence it was forced to review the way in which wastewater was managed, leading to new sewer system designs in Europe and United States, and primarily moving from decentralized to centralized systems (Poch et al., 2012). Examples of the first modern-days sewer networks can be found in the cities of Hamburg, London, Paris, New York or Chicago, constructed in the 1840s-1870s decades. Most of these sewer projects were built as combined systems, transporting both the wastewater and rain water through the same pipes. The debate on using separate systems instead of combined ones stepped in, and despite the advantages and conveniences of each type, it is still not clear which one is better (Geels, 2006).

The transportation of wastewater away from the sources was solved but, by the end of the 19^{th} century and early 20^{th} century, the final destination of the collected and untreated wastewater was still the receiving water bodies such as the sea or the river. In response to the public growing concern not only on public health, but also on environmental pollution, wastewater treatment technologies were developed and implemented in treatment plants which, following regulatory standards based on physical-chemical and biological parameters, ensured good water quality conditions in the receiving waters.

Together, the complex made up of the sewer system (combined or separate), wastewater treatment plant (WWTP) and the receiving waters is commonly referred in literature as the urban wastewater system (UWWS) (Figure 1-1).

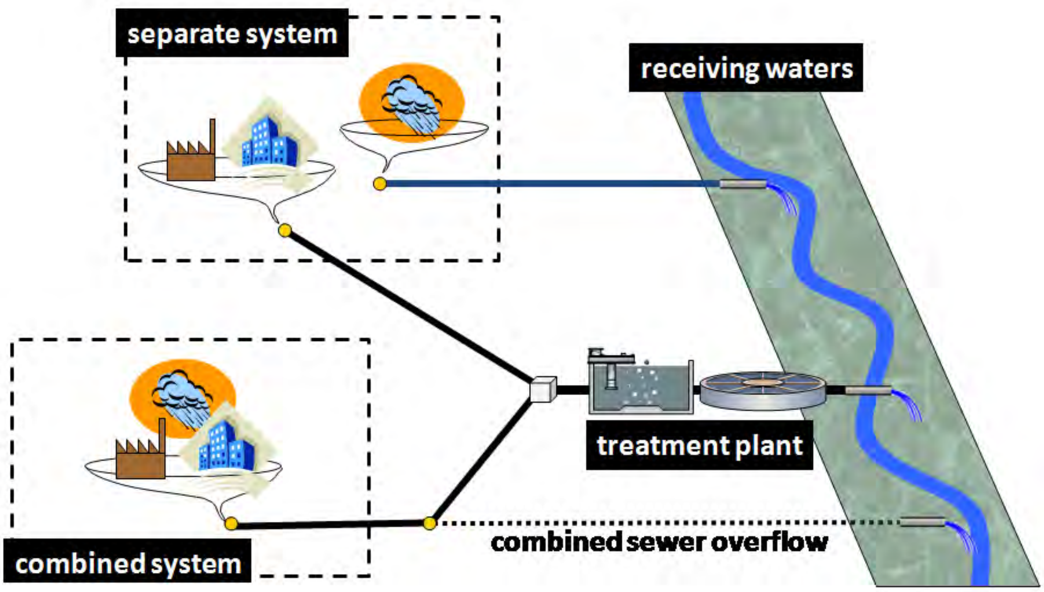

Figure 1-1. Conceptual scheme of an urban wastewater system (adapted from Devesa, 2006).

A problem associated with combined sewer systems (CSS) is that during severe rainfalls, when the mix of wastewater and rainfall runoff surpass the maximum capacity of the system, part of the combined flow is diverted into the receiving waters. This phenomenon is commonly known as combined sewer overflow (CSO), and since the second half of the 20th century it has been identified as a major source of pollution of receiving water bodies, yet representing nowadays a subject of study and concern. This thesis deals with the monitoring of CSOs and the use of the data obtained to improve the management of CSSs.

1.2 Legal background on the protection of water quality

United States

The United States (U.S.) has played a pioneer role in the protection of the water environment, when in 1948 the U.S. Congress passed the Federal Water Pollution Control Act (FWPCA), becoming the first law on water pollution control. The 1972 amendment of the FWPCA, generally known as the Clean Water Act (CWA), was a significant step forward in that regard. Among other provisions, the CWA established the National Pollutant Discharge Elimination System (NPDES), which required "point source" dischargers (like WWTPs) to obtain a permit, and developed technology-based limits to be met by NPDES permit holders. Since then, billions of dollars were invested by federal, state and local authorities to meet the CWA goals (Copeland, 2010), resulting in a major improvement in environmental quality and human health. However, a specific regulation on CSOs was still missing. Thus, in the first attempt to create a regulatory framework on CSO control, in 1989 the U.S. Environmental Protection Agency (EPA) enacted the CSO Control Strategy, which aimed the fulfillment of a threefold objective (EPA, 1989):

> *"1) To ensure that the occurred CSOs are only resulted from wet weather. 2) To bring all the CSO discharge points into compliance with the technology-based requirements of the CWA and applicable State water quality standards. 3) To minimize the impact of CSOs on water quality, aquatic biota, and human health."*

The CSO Control Strategy encouraged States to develop statewide permitting strategies to reduce, eliminate or control CSOs, and recommended six minimum measures. But the CSO Strategy resulted short at solving many fundamental issues, and five years later the EPA published the CSO Control Policy to speed up the implementation of the Strategy (EPA, 1995). The intent of the CSO Control Policy was (EPA, 1994):

> *"To provide guidance to permittees with CSOs, NPDES authorities and State water quality standards authorities on coordinating the planning, selection, and implementation of CSO controls that meet the requirements of the CWA and allow for public involvement during the decision-making process."*

Two key elements (among others) addressed in the CSO Control Policy were the nine minimum controls (NMC) and the long-term control plan (LTCP), which were mechanisms aimed at meeting the objectives of the Policy and which had to be implemented by the appropriate authorities. Guidance documents on these measures were developed and issued by the EPA. It should be pointed out the important role that monitoring had on these guides. One of the NMCs was the *"Monitoring to effectively characterize CSO impacts and the efficacy of CSO controls"*. This minimum control involved simple methods to determine the occurrence of CSOs, and was regarded as an initial characterization of the CSS, prior to the more detailed characterization and monitoring contemplated in the LTCP (EPA, 1995). In 2001 the EPA issued a report to Congress on the status of the implementation of the NMC and LTCP, which stated a significant progress on the regulation and control of CSOs as a result of the effort made by the EPA, States and municipalities (EPA, 2001).

European Union

In the European Union framework there are two key pieces of legislation related to the environment protection and water pollution control. These are, in chronological order of appearance, the Urban Waste Water Treatment Directive (UWWTD; UWWTD, 1991), and the Water Framework Directive (WFD; WFD, 2000). (see further details of wastewater-related EU directives in Corominas et al. (2013)).

The main purpose of the UWWTD was the protection of the environment from the adverse discharge of urban wastewater, which applied to domestic wastewater and the wastewater generated in certain industrial sectors. The Directive set minimum standards for the collection, treatment and discharge of urban wastewater. For instance, it required secondary treatment of all discharges from agglomerations of more than 2,000 population equivalents (PE), and more stringent treatment for agglomerations of more than 10,000 PE whose discharges impacted on designated sensitive areas.

Regarding CSOs, the UWWTD required the design of collecting systems to account for the limitation of pollution of CSOs, but recognized the impossibility to construct sewers and treatment plants able to capture all the incoming flow produced during intense rain episodes, and the control of CSOs remained not clear. The Directive suggested that control measures could be based on dilution rates, capacity in relation to dry weather flow, or a specific overflow frequency.

The WFD was adopted in the year 2000 with the purpose of preserving and, where necessary, improving the water quality of inland, transitional and coastal waters and groundwaters in the E.U. Member States. The very first and overriding objective of the Directive was to achieve the “good” ecological and chemical status for all surface waters, artificial and heavily modified waters and groundwaters, requiring the Member States to apply the necessary local measures to meet this objective.

In the particular case of Spain, the first important studies analyzing the problem of CSOs were made during the 90s (Puertas et al., 2008). The most significant contribution was the *Spanish National CSO Measurement Project* (PROMEDSU, for its acronym in Spanish), promoted by the Ministry of the Environment. This study focused on the characterization of the pollutant loads in CSOs from several urban catchments of different regions and climatic conditions (i.e. Barcelona, Madrid, Sevilla, Valencia and Vitoria). It was concluded that the pollutant concentrations in CSOs are significant, highlighting the potential danger that these urban discharges pose to the aquatic environment. For further details on methodological aspects and results from the PROMEDSU project see Suárez and Puertas (2005) and Puertas et al. (2008). The introduction of the WFD in 2000 exposed important shortcomings in terms of CSO control regulation, thus jeopardizing the environmental objectives of the aquatic environment. Hence the Spanish transposition of the UWWTD was updated in 2012 through the law RD 1290/2012 establishing a framework to limit the pollution of receiving water bodies by controlling runoff waters, and representing in fact a redefinition of sewer and urban drainage practices in Spain (Suárez et al., 2014). The construction of separate sewer systems, the updating of CSO structures to avoid the release of coarse solids, or the construction of the convenient facilities in order to intercept the first amount of runoff waters are some of the arrangements covered by this law. More recently, and in compliance with the RD 1290/2012, the Spanish Ministry of Agriculture, Food and Environment published in 2014 the *Recommendations Manual for Stormwater Tanks Design* (MAGRAMA, 2014). This document identifies and characterizes different stormwater tanks throughout Spain and evaluates the characteristics of CSOs, and it will serve as basis to elaborate the upcoming technical standards on stormwater tanks design.

1.3 Motivation and objectives

Why do we need to monitor CSOs?

The extent of CSSs over the world is significant. Some new urban projects are being connected to separate sewers, but the replacement of every existing CSS with separate ones would become cost-prohibitive and impractical to the majority of municipalities. The 1970 *Technical Committee on Storm Overflows and the Disposal of Storm Sewage Final Report* from the UK Ministry of Housing already stated, "*it would be unrealistic to contemplate eliminating, over the next few decades, all storm overflows, either by enlarging the sewer capacity or by providing separate sewers for surface water*" (Marsalek et al., 1993). Thus, the existing sewers remained as combined systems, and a large percentage of CSS is found in many European countries, usually around 60-80% (Table 1-1). In the United States, about 770 cities have CSSs, serving over 40 million people (EPA, 2004). The U.S. EPA's *Report to Congress – Impacts and Control of CSOs and SSOs* (EPA, 2004) estimated that CSOs release approximately 850 billion gallons of untreated wastewater and stormwater each year in the U.S.

Country	% CSS
Belgium	70
Denmark	45-50
France	70-80
Germany	67
Ireland	60-80
Italy	60-70
Luxemburg	80-90
Netherlands	74
Portugal	40-50
Spain	70
U.K.	70

Table 1-1. Estimated percentage of CSS in some European countries (UNEP, 2002).

The technological and scientific advances made during the second half of the twentieth century allowed to grasp the water pollution threat posed by CSOs. The EPA's *National CSO Control Policy* (EPA, 1994) stated:

> *"CSOs consist of mixtures of domestic sewage, industrial and commercial wastewater, and storm runoff. CSOs often contain high levels of suspended solids, pathogenic microorganisms, toxic pollutants, floatables, nutrient, oxygen-demanding compounds, oil and grease, and other pollutants. CSOs can cause exceedances of water quality standards. Such exceedances may pose risk to human health, threaten aquatic life and its habitat, and impair the use and enjoyment of the Nation's waterways."*

Concentrations of pollutants in combined sewers present a high variation during a rain event (Charbeneau and Barrett, 1998). For this reason the pollution load discharged from CSOs is typically analyzed in terms of event mean concentrations (EMC), defined as the total pollutant load by the total runoff volume (e.g. Lee and Bang, 2000). The reported data available in the literature concerning these concentrations vary from one study to another, mostly due to diverse factors such as the land use of the investigated catchment, the sampling frequency or the temporal variability of dry weather concentrations (Madoux-Humery et al., 2013). For illustration purposes, Table 1-2 shows the EMCs for typical pollutants from CSO events measured in different combined systems in Spain (achieved under the PROMEDSU project), along with the minimum standards set by the UWWTD.

	Catchment site					**Compliance criteria (UWWTD)**[a]
Parameter	**Barcelona**	**Madrid**	**Sevilla**	**Vitoria**	**Valencia**	
COD	456	680	834	1004	293	125
BOD	-	384	389	344	166	25
SS	580	597	733	562	229	35
TN	27[b]	57[b]	68[b]	31[b]	53[b]	15/10[d]
TP	10[c]	7[c]	5[c]	9[c]	6[c]	2/1[d]
Cu	-	0.05	0.03	0.02	0.02	-
Zn	-	0.32	0.38	0.83	0.16	-
Pb	-	0.1	0.38	0.08	0.04	-

[a] Sampling based on 24h composite; [b] TKN + N-NH_4^+; [c] Total P-PO_4^{+3}; [d] For sensitive areas

Table 1-2. EMCs (mg/L) for some pollutants from CSOs measured in different Spanish cities (Beneyto, 2004), and regulatory standards set by the UWWTD (UWWTD, 1991).

The concern generated by this potential source of pollution, led to report a large number of surveys and publications revealing the effects that these polluted discharges produce on the aquatic and human health (Table 1-3). The untreated wastewater eventually released from the CSSs may become a source of waterborne diseases in recreational fresh and oceanic waters, such as ear, nose, throat, respiratory and gastroenteritis illnesses, or less likely but more harmful such as hepatitis, giardiasis, cryptosporidiosis and toxic algal blooms (Patz et al., 2008). Although it is difficult to exactly determine the source of such illnesses (Tibbetts, 2005), it has been published several reports and epidemiological studies evaluating the impact of the CSOs on the human health (e.g. EPA, 2004; Donovan et al., 2008; Ashbolt et al., 2010; Hata et al., 2014). For instance, the U.S. EPA's *Report to Congress – Impacts and Control of CSOs and SSOs* (EPA, 2004) estimated that about 3,500 to 5,500 gastroenteritis cases potentially occur annually. The route of infection can not only be done by water-drinking or contact, but by ingestion of infected animals such as fish and shellfish too (Butt et al., 2004; Ueki et al., 2005; Le Guyader et al., 2006).

Regarding the negative effects that CSOs exert on the water environment, the impact of CSOs has been measured as a decrease in the oxygen concentration (e.g. Harremoës, 1982; Hvitved-Jacobsen, 1982) where immediate and delayed effects are observed. The toxicity effects on phytoplankton from heavy metals (e.g. Seidl et al., 1998), the impact on the microbiological water quality (e.g. Armstrong et al., 1980; Passerat et al., 2011) and the possible impacts on fish mortality of hypoxia and un-ionized ammonia (e.g. Magaud et al., 1997) have also been investigated. The spills of an untreated wastewater into the aquatic ecosystem are particularly damaging in Mediterranean countries with low river flow patterns, unable to dilute the undesired inputs (Barceló and Sabater, 2010). Furthermore, of more recent concern are the “emerging pollutants” as pharmaceuticals and personal care products (PPCPs), which are built up in the sewer sediments and washed off during rain episodes (Del Río et al., 2013).

Pollutants	Main consequences
Bacteria, viruses, parasites	· Beach closures · Odors · Shellfish bed closures · Drinking water contamination · Adverse public health effects
Trash and floatables	· Aesthetic impairment · Odors · Beach closures
Organic compounds, metals, oil, grease, toxic pollutants	· Aquatic life impairment · Adverse public health effects · Fishing and shell-fishing restrictions
Biochemical oxygen demand (BOD)	· Reduced oxygen levels and fish kills
Solid deposition	· Aquatic habitat impairment · Shellfish bed closures
Nutrients	· Eutrophication, algal blooms · Aesthetic impairment

Table 1-3. Summary of the main pollutants in CSO discharges and the main consequences on the environment and public health (EPA, 2001).

In response to the widespread public concern about the environment and human health impacts, the development of legislation addressing the water pollution has been pushed towards. As stated before, key pieces of legislation such as the Clean Water Act and the CSO Control Policy, in the United States, and the Water Framework Directive and the Urban Waste Water Treatment Directive, in the European Union, contributed towards the preservation and improvement of water quality and the reduction of the pollution coming from the CSO discharges. Monitoring plays a fundamental role in this ongoing legal framework which demands a more stringent control of CSOs. The National CSO Control Strategy (EPA, 1989) stated:

> *"Cost effective monitoring requirements should be developed to serve three purposes: (1) to characterize CSO discharges, including their frequency, duration, and pollutant loadings; (2) to evaluate the water quality impacts of these discharges; and (3) to determine compliance with CSO permit requirements."*

Reducing the occurrence of CSOs is an important part of reducing water pollution. To this end, engineers and managers need reliable data on the performance of CSO structures of a CSS, which requires proper monitoring. Gathering data on CSOs would help in better understanding the sewer network performance under wet weather conditions, and making it possible to meet current legal requirements.

Why do we need of low-cost monitoring methods?

Several monitoring methods have been applied in literature to characterize CSOs. Table 1-4 summarizes conventional methods commonly used to characterize a CSO describing the level of information that can provide (CSO occurrence, duration or volume), the strengths and constraints of each method and an indicative cost.
On the one hand, direct visual inspections represent a simple way to evaluate the occurrence and duration of the CSO, but require human presence on site. Simple inspection aids like chalk and bottle boards or block tests can alternatively be used (EPA, 1999a), but without providing information about the duration. On the other hand, the use of sensors allows managers and practitioners to perform accurate monitoring with minimal human involvement. Different sensors differing on principles and prices are currently available on the market. Occurrence and duration can be obtained by simple conductivity sensors (personal communication with Adasa Sistemas, 2014) or level sensors (e.g. Leonhardt et al., 2012) at moderate costs, or advanced water quality sensors (e.g. UV–VIS sensors, Gruber et al., 2005) at much higher cost but having also information about water quality. When the volume of the CSO needs to be measured at moderate cost, the information from water level sensors can be used together with overflow equations (DWA, 2010). Finally, flow measurements represent the most accurate and reliable option to characterize the overflow discharge. A common way to measure the flow consists on the combination of a level and a velocity sensor, although there is a wide variety of methods and devices in the market (Bertrand-Krajewski et al., 2000). The flow measurement option represents the most precise but also more expensive than level and conductivity sensors, and requires higher maintenance in certain cases (EPA, 1999a). In addition, flow and level sensors are subject to some operational conditions which need to be met for their proper functioning (e.g. block distance, measurement ranges, etc.).

Method	Information	Strengths	Constraints	Cost[a]	References
Visual inspection	Occurrence Duration	- Easy to implement	- High personnel requirement	Not available	EPA, 1999a
Conductivity sensor	Occurrence Duration	- Accurate data - Easy to implement	- Moderate cost investment - Low autonomy - High maintenance	1,000	Adasa Sistemas (personal communication, 2014)
Water quality sensor	Occurrence Duration	- Accurate data	- High cost investment - Technical knowledge of the sensor is required	20,000	Gruber et al., 2005 Caradot et al., 2011
Water level sensor	Occurrence Duration Volume[b]	- Accurate data - Easy to implement	- Moderate cost investment - Rough estimation of volume	500 – 1,000	Kleidorfer et al., 2009 Sonnenberg et al., 2011 Dirckx et al., 2013 Leonhardt et al., 2012
Flow sensor	Occurrence Duration Volume	- Best CSO characterization - Accurate data	- High cost investment - Technical knowledge of the sensor is required	6,000 – 17,000	Field et al., 1995 EPA, 1999a Blanksby, 2002 FWR, 2012 Leonhardt et al., 2012

a Indicative cost for sensors, which is in Euros and per unit, and including all required accessories for proper operation
b Volume obtained by means of overflow equations

Table 1-4. Review of methods used to characterize a CSO (Montserrat et al., 2013).

The problem arises when the entire CSO network is to be monitored simultaneously, since a large number of CSO structures are normally present in a CSS. The EPA estimated the number of CSO outfalls still active in the U.S. at 9,348 outfalls (EPA, 2004). Table 1-5 shows some figures on the number of overflowing locations present in the CSS from some international cities.

City	CSO outfalls	Reference
New Jersey (U.S.A.)	254	(EPA, 2004)
Winnipeg (Canada)	79	(Winnipeg CSO Study)
Osaka (Japan)	114	(Horie, 2011)
London (U.K.)	57	(Thames Tideway Tunnel)
Berlin (Germany)	530	(Schütz et al., 2011)
Barcelona (Spain)	250	(Personal communication with Aqualogy, 2014)

Table 1-5. Number of CSO structures in some CSSs from different countries.

Whether it is for evaluating the impact from CSOs on the water quality, to evaluate the performance of the system or to comply with the law, all or nearly all the CSO structures of a system should be monitored. For this purpose the investment required to implement the monitoring by means of some of the commonly used methods would be too high. This makes difficult for companies, institutions and water agencies to carry out this extremely important monitoring task. In this regard, the first objective of this thesis is,

Objective 1

To develop and validate a method based on low-cost temperature sensors to determine the occurrence and duration of CSO events.

Which are the potential applications of the occurrence and duration data obtained from low-cost methods?

Just as important as monitoring (i.e. data collection) is the analysis and application of data. Municipalities, industries, and research centers regularly collect large amounts of data using the vast array of measurement technologies available today. The ability to analyze and learn from collections of data is essential for making informed decisions. Managers of CSSs must make important decisions concerning the maintenance and upgrade of CSO structures. The maintenance of sewer systems and particularly CSO structures are a large cost to a municipality. For instance, the EPA estimated that for one CSO structure containing a screen facility, 10 overflows per year would have an annual operation and maintenance cost of approximately $10,000 USD (EPA, 1993). With a 50-year lifespan, CSSs eventually need to be replaced or upgraded (Center for Sustainable Systems, 2013). In the United States, the correction of CSSs could cost approximately $64 billion USD over the next 20 years (EPA, 2008). Many municipalities cannot afford to pay for CSS upgrades without federal and state aid, but federal spending on sewage infrastructure is falling (Tibbetts, 2005). Thus, municipalities or companies that manage sewers need to make the best use of the money that is available to them for CSS maintenance and upgrades.

If managers could monitor and analyze data on the occurrence and duration of overflows within each and every CSO structure of a CSS, then they could assess how the structures perform, pinpoint where the weak spots are within a CSS, and then make decisions accordingly. The structures in which overflows occur most often are prime candidates for maintenance and upgrades, and conversely, structures that have low frequencies of overflow need less attention. Ideally, managers would have access to a tool that assesses or predicts which structures are likely to overflow as a result of rain. Such a tool would help to coordinate post-rainfall maintenance tasks, and costs could be decreased by spending less time and effort checking on those structures that, through assessment, have been recognized as unlikely to overflow. Similarly, managers could focus on updating only those structures whose improvement would yield the greatest reduction of CSOs, which can best be determined through monitoring and assessment. Using data from monitoring CSOs can, therefore, help CSS managers to decide on the most appropriate and cost-effective strategies for maintenance and improvement, which is crucial when budgets for sewer infrastructures are decreasing.

The recent development of low-cost methods for monitoring the occurrence and duration of CSOs, such as the proposed in this thesis, offers an excellent opportunity to characterize the performance of a CSO network. The insight gained from such monitoring can be used to improve the overall performance of a CSS and reduce the negative impacts of CSOs. In this respect, the second objective of this thesis is,

Objective 2

To develop a methodology to evaluate the performance of combined sewer systems, using the data on occurrence and duration of CSOs obtained from the proposed method.

Another potential application of CSO data obtained through low-cost methods is the calibration of numerical models, which are typically used in the design and analysis of urban drainage systems. Because of the complexity of real systems, these models are always a simplification of some aspects of the system (Reichert, 2011), and discrepancies between modeled and observed results are always expected. For this reason a calibration process has to be conducted to obtain reliable results. Calibration is a crucial step in the modeling of UWWS in general, and particularly sewer systems, as recommended in several guidelines and publications (e.g. EPA, 1999a; WaPUG, 2002; Muschalla et al., 2009). The calibration of sewer models hydraulics has traditionally focused on predicting the flow discharge in the sewer inflow channel (e.g. Mourad et al., 2005; Artina et al., 2007; Muschalla et al., 2008; Gamerith et al., 2011). However, little attention has been given to calibrating the hydraulics in the CSO structures. It makes little sense to use a model which has not been calibrated for describing the behavior of CSO structures to evaluate the system's design, or the potential impact on the receiving water bodies. Few studies reported the calibration of CSO structures, and are normally focused on a single or few structures (e.g. Kleidorfer et al., 2009; Autixier et al., 2014). The calibration of a sewer model with measurements from all the network of CSO structures is not a common practice, probably because of the large investment on monitoring equipment and human resources (to obtain reasonable good data sets). However, in complex systems such as sewer systems, there is a need to collect more and reliable data to increase the representativity of the model and reduce the global uncertainty (Bertrand-Krajewski, 2007). Development of low-cost monitoring techniques can bridge the gap between monitoring and model calibration, providing sufficient information (at reasonable cost) for obtaining a proper calibrated model. In this respect, the third objective of this thesis is,

Objective 3

To demonstrate that it is possible to obtain similar accuracy in the calibration of a hydrodynamic sewer model when using low-cost sensors monitoring occurrence and duration of CSO structures, instead of using the conventional and expensive flow measurements.

1.4 Thesis structure

This thesis is developed according to the following structure:

Chapter 1 introduces the urban wastewater system after summarizing wastewater management practices from ancient times to nowadays. Some key legislations leading to the protection of water quality are described, which elaborated a legal framework to control pollution from combined sewer overflows. The chapter finishes with clear motivations of this thesis and the corresponding objectives set.

A list with the specific objectives of this thesis is presented in **Chapter 2**.

In **Chapter 3** the materials used are described and a general description of the methodology for each chapter is presented.

Chapter 4 presents the main results and discussions obtained. **Sub-chapter 4.1** describes the developed and validated method to monitor the occurrence and duration of combined sewer overflows, which is based on low-cost temperature sensors. **Sub-chapter 4.2** describes a methodology to assess, improve and maintain combined sewer systems based on the data collected from the temperature method. Finally **Sub-chapter 4.3** evaluates the performance of the calibration of a hydrodynamic sewer model when using 1) the expensive flow measurements or 2) the low-cost temperature measurements. Sub-chapters 4.1 and 4.2 are edited versions of published peer-reviewed papers. The contents presented in sub-chapter 4.3 have been submitted in a peer-reviewed journal to be considered for publication.

A general discussion is presented in **Chapter 5** considering all the outcomes presented in this dissertation, and also provides an outlook for future research.

Finally, **Chapter 6** presents the main conclusions of this thesis.

CHAPTER 2

OBJECTIVES

The aim of this thesis is to develop a method based on low-cost sensors to determine the occurrence and duration of combined sewer overflows, and to effectively use the data obtained from this method in the assessment and maintenance of CSSs, and in the calibration of hydrodynamic sewer models. Hence, in accordance with the motivations presented in the introduction, the specific objectives are threefold:

(1) To develop and validate a method based on low-cost temperature sensors to determine the occurrence and duration of CSO events.

(2) To develop a methodology to evaluate the performance of combined sewer systems, using the data on the occurrence and duration of CSOs obtained from the proposed method.

(3) To demonstrate that it is possible to obtain similar accuracy in the calibration of a hydrodynamic sewer model when using low-cost sensors monitoring occurrence and duration of CSO structures, instead of using the conventional and expensive flow measurements.

CHAPTER 3

MATERIALS AND METHODS

3.1 Locations

<u>The Besòs River catchment</u>

The Besòs River catchment (1,039 km^2) is located in Catalunya, at north-east of Spain (Figure 3-1). The confluence of two of the main contributory rivers, the Mogent and Congost Rivers, give name to the Besòs River, which flows into the Mediterranean Sea after its 18 km length. The hydrological regime of the catchment is highly determined by the Mediterranean climate typical of the region, which is characterized by hot, dry summers, and mild, rainy winters. A typical monthly pattern of the pluviometric regime of the region is shown in Figure 3-2.

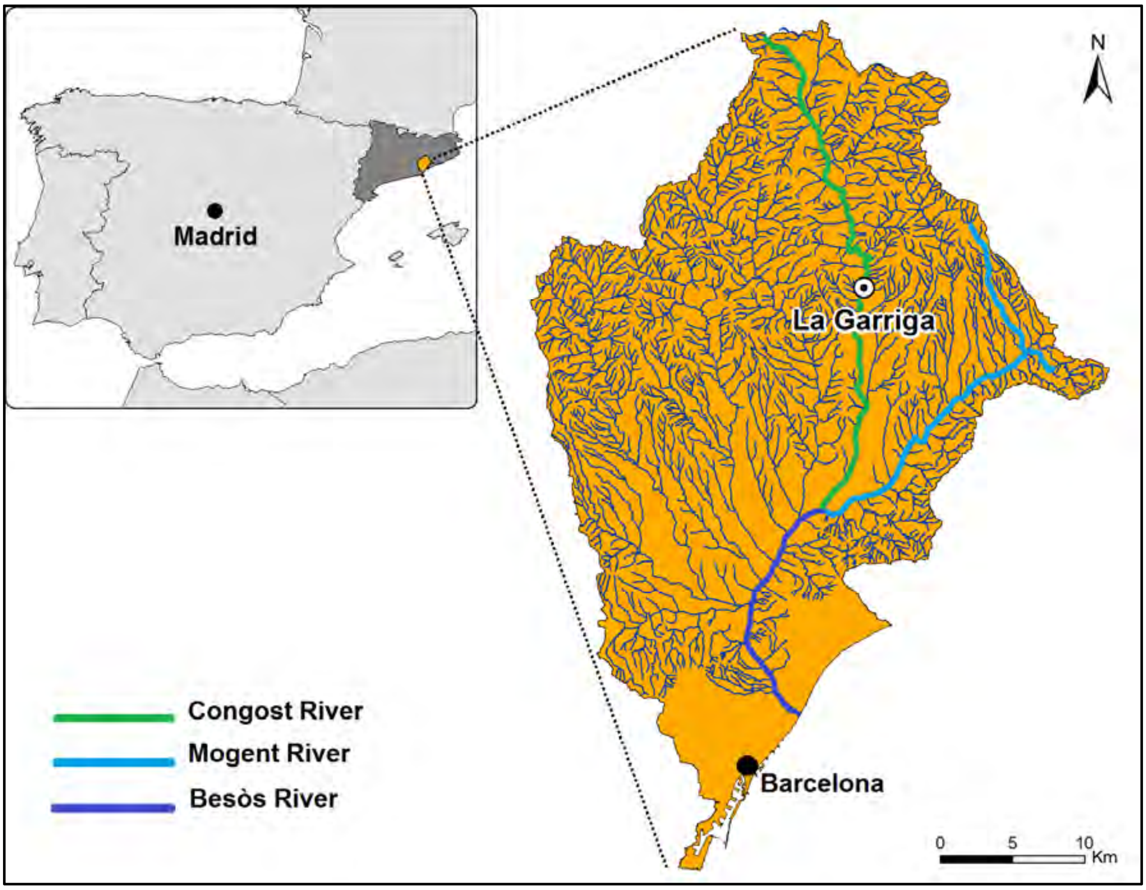

Figure 3-1. Situation of the Besòs River Catchment, and detail of the hydrographic network of the catchment.

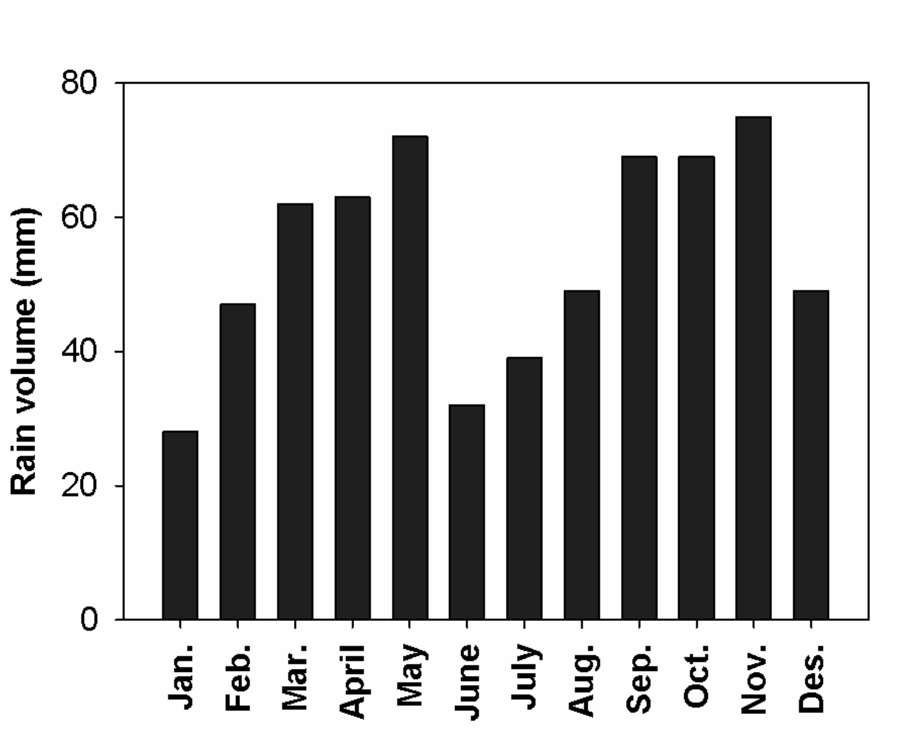

Figure 3-2. Average monthly precipitation measured in La Garriga (data from some years comprised in the period 1896-2013).

The catchment saw a strong industrial development in the 1960s-70s, along with a high growth of the population, which produced an abusive water use of the catchment. This effect, together with the fact that untreated domestic and industrial wastewaters were being discharged directly into the rivers, caused a significant environmental impact and water quality degradation, for what in the 80s it was even considered as one of the most polluted river basins in Europe (Devesa, 2006). Major efforts were made in the 90s decade to redress that situation, mostly promoted by the 'Consortium for the Defense of the Besòs River Catchment'. The construction of wastewater treatment plants or the implementation of river restoration plans were among the main measures that contributed to the recuperation of the river.

La Garriga UWWS

The UWWS of La Garriga village is located within the Besòs River Catchment (Figure 3-1). La Garriga has a population of around 15,500 inhabitants and a draining urban area of approximately 260 ha. The municipality is served by a CSS which collects the urban and industrial wastewater from La Garriga (and its surroundings), which is transported to the La Garriga WWTP. In this CSS the wastewater flows by gravity through 7,358 m long circular pipes, mostly made of concrete and corrugated polyethylene. Pipe diameters range from 300 to 800 mm. A total number of 13 CSO structures are allocated along the system, plus one structure at the entrance of the WWTP. Of these 14 CSO structures, eight are the side weir type and six are the transverse type (examples of each type are shown in Figure 3-3).

Figure 3-3. Examples of side weir (left) and transverse weir (right) from the CSS of La Garriga.

The La Garriga WWTP consists of primary treatment and secondary treatment (an activated sludge system) with a 'Ludzack-Ettinger' configuration for nitrogen removal (Corominas et al., 2013).

The receiving water body of this UWWS is the Congost River (15 km length) (Figure 3-4), a typical Mediterranean stream with low average flow rates and large seasonal variations. This strong variability is reflected in Figure 3-5, which shows the river flow discharge rate for the year 2012 registered in a gauging station in the Congost River near La Garriga. The average flow for this period was around 0.14 m^3/s, although it can be observed that occasionally the flow easily increases up to over 2 m^3/s. This is highly influenced by the specific pluviometric regime of the catchment commented above. The average annual precipitation in La Garriga is about 700 mm (ACA, 2015).

Figure 3-4. Middle reach of the Congost River, near La Garriga (July 2012).

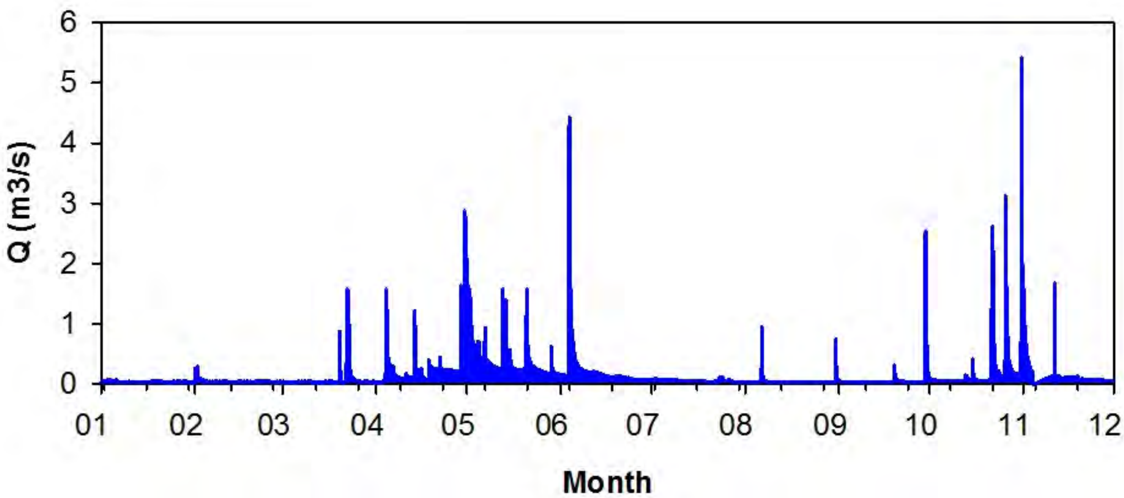

Figure 3-5. Flow discharge rate (in m^3/s) for the year 2012, measured by a gauging station in the Congost River.

An overview of the urban wastewater system of La Garriga is given in Figure 3-6 below.

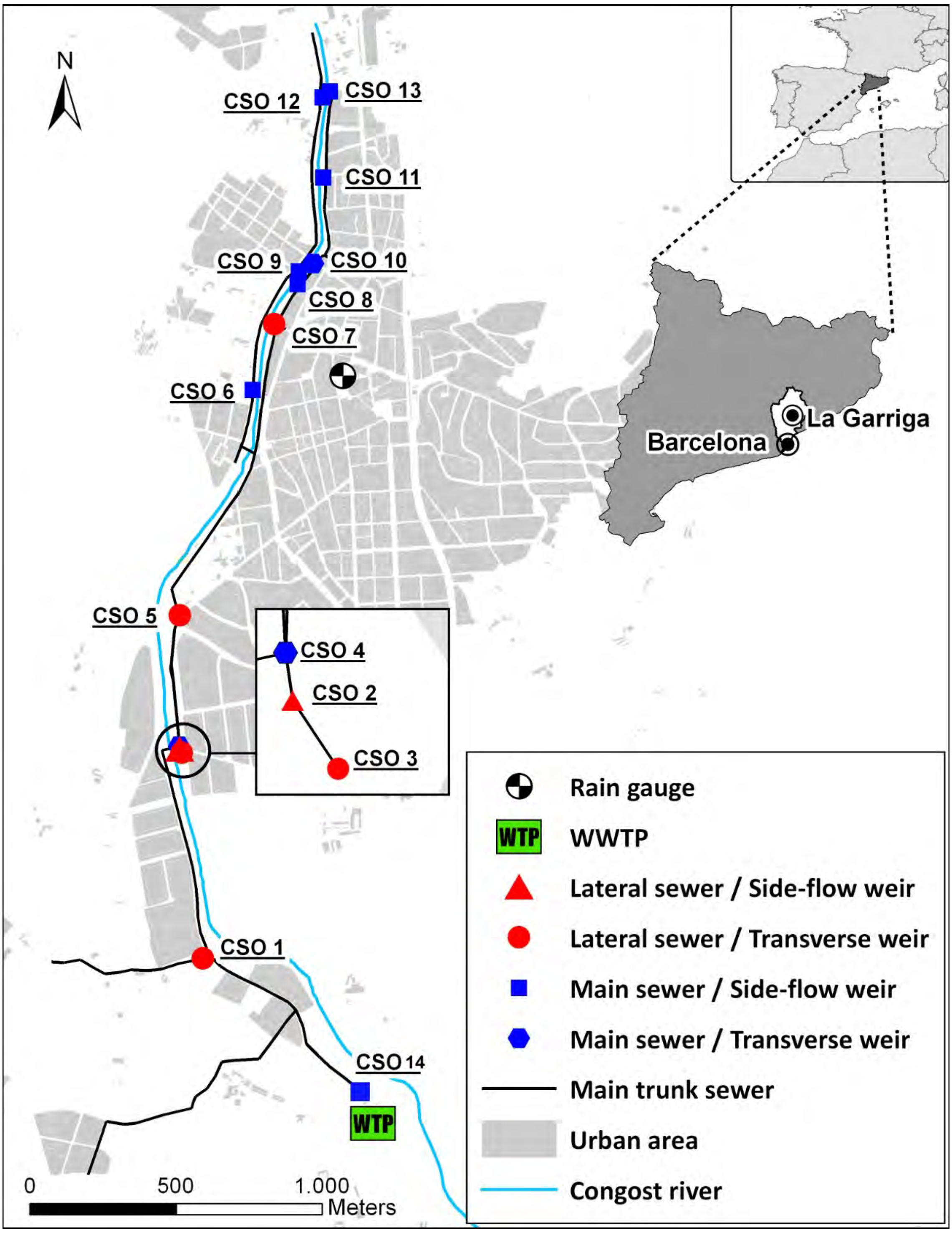

Figure 3-6. Overview of the urban wastewater system of La Garriga (Montserrat et al., 2013).

Graz West catchment

Another case study object of this thesis is found in the city of Graz, which is the capital of the province of Styria, and the second largest city in Austria. Specifically it is studied an urban catchment situated in the western part of Graz. The catchment, with a total population of about 19,500 inhabitants, serves an area of about 460 ha (Gamerith, 2011), and is drained by a combined sewer system with a side weir-type CSO structure at the outlet of the catchment. The average precipitation in the region is about 870 mm (Lazar and Podesser, 1999). A more detailed description of the catchment can be found in Gamerith (2011). A tipping-bucket rain gauge is located at the northern part of the catchment registering precipitation at 0.1 mm resolution. A layout of the Graz catchment is shown in Figure 3-7 below.

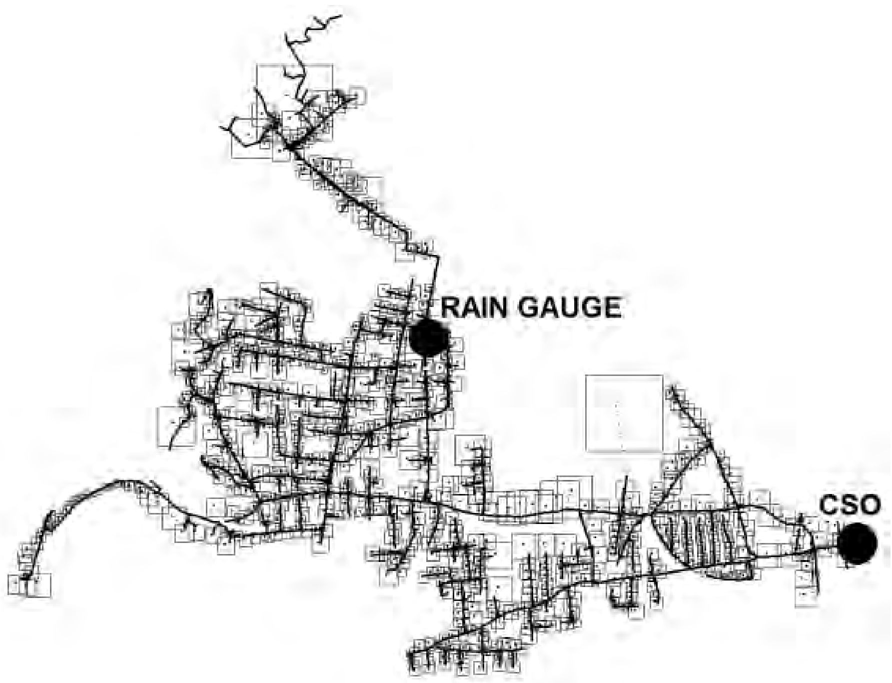

Figure 3-7. Overview of the Graz-West Catchment (Gamerith et al., 2011), indicating the location of the CSO structure (at the end of the system) and the rain gauge.

The receiving water body of this system is the Mur River (Figure 3-8), which runs through the city of Graz. The Mur is a transboundary river, which originates in the Austrian Alps and flows through Slovenia and Hungary, to finally discharge into the Drava River (Croatia), covering an approximately total distance of 450 km (Simon et al., 2011). In Graz, the Mur River has an average flow of 117 m^3/s (Gruber et al., 2005).

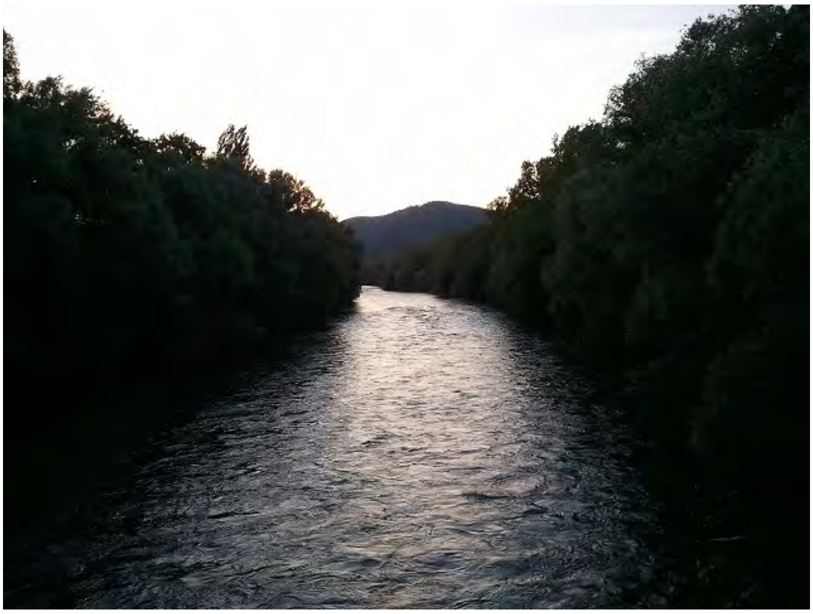

Figure 3-8. The Mur River, before reaching the city of Graz (June 2012).

Regarding the CSO structure, the side weir is 0.9 m height, and the crest of the weir has 8.9 m length. Following the weir, a 0.6 m diameter-8.5 m length throttling pipe connects with the main sewer. A monitoring station was installed at the CSO structure and has been measuring flow rate and quality data since October 2002 (Gruber et al., 2005). The station is equipped with flowmeters measuring the flow rate at the inflow and overflow channels. The station was upgraded in 2012 by installing low cost temperature sensors. A layout of the monitoring station is shown in Figure 3-9 below.

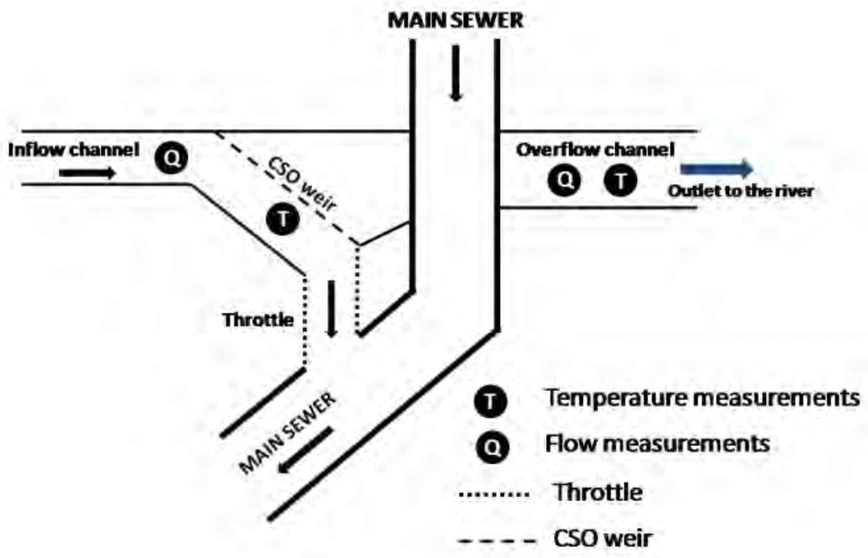

Figure 3-9. Layout and instrumentation of the monitoring station at the CSO structure of the Graz West Catchment.

3.2 Data collection

Temperature, flow and conductivity sensors, together with rain gauges were the specific equipment used in this thesis. Below, a detailed description of each device is provided.

Temperature measurements

The temperature sensor was a Hobo® Pendant UA-002-64 (Onset Computer Corporation) built in a 58 × 33 × 23 mm waterproof casing that provides protection against the overflowed water. The selected model is capable of accumulating up to 52,000 10-bit readings. The sensor is powered by a 3 V CR-2032 lithium battery which normally lasts, according to the manufacturer, one year with logging intervals greater than 1 min and can be easily replaced when necessary. The specifications of this model are summarized in Table 3-1. The approximate cost of one unit varied between 44 and 52 € (depending on the requested amount of units).

HOBO Pendant UA-002-64	
Operating range	-20º to 50ºC (in water/ice) -20º to 70ºC (in air)
Accuracy	± 0.53ºC from 0º to 50ºC
Resolution	0.14ºC at 25ºC
Drift	Less than 0.1ºC per year
Response time	Airflow of 2 m/s: 10 min Water: 5 min
Time accuracy	± 1 min per month

Table 3-1. Specifications of the HOBO Pendant UA-002-64 (Onset, 2014).

The readout of the temperature data was carried out with an optic interface reader model Hobo® Shuttle U-DTW-1 (Onset Computer Corporation). It is built in a 15.2 × 4.8 cm waterproof case and can store data from 63 different loggers of 64 kbytes. It had an approximated cost of 240€. An image of both the sensor and the data reader is given in Figure 3-10 below.

Figure 3-10. Image of the Hobo® Pendant UA-002-64 (left) and Shuttle U-DTW-1 (right) (Onset, 2014).

<u>Flow measurements</u>

Different flow monitoring devices were used. In the case study of the La Garriga, the Hach-Lange's 'Sigma 950' was used for the verification of the temperature method (see Chapter 4.1). In the case of Graz, the flow-meter in the overflow channel was a 'NIVUS CS2 Correlation Wedge Sensor'. Both sensors calculate the flow through the continuity equation (Equation 3-1),

$$Q = v \cdot A \qquad \text{(Eq. 3-1)}$$

where Q is the flow discharge; v is the velocity and A is the cross section. Thus two variables, the velocity and the cross-sectional area, are measured by means of combined or separated sensors. Technical specifications of the flow-meters are given in Table 3-2.

	Sigma 950		**NIVUS CS2**		
	Velocity	**Level**	**Velocity**	**Level**	**Level**
Measurement principle	Ultrasonic pulse	Bubbler	Ultrasonic Cross Correlation	Ultrasonic transit time	piezo-resistive pressure
Range	-1.5 to 6.1 m/s	0 to 3.6 m	-1 to 6 m/s	8 to 500 cm	0 to 350 cm
Accuracy	±2%	±0.033 m	-	-	-
Uncertainty	-	-	<1%	±2 mm	<0.5%

Table 3-2. Specifications of the flow measurement devices.

Rainfall measurements

Rainfall data was obtained by means of a weather station, model David Vantage Vue (Figure 3-11), located on the roof top of the La Garriga city Council, quite in the center of the village. The Rain sensor consists of a 'tipping bucket' type sensor, with a collection area of 116 cm^2, and a resolution of 0.2 mm.

Figure 3-11. Weather station installed on the rooftop of the La Garriga city Council.

Conductivity sensor

A conductivity sensor was used as an alternative approach for CSO monitoring. The sensor consisted on a stainless steel solid bar of 9 cm long and 2 cm wide, connected to a battery and a data logger. Data were transmitted via GPRS to a remote control center. The sensor was installed at the CSO structure by means of a mounting accessory consisting on a stainless-steel hollow bar (Figure 3-12). The technology was developed and provided by Adasa Sistemas S.A. The sensor and the data logger had an approximate cost of 1,100 € (personal communication with Adasa Sistemas, 2014).

Figure 3-12. On the left, detail of the conductivity sensor. On the right, detail of the mounting accessory (with the sensor inside).

The following Table 3-3 indicates on which case study were applied the devices described above.

Device	La Garriga	Graz
HOBO Pendant UA-002-64	✓	✓
Sigma 950	✓	
NIVUS CS2		✓
David Vantage Vue	✓	
Conductivity sensor	✓	

Table 3-3. Materials used for each case study.

3.3 General description of the methodology

This section provides a brief description of the methods applied to achieve each of the objectives of this thesis. A more in-depth description is given in Chapter 4.

<u>Objective 1 – Method to determine occurrence and durations of CSOs</u>

The CSO detection method is based on the assumption that temperature differences exist between the sewer gas phase and the overflowing mix of wastewater and rain water. Therefore, by installing a temperature sensor at the CSO structure, the observed temperature change during and/or after a rainfall episode can be associated to a CSO event. The method was verified and implemented in the CSS of La Garriga, where low-cost temperature sensors (model Hobo® Pendant UA-002-64) were installed at each CSO structure. This method was patented in Spain with the registry code P4103/2012 and the Application number P4103/2012.

Objective 2 – Assessment and maintenance of CSS

The data on the occurrence and duration of CSO events of the 14 CSO structures of the La Garriga CSS were acquired during a period of 11 months (from July 2011 through May 2012). During this period 53 independent rain episodes occurred. These data were analyzed in the following manner:

- The capacity of a CSS was assessed by plotting the duration of overflows versus rain volume for each rain episode and each individual structure.
- To characterize the sewer system performance the following parameters were calculated for each CSO structure in the network over the entire data collection period: (i) total number of overflows, (ii) total duration of overflows (sum of the durations of all overflows in the period), (iii) average overflow duration, (iv) the average chronological order that a CSO structure begins to overflow compared to all the other structures in the network, and (v) overflow probability. Also a CSO 'Ranking index' was developed to provide information about the order in which a structure overflows with respect to the others structures in a CSS.
- The total number of overflow events obtained for each structure was compared to the maximum number suggested by some CSO regulation guidelines.
- Finally, decision trees for CSO structures were constructed as part of a tool to help managers make decisions about CSS maintenance.

Objective 3 – Calibration of a hydrodynamic model with low-cost data

The methodology in this section aimed at calibrating a modeled CSO structure to properly describe the flow at its discharge. A new calibration approach was proposed using CSO duration data obtained from low-cost temperature sensors. This approach was compared to a conventional approach using flow measurements in the CSO structure. The methodology can be summarized with the following points:

- The CSO structure of the Graz urban catchment was used as case study to demonstrate the usefulness of the new calibration approach.

- The EPA storm water management model SWMM version 5.0 (Rossmann, 2007) was used to simulate the Graz catchment. The code was expanded to report on CSO duration for each rain episode after a simulation run. A calibrated SWMM model of the Graz catchment (Gamerith et al., 2011) was used as the reference model.
- The key model parameters were selected and their limits defined for calibration.
- The calibration approach was applied to five rain episodes differing in volume, duration and intensity.
- The criteria used to assess the goodness of model calibration and validation for the five rainfall episodes were the total CSO volume (m^3), CSO peak (m^3/s) and CSO duration (min), evaluating the deviation between the simulated and observed value of these variables.
- A sensitivity analysis was conducted to assess how key model parameters influenced the criteria used to assess the goodness of model calibration.
- Several objective functions were tested to find out which ones were useful for properly describing CSO volume, peak and duration errors between simulated and measured data.
- The model was calibrated automatically (using an optimization algorithm) following two approaches: the *overflow approach* and the *duration approach*. In the *overflow approach* the CSO structure model was calibrated using the flow measurements at the overflow channel whereas in the *duration approach* the CSO structure model was calibrated using CSO duration data.
- The calibration was conducted for single rain episodes and using single objective functions.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Field validation of a new low-cost method for determining occurrence and duration of combined sewer overflows

Conventional methods for monitoring CSOs have traditionally based on level or flow measurement devices, which provide an accurate characterization of the CSOs. The main drawback of these methods relies on the significant investment required if a large number of CSO structures are to be monitored simultaneously. Therefore the need of low-cost methods to obtain valuable information on CSOs, especially when mandatory laws are demanding stringent control on the CSOs. Accordingly, in this chapter is presented the development and validation of a new methodology to quantify the occurrence and duration of CSO events, for the entire CSO network of a CSS. The method is based on temperature monitoring by using low-cost sensors.

This chapter is an edited and extended version of the paper published in:

Montserrat, A., Gutierrez, O., Poch, M., Corominas, Ll. Field validation of a new low-cost method for determining occurrence and duration of combined sewer overflows. *Science of the Total Environment* 2013; 463-464, 904-912.

4.1.1 Description of the method

The CSO detection method is based on the assumption that temperature differences exist between the sewer gas phase and the overflowing water of the CSO. Therefore, by installing a temperature sensor at the CSO structure, the observed temperature change during and/or after a rainfall episode can be associated to a CSO event. Figure 4-1-1 represents the principle of the CSO detection method. The first section (A) refers to normal conditions with typical gas phase temperature profile following natural daily patterns. After a rain episode starts, and a CSO occurs, a sharp temperature shift takes place due to the contact of the sensor with the overflowing water, usually at different temperature (B). Once the CSO event is over, a progressive return to normal gas phase temperature conditions occurs (C).

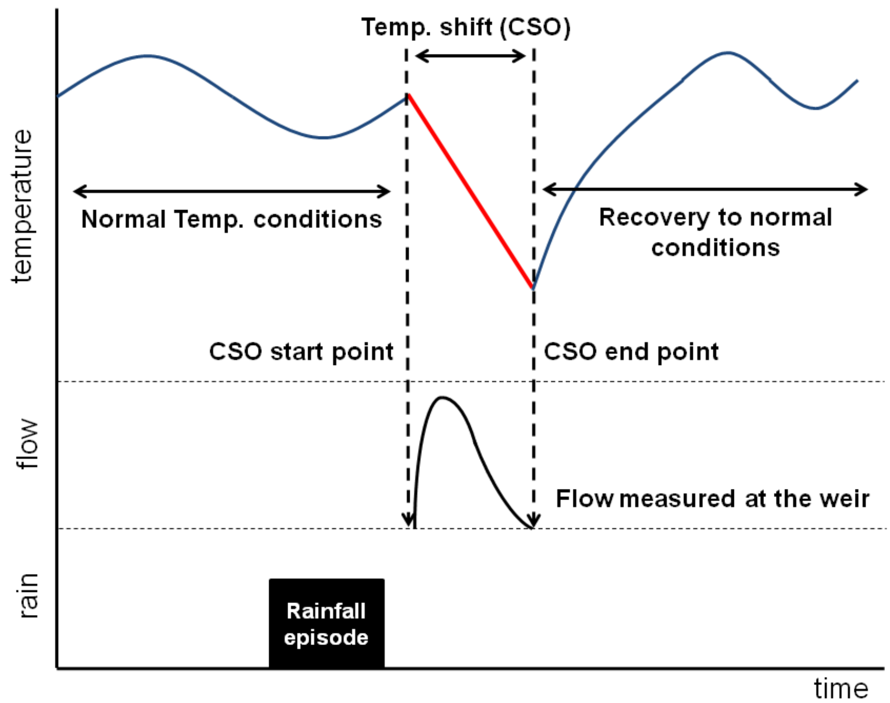

Figure 4-1-1. Theoretical graph representing the principle of the CSO detection method.

Two types of instruments were used, 1) temperature sensors with built-in data logger and 2) the data reader. The temperature sensor was a Hobo® Pendant UA-002-64, with an approximate cost of 45 €/unit. The logging interval time used in this study was set at 3 minutes frequency, thus allowing uninterruptedly data storage for 120 days. The readout of the temperature data was carried out with an optic interface reader model Hobo® Shuttle U-DTW-1 (Onset Computer Corporation), which had an approximated cost of 240 €. Further information on the technical specifications of these instruments is given in Chapter 3.

4.1.2 The case study

The method was verified in the CSS of La Garriga, in which a total number of 13 CSO structures are allocated along the system, of which 7 are the side weir type and 6 are the transverse type. The spilled wastewater is discharged into the Congost River. An overview of the case study with the type and location of each structure is shown in Figure 3-6 in Chapter 3. La Garriga main trunk sewer was upgraded for the last time in 1992, and is currently reaching its capacity limit due to new sewer connections coming from recent urban and industrial developments. This has led to a progressive increase in the frequency of occurrence of CSO events.

A total of 13 temperature sensors were installed in the CSS of La Garriga, one for each structure, from July 2011 until July 2012. Each sensor was attached to a stainless screw eye fixed on the sewer walls. For the transverse type structures the sensor was placed in the bottom center of the discharging pipe. In the case of side weir types it was installed either in the bottom center of the outlet pipe or in the most likely place along the weir crest according to the criteria of the operators and site-specific conditions (see Appendix I for details of the installation). The data readout was carried out on a monthly basis and downloaded to a computer by means of the sensor’s software. The total investment regarding the equipment, including the 13 temperature sensors, the data reader and software, for monitoring a combined sewer of 7.3 km was 924 €. Finally, for verification purposes, the CSO Structure 7 was equipped with a flow-meter model Sigma 950 (Hach®) and a second temperature sensor Hobo® Pendant UA-002-64 located on the top crown of the overflow discharging pipe (secondary sensor). See Appendix I for details of the verification installation.

Rainfall was monitored by means of a tipping bucket rain gauge, model *David Vantage Vue*, located in the center of the village with a 5 min resolution. Data from temperature sensors and rainfall records were analyzed together in order to look for reliable changes in the temperature profile during or/and after a rainfall episode. The Signal-to-Noise ratio (SNR) was calculated for each structure for the period from [01-12-2011] to [19-01-2012] when no rainfall episodes occurred. The SNR refers to the ratio between the mean and the standard deviation of the data (i.e. the inverse of the coefficient of variation). The SNR was calculated at each time-step using a moving window of 6 h. For each structure, the mean of all SNR values was computed to generate a single SNR value.

4.1.3 Verification of the method on a single CSO structure

The verification of the method is based on the comparison of the temperature, flow data registered at the CSO Structure 7 (CSO 7) and the rain intensities (Figure 4-1-2A) during 24 h within the period from [20-05-2011 00:00] to [21-05-2011 00:00]. It can be seen that the abrupt shifts of temperature detected by the temperature sensors (Black line, top part of Figure 4-1-2A) correspond to CSO events measured by the flow-meter (dashed line, middle part of Figure 4-1-2A). Six overflowing events were clearly and simultaneously detected by both instruments in that particular day. Data from the secondary temperature sensor (Grey line, top part of Figure 4-1-2A) also showed a very strong agreement with the other measurements. Furthermore, the temperature drops recorded by the secondary temperature sensor at the top crown of the spillway pipe suggests that the overflowing was produced at full pipe capacity. Figure 4-1-2B presents the first overflowing event shown in Figure 4-1-2A. According to the temperature-based method, the total duration of the presented event 1 was 1 hour, from [20/05/2012 03:43] to [20/05/2012 04:43]. Vertical dashed lines indicate the start and end points of the CSO event obtained from the flow-meter measurements. The marked start point coincides with the abrupt temperature decrease. The CSO event finishes at around 4:50, where the temperature recovers from the drop.

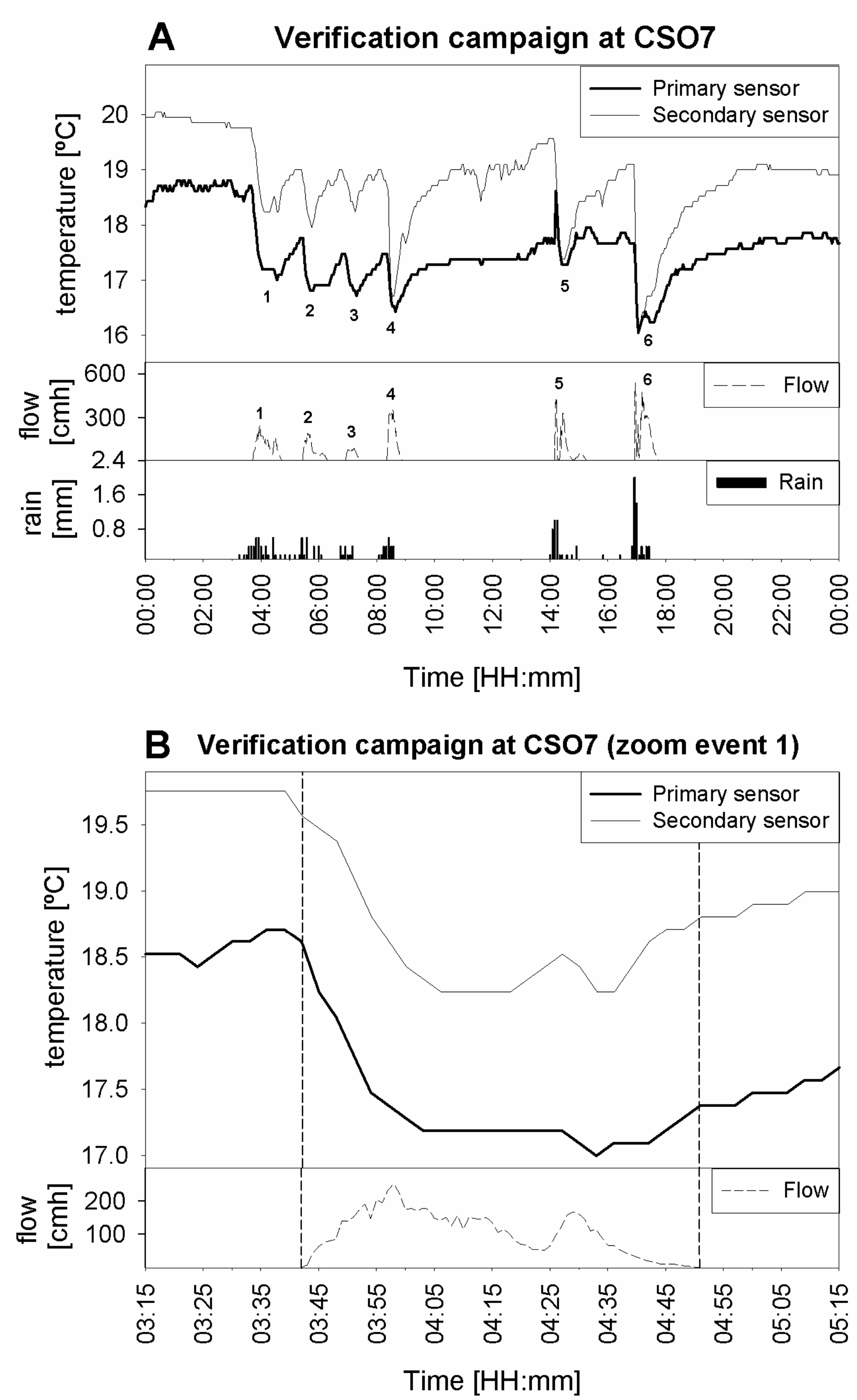

Figure 4-1-2. Temperature and overflow profiles from the method verification campaign. [A] plots temperature, flow and rainfall data from the verification period, representing 6 overflow events (numbered) within 24 hours, each CSO event corresponding to a temperature shift. [B] is a zoom of event 1 in which vertical dashed lines indicate the start and end points of the CSO event.

4.1.4 Evaluation of the method on multiple CSO structures

A total number of 57 rainfall episodes were registered for the period studied (between July 2011 and July 2012). The analysis of the temperature signals for the 13 structures and the 57 episodes was carried out manually. The effectiveness assessment of the method is done by defining three categories of response based on the obtained temperature profiles.

Response Category 1 (C1): *Clear* - Overflow

A *Clear - Overflow* response means that there is a clear temperature shift which is related to the CSO produced and to the corresponding rainfall episode. After the rainfall episode starts the temperature shift is fast and abrupt, which makes it easy to detect. The shift in the temperature profile can either be negative (Figure 4-1-3A) or positive (Figure 4-1-3B).

Response Category 2 (C2): Clear – No Overflow

A *Clear – No Overflow* response means that no variations in temperature are found during a rainfall episode (Figure 4-1-3C). That indicates that no CSO is produced. It is normally associated to very low rainfall volumes and/or intensities.

Response Category 3 (C3): *Not Clear*

This category is assigned when a temperature profile is characterized by high fluctuations of temperature at low time scale, whether it rains or not. Identifying a temperature response to a CSO for a given rainfall episode is not obvious (Figure 4-1-3D), since similar temperature oscillations are observed in dry weather conditions.

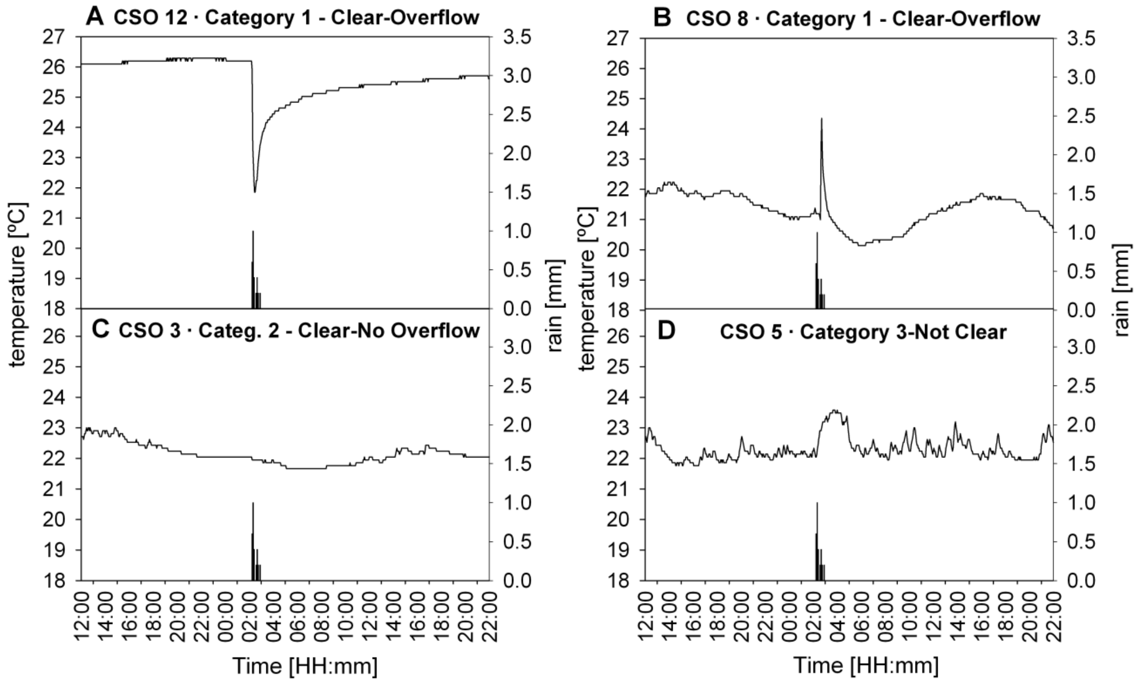

Figure 4-1-3. Different categories of temperature responses used to evaluate the method effectiveness. Black lines represent the temperature profiles. Vertical black bars represent the rainfall data. The four subplots correspond to the same time rainfall episode, from 04/09/2011. From A to D: *Category 1 – Clear-Overflow* negative, *Category 1 – Clear-Overflow* positive, *Category 2 – Clear-No Overflow* and *Category 3 - Not Clear* response.

For each structure and rain episode the temperature profile was manually analyzed and one of the categories described above was assigned. The *Expected Potential* (EP) was then calculated for each structure (Equation 4-1-1). The EP is calculated as the number (n) of clear responses (C1 and C2) divided by the total number of analyzed responses (C1, C2 and C3).

$$EP = \frac{n_{C1}+n_{C2}}{n_{C1}+n_{C2}+n_{C3}} \cdot 100 \qquad \text{(Eq. 4-1-1)}$$

Table 4-1-1 summarizes the number of each response category and the EP obtained for each structure for the analyzed 57 rainfall episodes. At the end of the study 723 responses were obtained. It can be seen that high EPs were achieved, obtaining values above 80% in 10 of 13 structures, 3 of them with 100% efficiency. However, there were

3 structures (CSO9, 11 and 13) that obtained significantly lower EP values (40%, 54% and 49% respectively). Overall, the mean EP was established at 80%.

Weir	CSO 1	CSO 2	CSO 3	CSO 4	CSO 5	CSO 6	CSO 7	CSO 8	CSO 9	CSO 10	CSO 11	CSO 12	CSO 13	TOTAL (%)
Clear Overflow	30	27	36	32	35	31	43	29	12	34	18	20	5	46.6
Clear No Overflow	27	5	13	15	18	15	14	17	11	18	13	37	23	28.9
Not Clear	0	7	8	10	4	11	0	11	34	5	26	0	29	22.1
No Data	0	18	0	0	0	0	0	0	0	0	0	0	0	2.4
EP(%)	**100**	**82**	**86**	**82**	**93**	**81**	**100**	**81**	**40**	**91**	**54**	**100**	**49**	**EP mean** **80**
SNR - mean	425.1	32.7	44.1	24.6	141.6	37.5	219.1	26.3	19.6	60.8	27.9	345.2	28.1	

Table 4-1-1. Number of responses for each category, Expected Potential rates (EPs) and SNR means for all monitored CSO structures during the 57 rainfall episodes.

The effectiveness of the method was closely related to the SNR, since the more stable and noiseless a temperature profile was, the easier became to detect the shift associated to the CSO event. The higher the SNR, the lower the standard deviation, allowing for easier detection of temperature shifts (even small shifts could be correlated to a CSO event). Figure 4-1-4 presents the SNR values for each structure (except for CSO13 due to the very low number of *Clear* responses) together with the percentage distribution of the temperature shift magnitudes calculated for each CSO event. The higher SNR values (i.e. SNR above 100 with a 6 h moving window) match with those structures with 100% EP: CSO1 (SNR = 425.1), CSO7 (SNR = 219.1) and CSO12 (SNR = 345.2). In contrast, the structure CSO9 which has the lowest SNR (19.6) got the lowest EP too (40%) and an exponential relationship can be drawn for the other structures in between. The calculated temperature shift magnitudes ranged from -9 ºC to +6 ºC. Positive and negative shifts were found for all the structures except CSO12, which only showed negative shifts. In general, most temperature shifts were located within the -4ºC to 0ºC magnitude range (CSO1, CSO3, CSO4, CSO5, CSO6, CSO7, CSO10, CSO11 and CSO12). It is worth noting that high SNRs coincided with the structures accounting for a higher percentage of small temperature shifts, with changes up to ±2 ºC: CSO5 (SNR = 141.6), CSO7 (SNR = 219.1), CSO10 (SNR = 60.8) and CSO12 (SNR = 345.2).

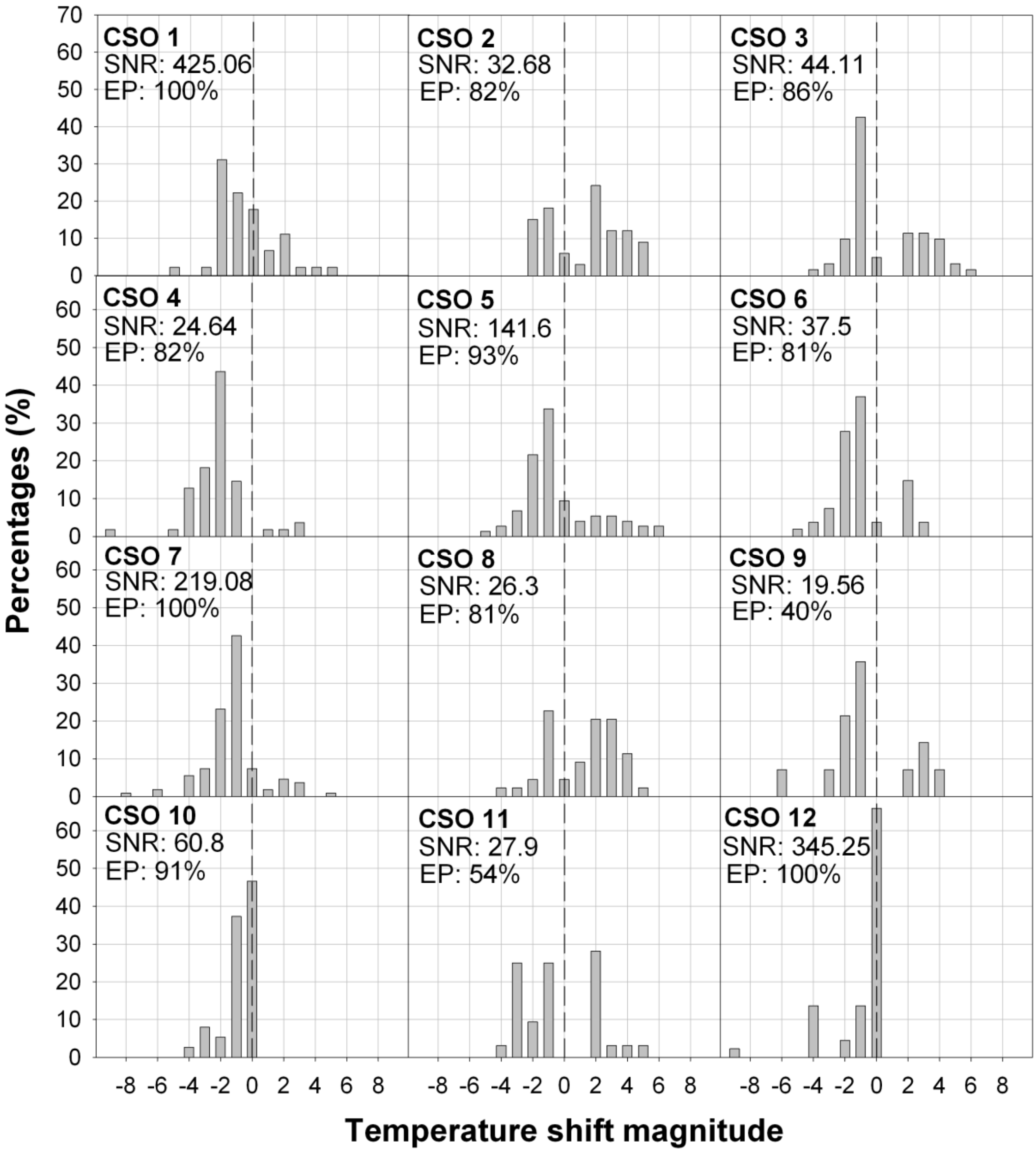

Figure 4-1-4. Percentage distribution of the temperature shift magnitudes for each CSO structure for all the period of study. The vertical black dashed line in each histogram marks the 0 ºC shift magnitude (grouping changes from 0 to ±1 ºC). For each structure the SNR and the EP are presented. Note that the structure CSO13 (SNR-28.09) is not represented due to the very low number of *Clear* responses.

Observed limitations

The causes that affect the response and hence decrease the potential of the method are closely related to the characteristics of the structure. In the case of CSO11 and CSO13 a poor design of the side weir did not allow to evacuate the total amount of overflowed water and the sensor was submerged even in dry weather conditions. Also, it was found that a drop structure in the sewer system, just before the structure CSO9, produced turbulences that affect the signal. Illustrations of these specific characteristics are provided in Appendix II. The main effect of this are high fluctuations of temperature at low time scale during wet weather conditions, which makes that linking a temperature response to a CSO for a given rainfall episode is not obvious and thus the CSO event falls into *Category 3 – Not clear*. It is noted that structures CSO9, CSO11 and CSO13 are side weirs, so this specific structure design can be considered more critical compared to other designs such as transverse weirs. A direct relation between the category response and the location of the structure was not found, since maximum rates are obtained either in lateral (CSOs 1 and 7) and main trunk structures (CSO 12). It was also found that the effectiveness of the method was not affected by seasonal temperature variations. Figure 4-1-5A shows the temperature of the sensor installed at the structure CSO6 from July 2011 to July 2012, ranging from 7 to 23 ºC. The EP (Figure 4-1-5B) was calculated separately for each month of this period and using the data of all the structures. Although the maximum EP rate was found for the coldest month (January) and the lowest rates for warmer months (July and September 2011) there is no clear relationship between temperature and EPs. The number of rain episodes per month (indicated at the top of the EP bars) and the characteristics of the rain (volume, duration and intensity) can be masking this effect. Overall, the EPs are above 70% most of the time.

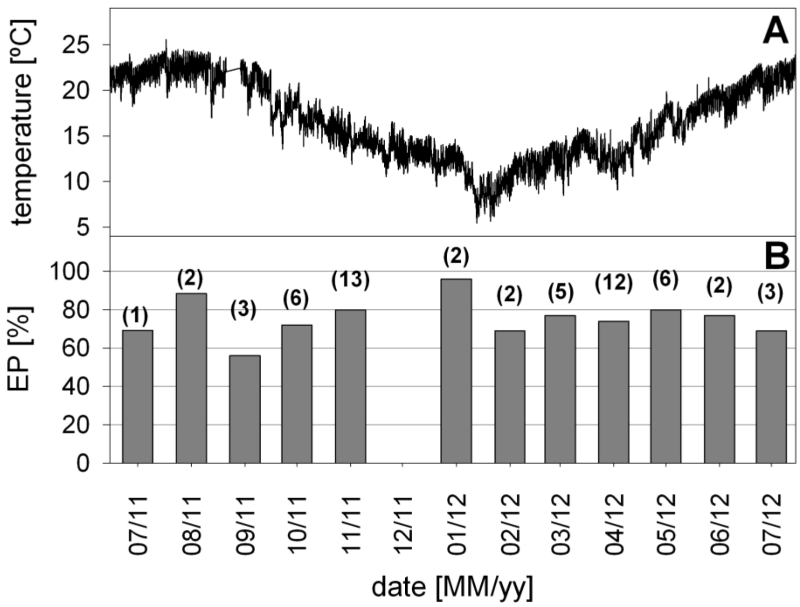

Figure 4-1-5. Seasonal variation of temperature. [A] shows the temperature profile registered at the structure CSO6 from July 2011 to July 2012. [B] shows the calculated monthly expected potential rates (EP's) averaging for all the structures. In parenthesis the number of rainfall episodes per month is indicated. Note that in December 2012 there is no bar chart because there were no rainfall episodes.

Data assessment

Using the information extracted from the temperature sensors an assessment of the potential danger of each structure can be conducted. Table 4-1-2 summarizes the CSO information from all the structures with EP above 80% for the registered 57 rainfall episodes (CSO9, 11 and 13 were considered non comparables due to their significant lower EPs). It can be seen that CSO7 is by far the structure with larger number of CSOs (103), followed by CSO5 (72), CSO10 (70) and CSO3 (64). The other structures resulted in between 43 and 56 CSOs. In terms of total duration, the structures CSO5 (2,137 min) and CSO7 (1,788 min) are the largest contributors. CSO's 3, 6 and 10 stay between 1,200 and 1,500 min, and the rest of structures between 600 and 1,000 min. Regarding mean duration of overflow, CSO5 presents the highest value (30 min), while CSO2 has the lowest (15 min). The other structures range between 19 and 23 min.

This methodology also allows for the identification of the overflowing chronological order of the structures regarding the starting point of CSOs (Figure 4-1-6). As stated in Table 4-1-2, CSO's 7 and 10 are the ones that overflowed in first and second position most often (15 and 10 times for the Structure CSO7, and 11 and 8 times for CSO10). Also CSO7 was in third position (7) and CSO2 in third position (8). This is important as the first overflows are supposed to be those with the highest pollutant concentrations due to first flush phenomena. Note that the total nº of CSOs for some structures exceeded the number of rain episodes (i.e. 57). This was because for this analysis it was considered an inter-event time between independent CSOs of 30 minutes, so more than one CSO occurred in some structures for the same rain episode.

Structure	CSO 1	CSO 2	CSO 3	CSO 4	CSO 5	CSO 6	CSO 7	CSO 8	CSO 10	CSO 12
Total Nº CSOs	43	45	64	57	72	56	103	47	70	43
Total CSO duration (min)	898	660	1214	1484	2137	1261	1788	993	1410	870
Mean CSO duration (min)	21	15	19	26	30	23	17	21	20	20
# Order 1	1	1	5	4	3	1	15	4	11	0
# Order 2	0	2	2	7	3	4	10	5	8	1
# Order 3	3	8	4	3	4	2	7	3	3	0

Table 4-1-2. Total number of CSO events, total and mean duration (in minutes) and number of times (#) that has overflowed in first, second and third order for all the structures which showed EPs higher than 80% for the 57 rainfall episodes.

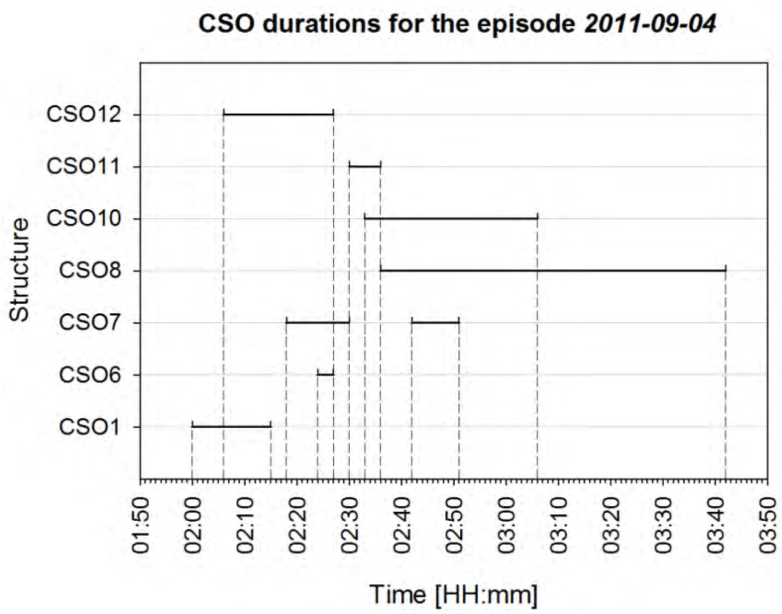

Figure 4-1-6. Duration of the CSOs produced at different structures for a 2.50 mm rainfall episode occurred on 04/09/2011. Horizontal black lines indicate the starting and ending point of CSO for each structure. It can be observed that CSO1, 12 and 7 are the ones overflowing at the beginning and that a consecutive activation/deactivation of all the overflows occurs. The structures that do not appear means that no CSO was produced for such structures.

Given this characterization of the entire network of CSO structures simultaneously for 57 rainfall episodes, appropriate control measures can be defined for the critical structures. In the studied case, Structures CSO5 and CSO7 are the ones with larger potential danger, CSO5 because it had the highest total and mean durations, and CSO7 because it showed the largest number of CSOs (although the total duration was not the highest) and overflowed normally at the beginning of the episodes. It should be noted that not only emission-based criteria (such as the occurrence and duration of CSOs) determine the potential danger of these overflows, but also mainly influenced by immission-based criteria which consider the conditions of the receiving waters (e.g. FWR, 2012). In this latter regard, in order to evaluate the impact of CSOs on the water quality, flow and water quality data would be necessary in order to estimate the pollutant load discharged into the receiving waters (e.g. Irvine et al., 2005).

4.1.5 Advantages, limitations and potential applications of the proposed single temperature-sensor method

Significant benefits can be drawn from the implementation of the method described. First of all a good characterization of the activity from the entire CSO network of a sewer system can be achieved with minimal investment, compared to other methods (Table 1-4). As well, according to the experience in this study, the temperature sensors a) are quite easy to install in the structure, b) do not require advanced technical knowledge for their implementation, c) do not require maintenance and d) are able to resist extreme conditions during large time periods as none of the temperature sensors had to be replaced throughout the study period. In addition, conventional monitoring methods such as flow and level sensors properly work under a certain range of operating conditions (see e.g. Table 3-2). Under pressurized flow conditions, these methods could fail. The use of temperature sensors, when properly installed, would also overcome this limitation in the determination of the occurrence and duration of CSOs.

However, the data retrieval is done manually, so the aid of the sewer operators is required. This might be a fact to keep in mind in order to organize the periodically data readout, especially when dealing with large systems that contain a large number of structures. If real-time monitoring would be required to trigger an alarm when CSOs occur, communication tools to transmit the data to a central storage location should be coupled to the temperature sensor, increasing the overall cost. Another limitation is related to the automatic analysis of temperature signal with low SNR, which requires further research as mentioned above. Hence, in chapter 4.1.6 a method is proposed to automatically analyze temperature signal to detect abrupt changes. Also, in chapter 4.1.7 two alternative low-cost approaches to monitor CSOs are presented (one, upgrading the temperature approach and another one based on electrical conductivity).

Among the most promising applications, this low-cost sensor technology can be used to characterize an entire CSO network simultaneously for the same rain episodes (as shown in Chapter 4.2). The information acquired can support the definition of upgrades in the sewer system, meaning installation of storm water tanks or implementing control. Some national regulations are already forcing proper monitoring of the CSOs (e.g. the Spanish Royal Decree RD 1290/2012). Another promising application is within the field of modeling. Calibration of hydrodynamic sewer models is traditionally conducted by means of flow measurements in the main inflow channel of the sewer system (e.g. Muschalla et al., 2008; Gamerith et al., 2011). Few cases can yet be found in literature in which information from the CSO (e.g. flow discharge or water level) is used for the calibration of the models, and normally are based on a single or few structures (e.g. Autixier et al., 2014). However, model calibration procedures for hydrodynamic sewer models as well as for more simpler lumped hydrologic sewer models can benefit from the information acquired by the methodology described here (as demonstrated in Chapter 4.3), to better describe the behavior of an entire sewer system.

4.1.6 Automatic detection of CSOs

The manual analysis of the temperature data to quantify the occurrence and duration of the CSOs has two major implications, 1) there is a big amount of data to be analyzed due to the large number of structures, and 2) the results are subject to the criteria of the person carrying out the analysis. Thus, mathematical solutions should be addressed to deal with such limitations.

For illustration purposes, a mathematical technique has been implemented to the temperature time series of the Structure CSO1. This technique explores the time series using a moving window. A window length is defined (in time units), which moves along the data set (time step per time step) and calculates at each move the difference between the maximum and the minimum temperature values (called *deviation*). A boundary is defined (*maximum deviation*) and all the deviations that exceed this boundary indicate that an abrupt change in the signal has occurred. The window length and predefined maximum deviation are adjusted based on a preliminary analysis of a few events of the time series (in this case the rain events occurred during August and September 2011). The selected window length and predefined maximum deviation for the studied structure were 60 minutes and 0.4ºC respectively. The obtained matching detections percentage was 100% (i.e. temperature shifts detected by both the manual and the automatic method). No false detections were obtained in dry or wet weather. Results are represented in Figure 4-1-7. For a period of 3 months it can be seen how each drop in the temperature signal is correlated with rainfall episodes and with the automatic detections. This method is suitable to detect CSOs in those structures in which the SNR is high. For structures showing low SNR further research is needed to develop a reliable method.

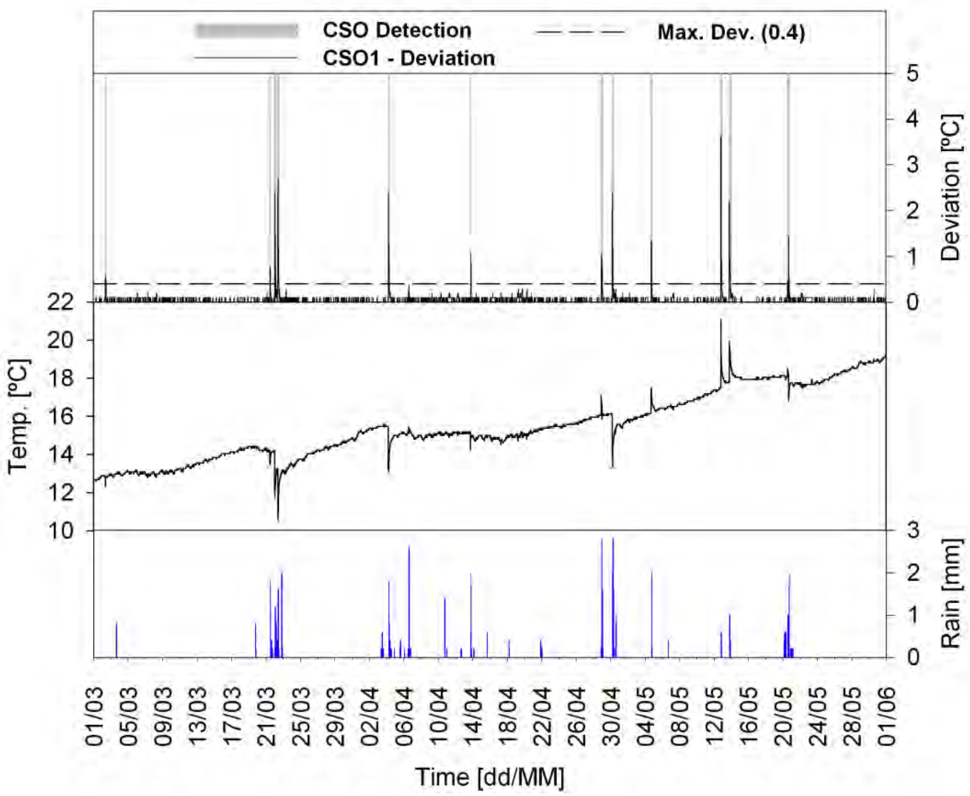

Figure 4-1-7. Automatic detection of CSO events for the structure CSO1 for the period from [01-03-2012] to [01-06-2012]. A window length of 60 min and predefined maximum deviation of 0.4 ºC were selected. On the top part, vertical grey bars indicate the automatic detection of the CSOs, matching with the temperature shifts below.

4.1.7 Alternative approaches for CSO monitoring

Two other low-cost approaches were implemented and evaluated. One method is based on the simultaneous use of two temperature sensors. The other method is based on conductivity detection. Both methods are presented below with illustrative results.

4.1.7.1 Double temperature sensor approach

The double temperature approach consists on the simultaneous monitoring of temperature both at the wastewater inflow channel (measuring the wastewater temperature) and at the CSO structure (measuring both the sewer atmospheric temperature if there is no CSO and the spilled wastewater temperature if there is an overflow). The method is based on the assumption that, during dry weather conditions, both profiles lay within a different range of temperature magnitudes. When a CSO occurs, both temperature profiles converge (as the temperature at the inflow channel and at the CSO structure would equal), indicating the total duration of the CSO event. This principle is illustrated in Figure 4-1-8 for an implementation in the CSS of Sant Feliu de Guíxols, a village located north-east of Catalonia. This approach provides a more robust detection in cases where the temperature pattern at the CSO structure show large variability (low SNR). Also, the use of the second temperature signal facilitates the implementation of mathematical techniques for an automatic detection of the CSOs. Still, two limitations were observed: first, both temperature signals matched during dry weather conditions for a short time period. This was due to the daily temperature cycle variations during a particular season of the year. Second, for a particular rain episode it was observed that solids were attached to the inflow channel sensor, which resulted in a prolonged convergence of the temperature signals (biasing the real duration of the CSO event) (further details are shown in Appendix III).

This method was also validated in the Graz sewer system, demonstrating the robustness of the method for several rain episodes, comparing to flow measurements and showing a simple implementation of an algorithm for the simple automatic detection of CSOs (Hofer et al., in preparation). The limitations observed in Sant Feliu de Guíxols system were not observed in Graz.

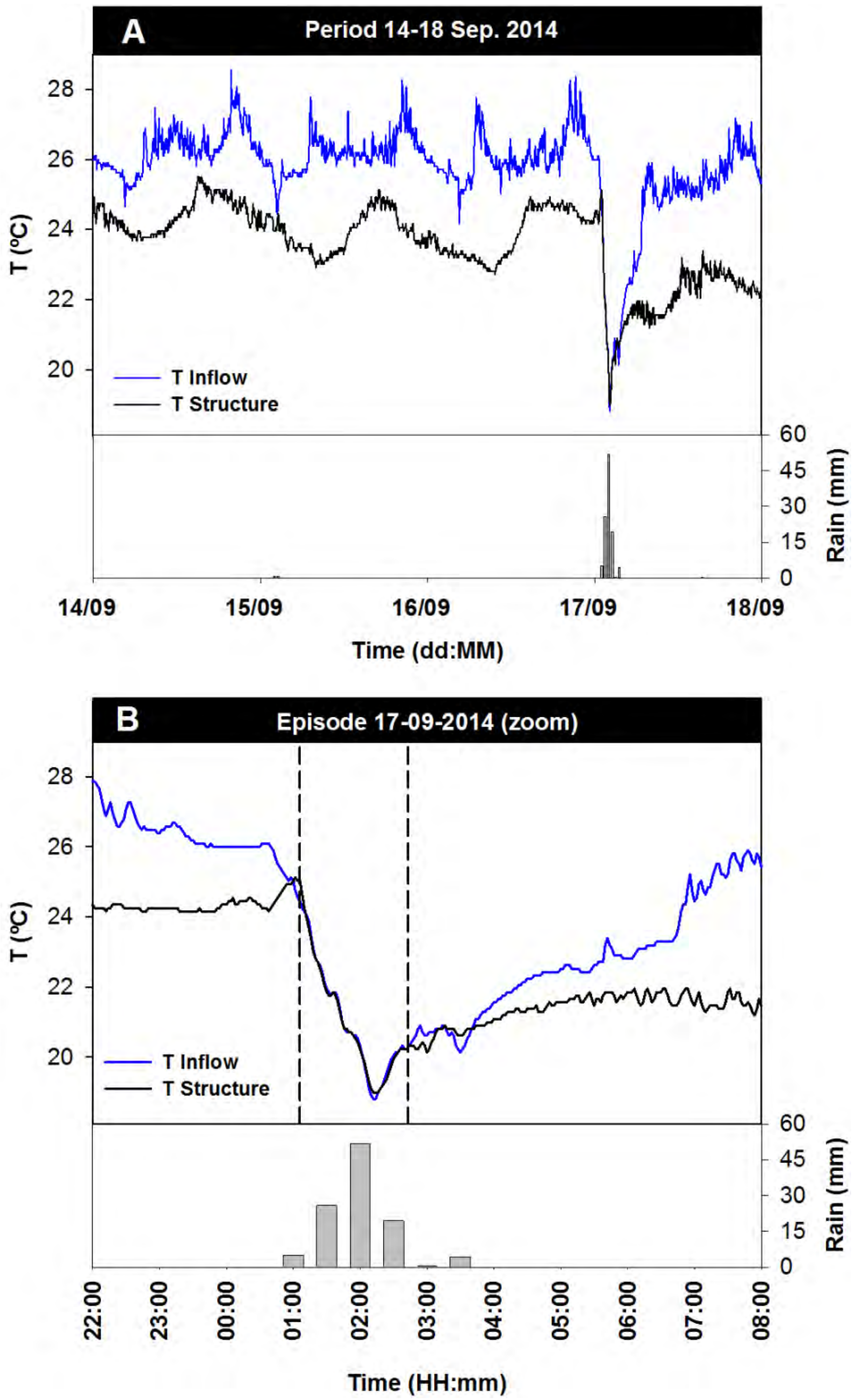

Figure 4-1-8. Results from the alternative temperature approach. [A] plots the temperature profiles for a four days period from 14 to 18 September 2014; The blue line corresponds to the temperature measured at the inflow channel, and the black line represents the temperature measured at the CSO structure. [B] is a zoom of the CSO event occurred for the rain episode of 17-09-2014; the vertical dashed lines indicate the start and end points of the CSO event, based on the convergence of both profiles.

4.1.7.2 Conductivity approach

A conductivity sensor (see details in Chapter 3) was installed at the CSO Structure 14 of the CSS of La Garriga, during a period comprised between October and November 2012. During dry weather conditions the sensor was in contact with the sewer atmospheric phase and hence did not signal electrical conductivity (generating the signal 0: 'No overflow'). During a CSO event, when the overflowed wastewater makes contact with the sensor electrical conductivity is generated (the wastewater acts as electrical conductor), and the signal 1: 'Overflow' is generated. That signal is registered in the data logger (developed by Adasa Sistemas S.A.) and sent to a central data storage system through a SIM card. Figure 4-1-9 outlines the results for three rain episodes occurred on 25, 26 and 31 October 2012 in comparison to a parallel installed flowmeter in the overflow channel. It is observed how the detection made by the conductivity sensor accurately matches with the flow measurements.

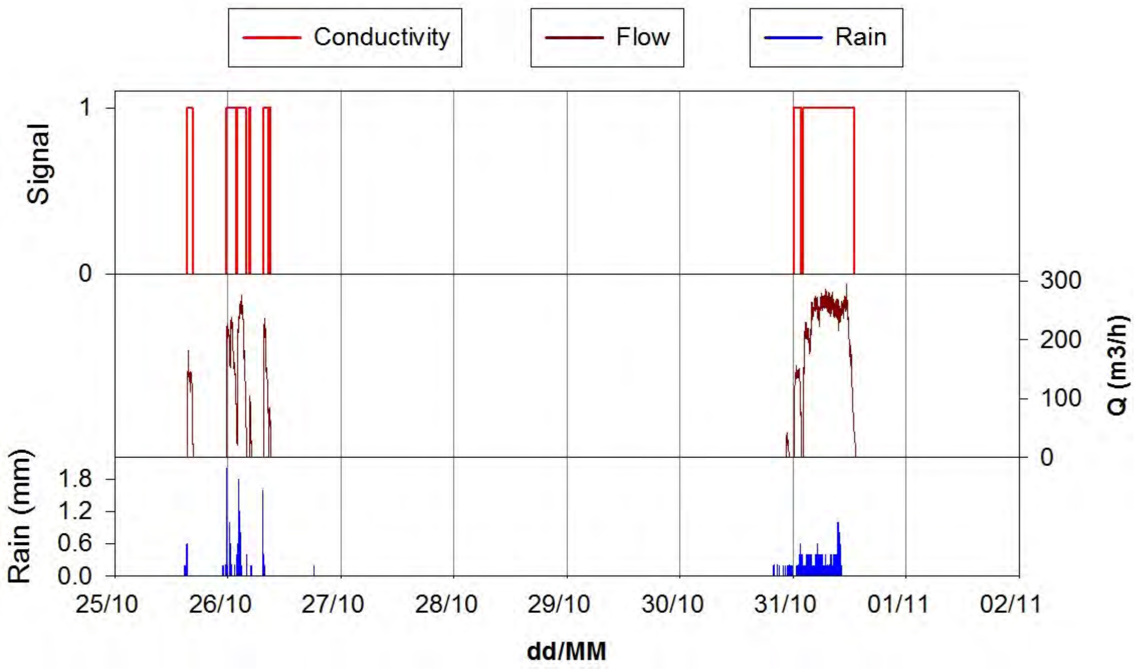

Figure 4-1-9. Monitoring period from 25-Oct to 02-Nov 2012 in the CSO Structure 14 from the CSS of La Garriga. The start and end point of the conductivity signal coincide with the flow measurements.

In a few cases a prolonged detection of a CSO event was observed which did not match the corresponding measured flow profiles. This was mainly caused by clogging of the sensor during/after some rain episodes. This led to erroneous information of duration of the CSO events, and the masking of other events that occurred afterwards (see Appendix III). For the same episodes the temperature sensor showed more robust, indicating the lower level of maintenance required. Still, further validation of the conductivity sensor would be required after investigating alternative setups.

4.2 Using data from monitoring combined sewer overflows to assess, improve, and maintain combined sewer systems

In Chapter 4.1 a low-cost method was proposed to detect CSOs. In this chapter a comprehensive methodology to evaluate the performance of CSSs using data from low-cost monitoring is presented which has four components: (1) assessing the capacity of a CSS, (2) characterizing the performance of CSO structures, (3) evaluating the compliance of a system with government guidelines, and (4) providing support for managers to make decisions about system maintenance. The methodology is illustrated using 11 months data from the CSS of La Garriga.

This chapter is an edited version of the paper published in:

Montserrat, A., Bosch, Ll., Kiser, M.A., Poch, M., Corominas, Ll. Using data from monitoring combined sewer overflows to assess, improve, and maintain combined sewer systems. *Science of the Total Environment* 2015; 505, 1053-1061.

4.2.1 Data collection

The CSS of La Garriga was used as case study to demonstrate the methods described in this section, though they can be applied to any CSS. A map of the system with the labeled CSO structures is illustrated in Figure 3-6 (Chapter 3). It was used data on the occurrence and duration of CSOs monitored in the La Garriga CSS over the course of 11 months (from July 2011 through May 2012). Detailed information about the materials and methods used to collect the data is given in Chapters 3 and 4.1. Of the 14 CSO structures that were monitored, it was analyzed data from 12 structures; data from Structures 9 and 13 were not considered in the study due to the poor quality (high background noise) of the gathered data. The data used in this study concerning the duration of the CSO events and overflowing chronological order for each structure, as well as the information on the rain episodes, is provided in the electronic version of Montserrat et al. (2015).

During the evaluated period 53 independent rain episodes occurred and were monitored. The inter-episode time between independent rain episodes was calculated as the average time the system needs to return to dry weather flow conditions (6 hours in the La Garriga system; see details in Appendix IV).

4.2.2 Methodology for CSS evaluation

The presented methodology has four components: (1) assessing the capacity of a CSS, (2) characterizing the performance of CSO structures, (3) evaluating the compliance of a system with government guidelines, and (4) providing support for managers to make decisions about system maintenance. The methodology is demonstrated in the CSS of La Garriga.

4.2.2.1 Assessing the capacity of a CSS

It was assessed the capacity of a CSS by plotting the duration of overflows versus rain volume for each rain episode and each individual structure. Figure 4-2-1 shows two examples of how the capacity of the CSS can be assessed by evaluating the behavior of individual structures using overflow duration and rainfall data. The first example,

Figure 4-2-1A, belongs to a structure with high activity in which overflows occur even with rain volumes as low as 2 mm. This example indicates that the CSS does not have the capacity to assimilate the increased flow from rain episodes. The second example, Figure 4-2-1B, shows a CSS in which the structure starts to overflow only after rainfall reaches a volume greater than 25 mm. In case A, data were fitted by a linear curve (R^2: 0.98), while data in case B were fitted better by a quadratic curve (R^2: 0.95). It was also determined the *breaking point* of each CSO structure, defined as the rain volume at which the structure starts to overflow, shown as dashed line in Figure 4-2-1B. The lower the slope and the greater the *breaking point*, the higher the capacity of the system or the better the stormwater retention capacity of the catchment. These cases are examples of two extreme scenarios and qualitatively show how CSS behavior changes as storage capacity increases.

Figures 4-2-1A and 4-2-1B were generated using a numerical model example of an urban catchment of the case study, and afterwards the methodology was applied to the collected field data. The model was developed using the Storm Water Management Model version 5.0.022 (Rossmann, 2007), and details about the model development and the making of the CSO duration-rain volume curves are provided in Appendix V.

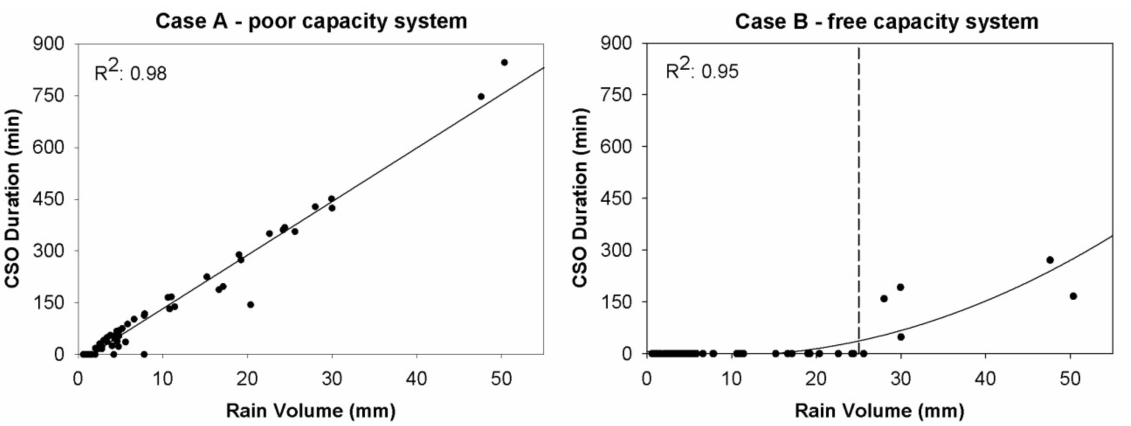

Figure 4-2-1. CSO duration versus rain volume for two hypothetical CSSs. Case A shows data from a CSS with high CSO activity, while case B shows data from a system with higher capacity. In case B, the vertical dashed line indicates approximately the maximum volume of rain (about 25 mm) that the system can assimilate before it begins to overflow.

4.2.2.2 Characterizing the performance of CSO structures

It was developed a detailed statistical analysis on the collected data of the occurrence and duration of CSO events. To characterize system performance, it was calculated and plotted the following parameters for each CSO in the network over the entire data collection period: (i) total number of overflows, (ii) total duration of overflows (sum of the durations of all overflows in the period), (iii) average overflow duration, (iv) the average chronological order that a CSO structure begins to overflow compared to all the other structures in the network, and (v) overflow probability. These parameters are indicators of the performance of each CSO structure and can be used to compare different structures within the same system. To calculate the total number of overflows, it was counted any number of overflows that occurred during one independent rain episode as a single, independent CSO event. 53 independent rain episodes occurred during the study period, so the maximum number of CSO events per structure would be 53 for this case-study.

Ranking curves were developed to provide information about the order in which a structure overflows with respect to the other structures in a CSS. For each rain episode, it was identified which structure overflowed first and assigned a value of 1 as its overflow position; then it was assigned consecutive values of overflow positions to the other structures in the order that they overflowed. For a particular structure (*z*) and for each overflow position (*i*), Equation 4-2-1 was used to calculate the *CSO ranking index* – the fraction of CSO events in which the structure overflowed in position *i* or lower.

$$CSORanking_{(z,n)} = \frac{\sum_{i=1}^{n} C_{i,z}}{\#_z} \qquad \text{(Eq. 4-2-1)}$$

where $\#_z$ is the total number of times during the monitored period that *z* overflowed, $C_{i,z}$ is the number of times that *z* overflowed in i^{th} position, and *n* is the number of CSO structures in the CSS. The maximum value of *i* is equal to *n*.

The *ranking* curves are obtained by plotting the ranking index of each CSO structure with respect to overflow position *i* and reach a maximum y-axis value of 1. To compare the performance of different structures, each curve was fitted by a power function

($F(x)=X^b$), and the exponent b of the function was used to rank the structures according to their ranking index.

Confidence intervals were calculated to see whether significant statistical differences existed among the parameter values of the different CSO structures. The confidence interval (*Ci*) (Equation 4-2-2) gives the range of values in which the true average is located.

$$Ci = Avg \pm E\frac{SD}{\sqrt{n}} \qquad \text{(Eq. 4-2-2)}$$

where *Avg* is the average value of the sample, *SD* is the standard deviation of the sample, n is the number of samples, and E is a statistical value that depends on the size of the sample and the confidence limits. The value for E is found in the *T-table* (for $n< 25$) or *Z-table* (for $n \geq 25$). The *Ci* with 95% confidence limits was calculated for each parameter. In the case of parameters that represent proportions, the Ci_p was calculated as,

$$Ci_p = p \pm E\frac{\sqrt{p(1-p)}}{\sqrt{n}} \qquad \text{(Eq. 4-2-3)}$$

where p is the proportion of the studied variable.
The confidence interval *Ci* was calculated for the variables *average overflow duration* and *average chronological order*, while the Ci_p was calculated for the *overflow probability*. The calculated confidence intervals are valid for normally distributed variables, such as those calculated here, since they represent averages or proportions over a sample of data from each variable.

4.2.2.3 Evaluating the compliance of a CSS with government guidelines

The number of overflows per year per CSO structure is a common emission standard referred to in CSO regulation guidelines. Hence, the compliance of a CSS with government guidelines can be evaluated by comparing the number of overflows measured in each CSO structure of a CSS to the maximum number of overflows suggested by the guidelines. Table 4-2-1 gives some examples of the permitted number of overflows per year in six countries. In some cases, such as in Belgium, Denmark, or the Netherlands, the permitted number of overflows is dependent on the sensitivity of the receiving waters (Zabel et al., 2001). Sometimes, the threshold is estimated using models fed with representative pluviometric data of the region (e.g. the ITOGH in Spain described in Hernáez et al., 2011). It is worth noting that the guidelines are site-dependent and differ in the permitted number of overflows. Furthermore, the definition of overflow frequency is crucial. For instance, overflows can be counted as events (or spills), or as overflow days (which can be calendar days or running days). Taking one definition or another significantly changes the results (Dirckx et al., 2014).

Country	Belgium (Flanders)	Denmark	Netherlands	USA	U.K.	Spain (Galicia)
Nº CSOs per year	7	2-10	3-10	4-6	3-10	15-20

Table 4-2-1. Permitted number of overflows proposed by CSO regulation guidelines in different countries (adapted from De Toffol, 2006; Hernáez et al., 2011; FWR, 2012).

4.2.2.4 Providing support to managers for CSS maintenance

Decision trees are predictive models based on supervised machine learning. In supervised learning, a teacher (the user) gives a computer program example input data and their desired or known outputs, and the program learns a general rule that maps inputs to outputs. The map is known as a decision tree, which can then be used to predict the results of input data with unknown outputs. If trained on high-quality data, decision trees can make accurate predictions (Kingsford and Salzberg, 2008). The output of decision trees visually and explicitly represent predictions and can therefore be an important tool for decision making.

Because of their power and utility for aggregating diverse types of data and making predictions, decision trees have become very popular in a variety of fields, such as environmental engineering, medicine, and bioinformatics (Kingsford and Salzberg, 2008; Rudin, 2012). In the field of wastewater treatment, decision trees have been used to design and develop tools to cope with highly complex environmental problems such as wastewater plant supervision or the selection of wastewater treatment systems (Poch et al., 2004), aimed at assisting in the decision-making process to find an optimal solution.

Decision trees for CSO structures were constructed as part of a tool to help managers make decisions about CSS maintenance. A decision tree consists of nodes connected by branches. There are two types of nodes in a decision tree: (1) internal nodes that represent explanatory variables, and (2) terminal nodes, or leaves, which give the response variable. Branches extend from internal nodes, with each branch defining a range of values for the internal node. The appropriate branch will be selected depending on the value for the internal node input by the user, leading to the next node. The process of branch selection continues until a prediction (leaf) is reached.

The specific technique used to induce the decision trees was the *J48 algorithm*, which is based on the *C4.5 algorithm* (Quinlan, 1993). Waikato Environment for Knowledge Analysis (WEKA) Version 3.6.0 was used to generate the trees. The input data, or explanatory variables, were rain characteristics (total volume, duration, maximum intensity, and time since the previous rain episode), and the output, or response variable, was whether or not the CSO structure overflowed. Data on rain episodes and CSO occurrence and duration were used to build each decision tree through a *k*-fold cross-validation procedure; the data set is randomly split into more or less equal *k* folds (or subsets), and the algorithm is run *k* times. At each time, *k-1* folds are used as training data to generate the tree, while the remaining fold is used as validation data. The prediction error (i.e. the accuracy) of the trees is calculated from the validation data. A thorough description of the cross-validation procedure is given in Rokach and Maimon (2008). This technique is especially suited for relatively small data sets (n<1000; De'ath, 2007), since the trees are trained on all the data sets. In this study, k=10 folds was used. Furthermore, it was developed a user-friendly computer application to visualize the different decision trees that are obtained with known characteristics of a rain episode. The application was programmed in JScript and is available in the electronic version of Montserrat et al. (2015).

4.2.3 Results and discussion

4.2.3.1 Assessing the capacity of a CSS

For each of the 12 structures evaluated, it was plotted the CSO duration versus rain volume for each rain episode during the 11-month study period. The rain episodes ranged in volume from 0.4 to 51.4 mm. Figure 4-2-2 illustrates two examples with different behaviour obtained from the collected data. Figure 4-2-2A refers to Structure 11 and shows that for rain volumes lower than 20 mm only a few overflow events occurred, with durations between 6-27 min. Even for rain volumes larger than 20 mm all but one of the overflow durations were less than 50 min. In this case, the rain volume *breaking point* at which the structure starts to overflow was established at 2.2 mm. For that case, non-linearity holds between the rain volume and the overflow duration (R^2: 0.31). Figure 4-2-2B corresponds to Structure 7, for which the *breaking point* of the system was also set at 2.2 mm. However, after a rain volume of 15 mm, increasing rain volumes resulted in longer CSO durations, reaching saturation around 200 min. The data were fitted by a sigmoidal curve (R^2: 0.86). The rain volume *breaking points* for the other structures ranged from 0.6 mm to 2.8 mm (see Appendix VI).

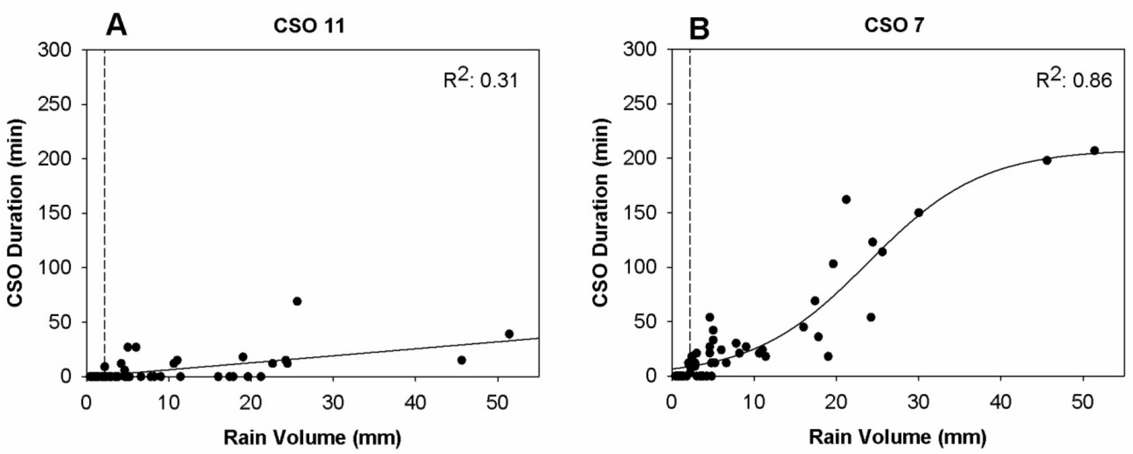

Figure 4-2-2. Rain volume versus overflow duration obtained for CSO Structures 11 and 7 during the studied period (53 rain episodes). The vertical dashed line indicates approximately the maximum rain volume that the system can assimilate before it begins to overflow, which was 2.2 mm in both cases.

Plotting overflow duration versus rainfall volume and fitting the data is useful to assess the behavior of each CSO structure and evaluate the efficacy of the CSS's design. CSSs are typically designed with a target value for the capacity of the system, for instance two times the mean dry weather flow (De Toffol, 2006). Whether or not the target capacity is achieved by the CSS can be determined from collecting and analyzing data as described here.

4.2.3.2 Characterizing the performance of CSO structures

By applying the proposed characterization method to the case study, it was able to gain an understanding of the performance of each CSO structure in the La Garriga CSS and highlight the system's weak points. Structures 7 and 14 each had the greatest numbers of overflow events, 36 and 49 respectively, during the 11-month study period. By far, Structure 14 (at the inlet of the WWTP) had the greatest total overflow duration, with close to 10,000 minutes (about 7 days) for the 53 rain episodes (Figure 4-2-3). The other CSO structures had total overflow durations ranging from 294 to 2,113 minutes.

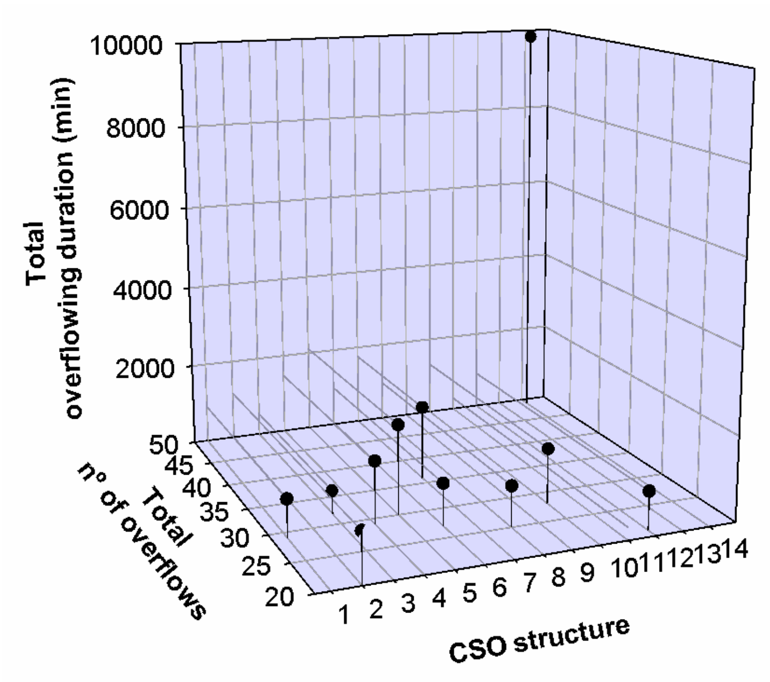

Figure 4-2-3. Total number of overflows and total overflow duration for each CSO structure for the 53 rain episodes of the evaluated period.

Figure 4-2-4 shows the evaluated averages of the variables with a 95% *Ci*. For *overflow probability*, Structure 14 had a probability of overflowing (avg = 0.9) during any given rain episode that was significantly greater than the probabilities of all the other CSO structures. Structure 7 had the second highest average overflow probability (avg = 0.7), but not significantly different than other structures. Structure 11 had the lowest probability (avg = 0.3). As for *average overflow duration*, Structure 14 had a significantly higher value (avg = 186 min) than the other structures, and Structure 11 had the lowest overflow duration on average (5.5 min). The overflow durations of the other structures in the network were between 10 and 40 minutes, with no significant difference among them. Finally, analysis of the *average order of overflow* showed that Structure 7 tended to overflow first (average order of overflow = 2.6), with a significant difference between the order of overflow of most of the other structures. Structure 10 had the second average value for overflow order (avg = 3.1), and Structures 1, 11, and 12 tended to overflow last (averages around 7).

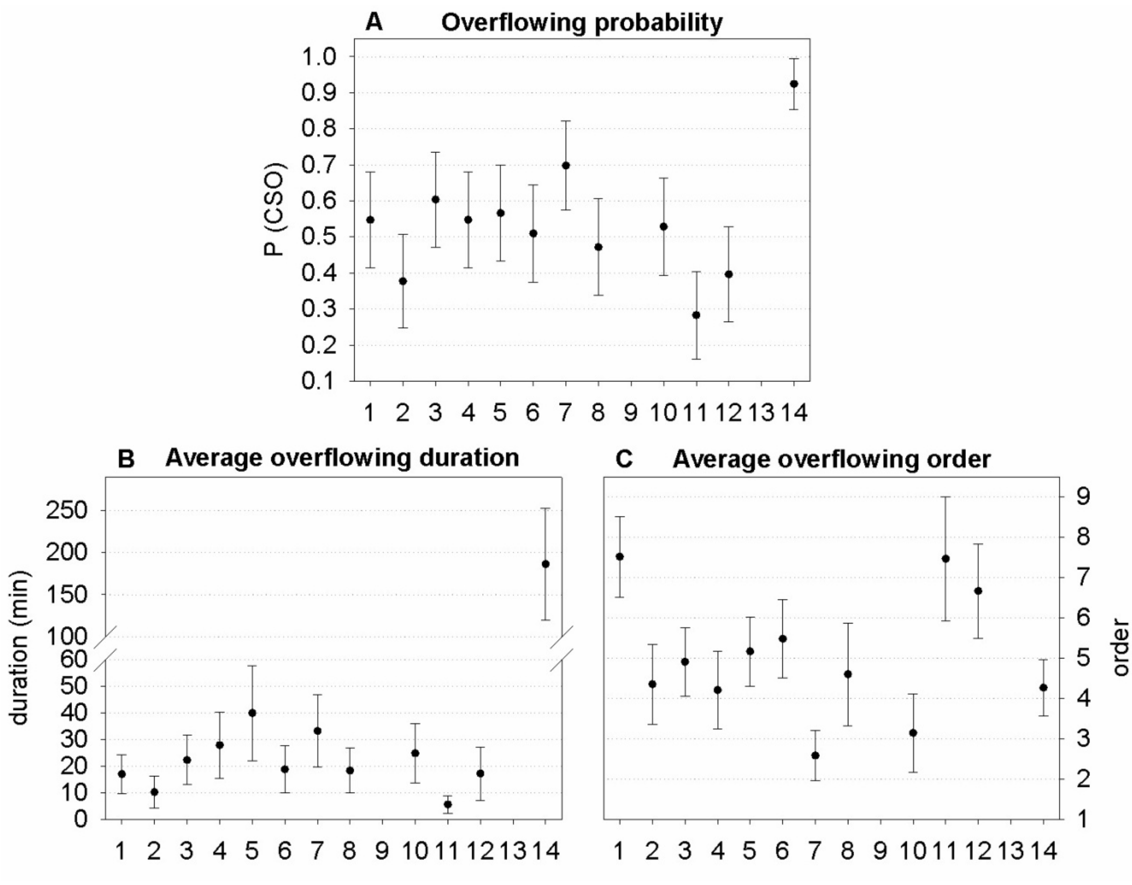

Figure 4-2-4. Evaluated parameters of the CSO structures (dots represent the average value, and the lines represent the 95% *Ci*). The x-axis is each structure of the CSS (note that Structures 9 and 13 do not have values because they were not used in this study).

The inclusion of the *Ci* in the average allows us to state with 95% confidence whether or not there is significant difference among the evaluated variables of the different CSO structures. In addition to the obvious importance of Structures 14 and 7 for the performance of this CSS, comparisons can be made between select groups of structures in order to find significant differences between them. For instance, Structures 2 and 11 had on average less *overflow duration* than Structures 5 and 7, and Structures 7 and 10 overflowed on average before Structures 1, 5, 6, 11, and 12.

Each CSO structure can be characterized by a *ranking index*, based on the chronological order in which a structure overflows during rain episodes. Figure 4-2-5 shows the *ranking* curves for each CSO structure and its corresponding exponent *b*. The vertical axis of the plot is the ranking index and the horizontal axis is the i^{th} place of overflow in the network. For example, in the case of Structure 7, almost 80% of the times that it overflowed, it was in the first 3 places (1^{st}, 2^{nd}, or 3^{rd} structure in the network to overflow). Structure 10 had a similarly high ranking. On the other hand, Structure 11 overflowed in the first three places only around 7% of the times that it overflowed. Looking at the ranking curves, Structures 7 and 10 had curves with the lowest value for exponent *b* (0.26 and 0.31, respectively), while Structures 1 and 11 had the highest exponents (1.3 for each). Structures 7 and 10 overflowed in the first 4 places around 80 to 85% of the time – more than any other structures, and Structures 1 and 11 overflowed in the first 4 places the least – approximately 20% of the time. The lower the value of *b*, the sooner the structure is likely to overflow within the network. It should be noted that, for this particular analysis, the time shift among the different sensors was assumed to be null. However, in future calculations of the *ranking index* or other analysis involving long-term monitoring using multiple sensors, this issue should be addressed in order to not bias the final results.

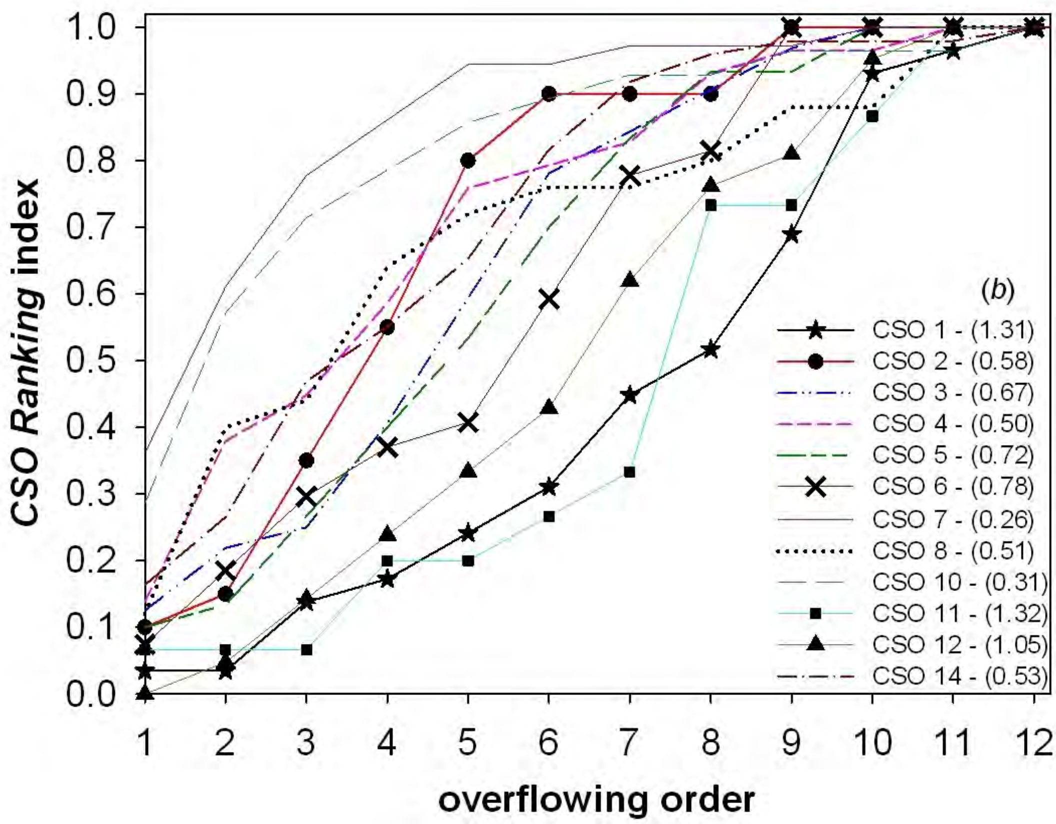

Figure 4-2-5. *Ranking* curves for each CSO structure. The y-axis is the ranking index, and the x-axis is the i^{th} place of overflow in the network. In the legend shows in parentheses the value of exponent *b* of the power function fitted to each curve.

Using these methods for characterizing system performance, Structures 14, 7, and 10 stand out as problematic, at least compared to the other structures. Characterization of the structures highlighted those with the best and worst performance in terms of overflow. It should be noted that for a CSO structure that overflows often, the problem may not be with the structure itself but may originate from other, more distant factors, such as the overloading conditions downstream from the system. A proper investigation must be carried out to determine the true cause of frequent overflows. Nonetheless, from the characterization information, management strategies can be devised and implemented, such as seeking out the cause of overflows or installing upgrades or extra reinforcements. Without an analysis like the presented here, it would not have been possible to know which of the CSO structures were most reactive to rain episodes.

4.2.3.3 Evaluating the compliance of the CSS with government guidelines

Figure 4-2-6 is a schematic of the CSS of La Garriga and includes the number of CSOs measured during the 11-month study for each CSO structure. It was compared the number of overflows for each CSO structure in the La Garriga CSS during the study period to the number of overflows per CSO structure per year permitted by Spain's ITOHG, which is 15-20 overflows. It is worth remarking the specificity of ITOHG to the Galician region with a very particular pluviometric regime. Hence, the results obtained here are for illustration purposes only. The 11 months of study accumulated a rainfall volume of 525 mm. The analysis of the rainfall series from 2009 to 2013 registered in the La Garriga rain gauge resulted in an average annual precipitation of 642 mm. Considering a 95% confidence interval, the precipitation of the evaluated period was assumed to be representative of an average pluviometric year. The study period presented here was only 11 months, and it is recognized that a 12-month study period would have been best for comparison with government guidelines for annual overflows. Most of the structures in the 11-month case study exceeded the number of recommended overflows per year. Only three out of the 12 CSO structures (Nos. 2, 11, and 12) in the La Garriga CSS meet or closely meet the ITOHG guidelines. None of the CSO structures in La Garriga would comply with the CSO guidelines of the countries outside of Spain shown in Table 4-2-1.

The CSO structures with the least overflows were CSO 2, 11, and 12 (≤ 21 overflows). CSO 2 is a lateral structure that receives discharges from a residential neighborhood with a highly pervious surface. CSOs 11 and 12 are located at the beginning of the system. Moving further down the system, the number of overflows is higher. CSO 5 (30 overflows) and 7 (36 overflows) are lateral structures located at the outlet of densely urban areas. CSO 4 (29 overflows) is located along the main sewer trunk and receives most of the runoff from La Garriga and contributing areas (all the urban and part of the industrial areas). CSO 3 (32 overflows) is a lateral structure at the outlet of a recently developed industrial area with a mostly impervious surface. CSO 1 (29 overflows) is a lateral structure that receives wastewater from part of a neighboring municipality. Given that CSO 1 is located towards the end of the system, backwater effects could be increasing the number of overflows at this point. At the very end of the system and at the entrance of the WWTP is CSO 14, which had by far the highest number of overflows (49) of all the CSO structures.

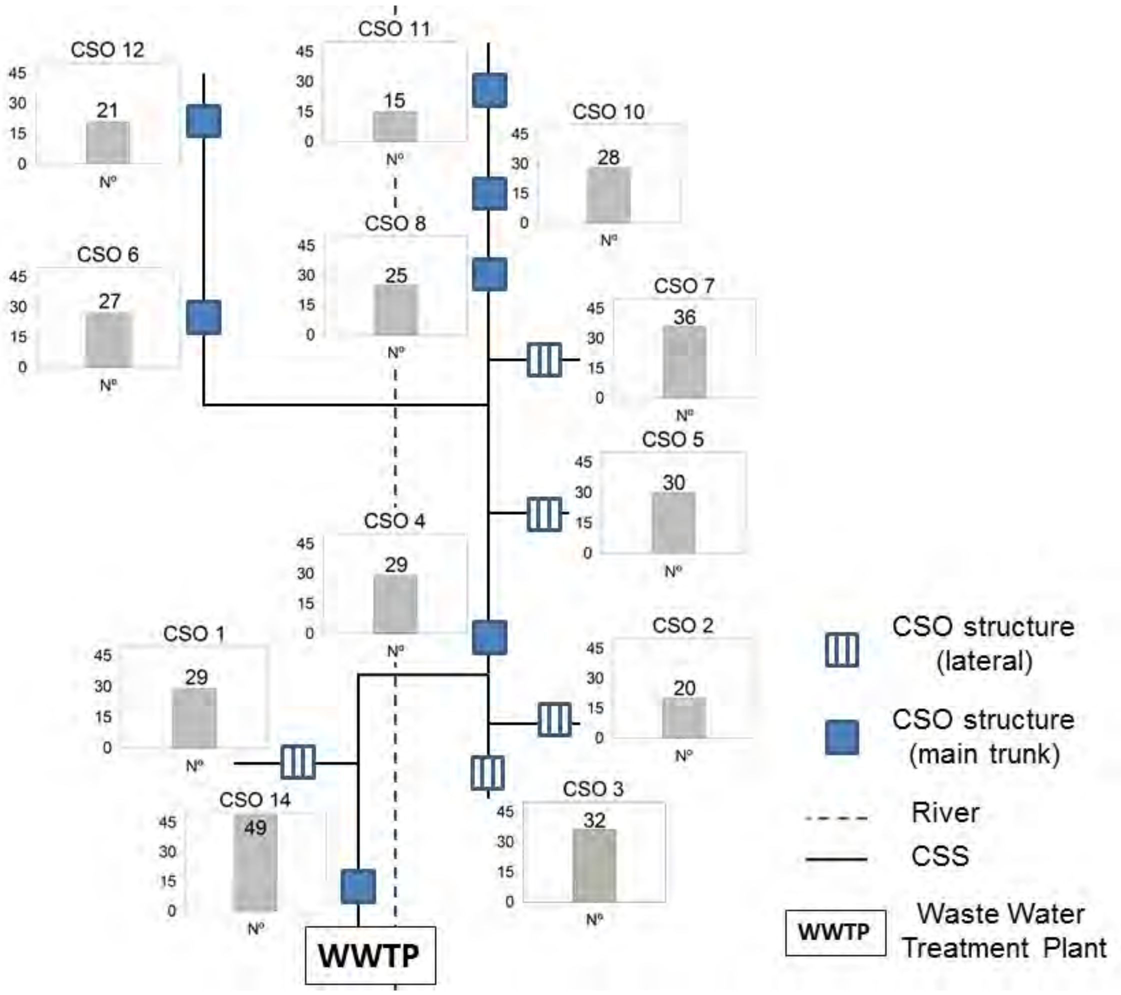

Figure 4-2-6. Schematic of the La Garriga CSS. The number of overflows that occurred in each CSO structure during the 11–month study is graphed.

Evaluating the compliance of a CSS with government guidelines can help to define appropriate management strategies, which can range from upgrades to improve CSS performance, to measures aimed at increasing the stormwater retention capacity of the catchment, so that local overflow recommendations are met. However, as stated above, compliance with standards is a major issue in which site-specific regulations have to be considered.

4.2.3.4 Providing support to managers for CSS maintenance

For the case study of the La Garriga CSS, it was constructed a decision tree for each CSO structure. In Appendix VII is given a summary of the configurations and accuracies of the decision trees constructed for the La Garriga CSS. Overall, the trees had simple configurations. The number and types of explanatory variables needed to make predictions differ among the CSO structures. In other words, different rain characteristics will cause different structures to overflow more than others. For instance, Structures 3, 7, 8, and 10 need only one explanatory variable to reach the response variable. Rain volume will be the primary determinant of whether or not Structures 3 and 7 overflow, while the maximum intensity of a rain episode will mainly control whether or not Structures 8 and 10 overflow. The more complex a tree is, the more explanatory variables are involved. An exception was the tree for Structure 7, which had 8 branches, 4 nodes, 5 leaves, and only one explanatory variable (rain volume). As an example, a description of the decision tree made for Structure 14 is included in Appendix VII. Structure 14 had the highest accuracy (91%) and Structure 2 the lowest (57%). The accuracy of the other trees ranged between 70 and 83%.

Figure 4-2-7 shows both the successful and the incorrect overflow predictions made by the model for each CSO structure during 53 rain episodes. In this example, the trees predicted whether or not a CSO structure would overflow with given rain volumes of each rain episode, which were sorted from highest to lowest rain volume along the *x*-axis. The white spaces in the figure denote correct predictions of structures that did not overflow during a particular rain episode, while the black spaces represent correct predictions of the occurrence of overflow. Grey squares show where the model's predictions did not match observations (real data from monitored CSOs). For all the rain episodes and structures, the prediction succeeded in 89% of cases.

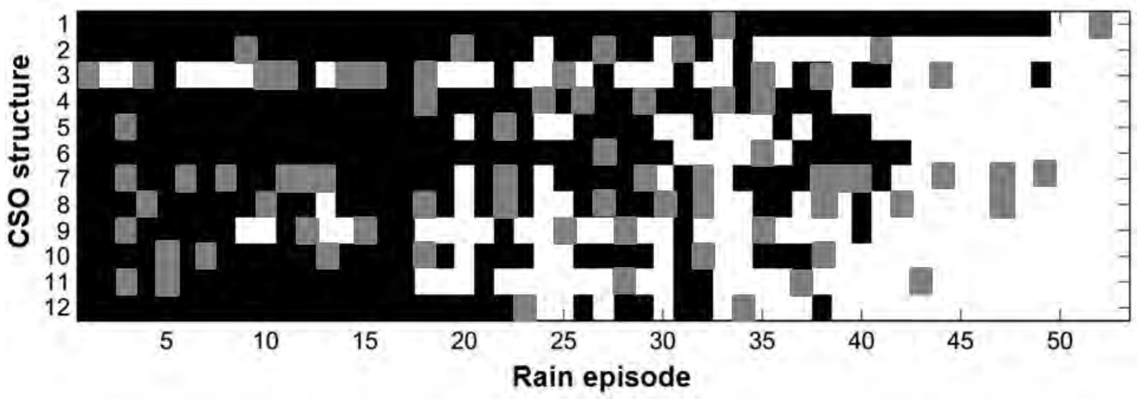

Figure 4-2-7. A plot of the predicted and observed responses of each CSO structure for 53 rain episodes that occurred in La Garriga. The black squares indicate instances where the model correctly predicted overflow (the prediction matched observation), the white squares indicate when the model correctly predicted that an overflow did not occur, and the grey squares show where the model incorrectly predicted overflow or no overflow (the prediction did not match observation).

It was developed a computer application, called "La Garriga CSO Network Simulator", to visualize the different decision trees that are obtained with known characteristics of a rain episode. The application has a user-friendly interface that allows predictions to easily be made and clearly understood for the La Garriga CSS. Though this particular application was made for the La Garriga CSS, the same application format can be developed for any CSS and used by managers, engineers, or maintenance crew. A description of the application interface is given in Appendix VII. The full application is available in the electronic version of Montserrat et al. (2015).

A common practice in the investigated catchment (which could be in others too), is that sewer maintenance crew have to visit each CSO structure in a CSS after rainfall to check if overflow occurred and to do any maintenance work that might be necessary. Structures that don't overflow usually would not require checking or maintenance post-rainfall. Maintenance time, and therefore money, would be better spent by focusing on the structures that have a tendency to overflow. Thus, the CSO prediction tool described here could save time and money for sewer managers and crew by indicating the CSO structures that need to be checked after a rain episode with given characteristics. This is especially true for large CSSs with high numbers of CSO structures, when one sewer management company must manage several CSSs in one or more municipalities, or when maintenance crew is limited. The prediction of overflows through decision trees would also present an advantage for real-time control of CSSs. By means of weather forecast information (rain volume, duration and max. intensity), it would be possible to identify which structures overflow and take actions to maximize the usage of CSS volume (Schütze et al., 2004).

4.3 Using the duration of combined sewer overflow events for the calibration of sewer hydrodynamic models

The aim of this chapter is to demonstrate that similar accuracy can be obtained in the calibration of hydrodynamic sewer models either using duration of CSOs or the conventional and expensive flow measurements at the CSO discharge. For that purpose, an existing model from the CSS of the city of Graz was used, which had been thoroughly calibrated against the flow rate and pollutant concentrations at the inflow channel of CSO structure R05 (Gamerith et al, 2011). Then, that model was further calibrated, adjusting CSO structure model parameters to properly describe the flow at the discharge of this CSO structure. This chapter focuses on that CSO structure calibration step, which has been understudied in literature, and has been applied to the study-site of Graz which was monitored and modeled with state-of-the art tools. For this, the comparison between the duration of CSOs and the flow measurements approaches is conducted to achieve the goal of the chapter.

This chapter is an edited version of the manuscript *Using the duration of combined sewer overflow events for the calibration of sewer hydrodynamic models,* submitted to *Urban Water Journal* in April 2015 to be considered for publication by A. Montserrat, T. Hofer, M. Poch, D. Muschalla, and Ll. Corominas.

Using the duration of combined sewer overflow events for the calibration of sewer hydrodynamic models, submitted to *Urban Water Journal* in April 2015 to be considered for publication by A. Montserrat, T. Hofer, M. Poch, D. Muschalla, and Ll. Corominas.

Case study and data

The suitability of the use of duration from CSOs for hydrodynamic model calibration was demonstrated in an urban catchment from the city of Graz (Austria). The investigated catchment is drained by a CSS, with a CSO structure (side weir type) called R05 and located at the outlet of the catchment. Data were collected from a monitoring station installed in the CSO structure. Flow measurements were obtained by means of a flowmeter installed at the overflow channel. The CSOs duration data was obtained from low-cost temperature sensors (model Hobo Pendant UA-002-64; see description in Chapter 3) following the methodology described in Hofer et al. (in preparation). More information on the catchment and the monitoring station is given in Chapter 3.

CHAPTER 5

GENERAL DISCUSSION

In the following paragraphs, a general discussion of the different outcomes of this thesis is presented, which includes the main contributions, an overview of the implementation of temperature measurements in sewer systems, potential application, and the future outlook.

5.1 Main contributions

Outcome 1: Low-cost CSO monitoring

In the framework of this thesis, research was conducted to develop a method to monitor CSOs based on low-cost temperature sensors. The method has been fully verified and implemented in a real combined sewer system for a period of over two years, and high efficiencies in determining the CSOs were obtained. This research resulted in the application for a Spanish patent in 2013 (registry code P4103/2012 and Application number P4103/2012).

Low-cost temperature sensors for determining CSOs have proven to be efficient, waterproof, robust, low-maintenance, and capable of unsupervised operation for a minimum of one year. The installation proved to be highly robust, since only one sensor was lost out of the 14 that were installed in July 2011 and monitored for more than two years. In general, no problems of solids attachment were reported, mainly because of the reduced size (about 6x3x2 cm) of the sensors, and the minimal size of the mounting accessories. In contrast to the temperature sensors proposed in this research, current conventional sensors are extremely expensive, ranging from 500-1,000€ for level sensors to at least 6,000€ for a flowmeter that provides the maximum degree of characterization (Table 1-4). In addition, temperature sensors are not influenced by typical operational constraints of level and flow sensors. Although temperature sensors cannot report on the volume of the CSO event, they provide trust-worthy information on the occurrence and duration of CSOs at 80% lower costs than the other alternatives.

The simple principle upon which the method is based, together with the affordable prices of temperature sensors, are the main strengths of the proposed method. Additionally, a great benefit is the compliance with current and upcoming legislations on water quality protection at lower costs. In this regard, a turning point occurred with the adoption of reference laws such as the Clean Water Act in the U.S. and the

European Water Framework Directive. The implementation of the WFD poses a major challenge (Hering et al., 2010). The very aim of the WFD is to achieve 'good ecological status' for all surface waters of the EU Member States by 2027. To achieve this objective, the WFD requires the collection of information on the type and magnitude of significant anthropogenic pressures (IMPRESS, 2003) so that appropriate measures can subsequently be taken. The identification and characterization of the pressures is the step the presented method would fit and aim to address. National legislations are being updated, driven by the objectives of the WFD. A very illustrative example is given by the Spanish Royal Decree 1290/2012, which requires the monitoring of CSO structures and demands significant penalties for non-compliance (a more in-depth analysis of this law is given below). The large number of CSO structures normally present in combined sewer systems necessitates the implementation of a large monitoring network to characterize the whole system. If characterization were to be performed by conventional technologies, the simultaneous monitoring of all the structures would become cost prohibitive in terms of materials, operation and maintenance. A method based on temperature sensors would lead to great savings in overinvestment and administrative sanctions and would enable even small municipalities with tight budgets to monitor CSO structures.

Outcome 2: Assessment and maintenance of a CSS

The use of low-cost sensors allowed the simultaneous monitoring of all the CSO structures of the CSS of La Garriga, which would not have been possible otherwise (taking into account the investment required). As a result, it was possible to determine the limitations of the CSS by identifying capacity problems and potentially problematic structures (as shown in Chapter 4.2).

This analysis also led to a significant contribution related to the maintenance of CSO structures. Inspection and maintenance programs of CSS consist of typical operational and management tasks developed and implemented by sewer operators, aiming at maintaining the maximum flow to the WWTP and maximizing the storage capacity of the system (EPA, 1999b). Such programs normally consist of routine inspections, maintenance and cleaning of the CSS, as well as plans to determine which structure overflowed. A predictive tool able to predict the occurrence of CSOs based on rainfall characteristics (like the method proposed in this thesis), can greatly help to optimize maintenance tasks, pointing out to operators the structures that should be inspected, instead of checking all the structures.

Outcome 3: Model calibration

Another contribution is related to the calibration of sewer models. Many private companies, such as engineering and consulting firms, make use of numerical models in the evaluation and development of studies and projects. The calibration of hydrodynamic models with measured data on CSOs is a practice still not widely applied, partly due to the significant expense required to monitor several CSO structures. In addition, technical constraints such as physical characteristics in some structures, could prohibit the proper installation and operation of conventional level or flow sensors.

However, large differences can be found in the performance of modeled sewer systems when comparing a calibrated model to a non-calibrated one. For instance, Liefting et al. (2011) found that the CSO frequency with a non-calibrated model was on average one per year, while a long-term monitoring program counted ten events per year. It is best, therefore, to make decisions based on accurate information, especially when investments in new projects rely upon the results of a model. The duration of CSOs obtained with low-cost sensors (such as temperature sensors) can be used in the calibration of a hydrodynamic model and lead to results similar to (but cheaper than) flow or level sensors, as shown in Chapter 4.3.

5.2 The implementation status of in-sewer temperature measurements

In the last decade, much effort has been put into gaining information from the measurement of temperatures inside sewer systems, resulting in a number of relevant studies. Schilperoort et al. (2006) conducted one of the first known studies, carried out in the Graz monitoring station (see details in Chapter 3), and evaluated the possibility of using the temperature of wastewater in sewer inflows as an indicator of wastewater dilution, based on the measured temperature change produced at the onset of a rainfall episode. In the Netherlands, Schilperoort and Clemens (2009) and Hoes et al. (2009) demonstrated the effectiveness of fibre-optic distributed temperature sensing to detect illicit connections or infiltrations in sewer systems. Afterwards, Langeveld et al. (2012) also made use of this technology to evaluate the performance of a stormwater system. The temperature has long been recognized as a parameter with a strong influence on the performance of wastewater treatment plants, especially for nitrogen removal (e.g. Durchschlag et al., 1992). In this regard, Kaczor and Bugajski (2012) performed a temperature monitoring campaign in different sewer systems of several Polish municipalities in order to quantify the impact of spring snowmelt infiltration on the temperature of raw wastewater. Recently, Dürrenmatt et al. (2013), arguing that flowmeters are not always a reliable option due to the harsh conditions of sewer systems, developed a method to estimate sewer flow velocities using continuous temperature measurements.

As yet, the number of cases using temperature to specifically monitor CSOs is still limited. The combined sewer system of La Garriga, to the best of my knowledge, was the first sewer network where temperature measurements were applied to determine occurrence and duration of CSOs for all the CSO structures, becoming the first reported study of this kind. Afterwards, the University of Technology of Graz (Austria), experts in the field of sewer monitoring, was contacted to offer them the technology in exchange for demonstrating the technical feasibility of the method in a continental context (non-Mediterranean), in the city of Graz. The demonstration of the method in Austria produced very promising results, which remarks its wide application scope. In addition, the demonstration resulted in the development of an improved version of the method, using two temperature sensors simultaneously, and aimed at maximizing the CSO detection rate, minimizing false detections and to facilitate the detection automatically (Hofer et al., in preparation). This latter setup was successfully implemented in 2014 in the CSS of Sant Feliu, a village situated in the northern part of Costa Brava (Catalonia).

Most of the aforementioned studies have been partly motivated by the simplicity of the measurement principle, which provides accurate data (it is a mature technology), and by the low cost, robustness, and the low maintenance requirements provided by modern temperature sensors. In fact, many technological devices widely used in wastewater systems, such as water quality probes, already incorporate a temperature sensor. Overall, this has led to the need to explore the potential gains from this simple technology (all limitations considered). However, despite the good results achieved so far, we are still at the infancy of the technology in terms of implementation. As more research and field studies appear, and more knowledge concerning methodological requirements is available, a wider and normalized application of the presented and other methods is expected.

Observed limitations in the applicability of temperature methods

Regarding the applicability of temperature methods in sewer systems to monitor CSOs, the main factor of concern is related to specific temperature conditions, both within and outside the sewer, that could compromise the efficacy in detecting an overflow event.

In the method presented in this thesis, the effectiveness in determining the occurrence of CSOs was based on the assumption that different temperatures exist between the sewer gas phase and the overflowing wastewater. In the tested case study of La Garriga CSS, it was proven that the method worked equally well whether the temperature of the overflow was lower or higher than the sewer air phase, leading to negative or positive temperature changes (as shown in Figure 4-1-3). A similar phenomenon was already observed by Schilperoort et al. (2006) in the CSS of Graz, who found that temperature differences between the storm water runoff and the dry weather flow led to negative or positive changes in the temperature of the inflow discharge in the combined sewer. The main cause for this was related to the broad range of temperatures of the runoff, which is influenced by many different factors (e.g. temperature of the rain, site seasonal conditions, hours of sun, cloudiness, etc.). Nonetheless, it is possible that a minimal difference in temperature between both phases is found during a rain episode, which would hinder the identification of the CSO. This could have been in fact one major cause that led to some of the categories identified as *Not Clear Response* in the study made in La Garriga.

A similar problem could happen when using the alternative setup consisting of two temperature sensors, one in the inflow channel measuring wastewater temperature and the other at the CSO structure measuring the temperature of the sewer gas phase (as described in Chapter 4.1.7). Due to strong daily temperature variations, both signals could overlap for short periods of time during dry weather conditions (see Appendix III).

The exceptional circumstances of the two possibilities shown above are caused by very specific conditions which are mostly driven by random natural events. The frequency at which these circumstances are produced in a specific place will determine the potential effectiveness of one or the other method. These findings should also serve as the basis for future development of improved methods.

5.3 Potential application

As stated in the first paragraph of this chapter, one major application of the method is connected with law enforcement regarding environmental protection. Using the example of Spain, we found the Royal Decree 1290/2012 (RD 1290/2012), approved on the 7th of September 2012 by the Ministry of Agriculture, Food and Environment. The RD 1290/2012 was issued partly to update the Spanish national laws resulting from the transposition of the UWWTD, in order to introduce specific regulation on the pollution caused by combined sewer overflows, which until then had been unclear or missing. As to specific measures for controlling overflows, Article 1(43) of the Royal Decree states that holders of discharge permits shall equip the CSO structures with overflow quantifying systems within four years of the enactment of the Royal Decree. Specifically, the law requires quantification of the overflows for CSO structures belonging to 1) urban agglomerations with a PE of more than 50,000 inhabitants, 2) industrial areas, and 3) urban agglomerations with a PE of more than 2,000 inhabitants located in a protected area declared as bathing waters[2]. Such legal requirements have led to a niche market with great potential for application in Spain. In Catalonia alone there are 23 municipalities of over 50,000 inhabitants (Idescat, 2014), and 47 municipalities between 2,000 and 50,000 inhabitants located in protected bathing waters (ACA, 2010). Considering an average number of 100 CSO structures for populations greater than 50,000 inhabitants, and 15 structures for populations between 2,000 and 50,000 inhabitants, a total of about 3,000 CSO structures need to be monitored by law. By a conservative estimate, this would mean moving from a minimum investment in materials of 1,500,000 € if using a simple level sensor at each structure to 300,000 € using temperature sensors, resulting in savings of 80%. Following the same approach as in Catalonia, the total number of CSO structures to be monitored in Spain is estimated at about 20,000 structures, for which the impact of the application of the method would be significant.

At European level, countries such as Belgium and the Netherlands already had national laws before the adoption of the Water Framework Directive (WFD) that limit the number of overflows per structure per year (Zabel et al., 2001). Key legislations such as the UWWTD and the WFD will push forward the development or update of national regulations considering more stringent control of combined sewer overflows. Thus, the same need detected in Spain is also expected to be found in other European Member States.

Thus, a method based on low-cost temperature sensors to quantify the occurrence of CSOs offers an **excellent opportunity for sewer operators (including public administrations and private companies)** to comply with the law at reasonable costs. This is especially true in the case of small municipalities, which normally have to face several expenses in a context of limited budget.

Each River Basin Authority in Spain (e.g. the Catalan Water Agency in the case of Catalonia), aiming at identifying the anthropogenic pressures as foreseen in water planning, must create an inventory with all the overflow structures from the combined sewer systems and, after implementing monitoring, define possible actions for the

[2]According to the register of protected areas referred to in the Spanish Royal Decree 907/2007, which approved the Hydrological Planning Regulation and contained aspects of the hydrological planning from the European Water Framework Directive.

future. Although the monitoring of each structure is done separately, what is important is to make an assessment for the whole catchment, evaluating the strengths and weaknesses of the system in order to make proposals for improvement, such as the assessment proposed in Chapter 4.2 that is based on a statistical analysis from the simultaneous monitoring of the whole CSO network. It is worth noting the importance of this simultaneity, obtaining information for several structures for the same rain episodes; otherwise, the information received by the Authority would not be useful for making improvements afterwards.

In addition, the analysis presented in Chapter 4.2 can be complemented with a detailed modeling study such as that described in Chapter 4.3. Such a study would allow making a reliable evaluation of alternatives and an optimum design of the proposed measures. It is worth noting that such modeling studies have to be developed based on an accurate calibration methodology. There are currently different guidelines for the hydraulic modeling of wastewater systems, including the calibration as a fundamental step. Depending on the final use of the model, more or less calibration should be considered. Particularly, for more ambitious targets, such as to predict the overflow volume or evaluate the performance of a CSS or CSO structure, a more elaborate calibration should be undertaken. This is clearly seen for instance in the Austrian OEWAV Guideline 19, which is a key reference guideline in the design of CSO structures. The Austrian guideline is based on the concept of "CSO efficiency rate," defined as the annual volumetric flow rate of stormwater discharged to the wastewater treatment plant and obtained by a long-term simulation for a minimum period of 10 years by means of hydrological or hydrodynamic models (Kleidorfer and Rauch, 2011). In this guideline, some specific minimum requirements for model calibration are recommended for systems of more than 5,000 PE (OEWAV, 2007):

- *Using yearly time series for calibration (minimum 1 year), requiring:*
    - *Rainfall time series*
    - *Flow time series in the inflow to the WWTP*
    - ***Overall yearly duration and frequency of CSOs**, or overall yearly CSO volume*
- *Using single rain episodes for calibration, requiring:*
    - *At least 3 independent rain episodes in which CSOs occurred*
    - *Water level in the CSO tanks and at the CSO weir crests*
    - *Flow time series in the CSO throttles*

The previous required data measurements apply to all the relevant CSO tanks and CSO structures in the system. Thus, the findings of the research presented in Chapter 4.3 could help in meeting the requirements of existing and future guidelines in the design and evaluation of wastewater systems.

Furthermore, both outcomes 2 and 3 also have great potential in research applications. In the last few decades, much work has been done in the modeling of combined sewer overflows and its effects on receiving waters. Thus, several studies have been reported on the dynamic simulation of water quality changes produced by CSOs, making use of hydrodynamic and water quality models (e.g. Petruck et al., 1999; Reda and Beck, 1999; Even et al., 2007). Also, models have been used to evaluate the impact of different upgrades in the sewer system on the reduction of CSO activity (e.g. Wisner et al., 1981; Lau et al., 2002; Andrés-Doménech et al., 2010). In the last few years, a large number of studies focused on the evaluation of source-control measures as strategies to reduce urban runoff and, consequently, the occurrence of CSOs (e.g. Montalto et al., 2007; Roldin et al., 2012; Autixier et al., 2014; Lucas and Sample, 2015). Although this thesis does not report results on the water quality of the CSOs or receiving waters, a detailed analysis of the whole network of CSO structures with real monitored data (thus determining the most critical structures), together with a calibration of the CSO structures, can greatly contribute to getting results closer to the real performance of the evaluated system, which would help to improve model-based evaluations of the UWWS.

5.4 Outlook for the future

The results of this thesis have contributed to the monitoring, analysis, and modeling of sewer systems, but is yet not sufficient.

Future work related to temperature measurements to detect CSOs should address limitations like those described above by investigating other feasible configurations and data analysis, with the goal of increasing the robustness of the detection of CSOs. In the presented temperature method, data were collected from sensors by manually downloading the data onto a computer once per month. To make CSO monitoring even more efficient and effective, future studies should use online low-cost sensors that collect and transmit data to online data storage in real time. A program could be set up to analyze the raw data as it is transmitted. Real-time data collection and analysis would negate the need for predictive models and could further reduce maintenance costs. This would also help in the implementation of real-time control strategies on sewer systems and treatment plants, which have proved to be reliable options to minimize the impact on the environment and costs (Schütze et al., 2004).

Another interesting line of research of great value would be the estimation of the CSO flow discharge from temperature measurements. For instance, a relation could be established between the CSO duration and CSO discharge considering both hydraulic design parameters of CSO structures and rainfall information.

The method of calibrating CSO structures presented in this thesis was done with data on the duration obtained from the temperature sensors. The next step would be to investigate whether the overflow frequency for a long time period (e.g. 1 year) is a good indicator to calibrate a CSO structure. Regarding long-term simulations based on long-term rainfall time series, detailed sewer models of large UWWSs could result into a significant computational burden, so conceptual lumped sewer models are commonly used which are also not exempt from calibration and validation procedures (e.g. Breinholt et al., 2013). Therefore, it would be worthwhile to investigate the calibration of these more simplistic models against CSO occurrence and duration obtained by low-cost temperature sensors.

Finally, modern approaches for the management of the UWWS consider the system from an integrated perspective (Butler and Davies, 2004), mainly motivated by the adoption of legislations such as the WFD. The integrated modeling of the whole process has proven to be especially suitable to evaluate the consequences of the CSOs in the receiving waters (Rauch et al., 2002), in which good modeling practices including proper monitoring and model calibration are required. Therefore, further research needs to be done on the integration of water quality sensors in order to quantify the pollutant load discharging from CSO structures, which is essential to evaluate the impact of CSOs from an immission-based perspective. Following the line of this thesis, sensor developers and research centers should put effort into the development of robust low-cost sensors or equivalent indicators for water quality measurements so that the integrated system could be properly monitored and analyzed. The integrated management of the UWWS stands as a reliable approach to decrease the negative impact on the receiving waters and at the same time not increasing the treatment costs in the WWTP (Corominas et al., 2013).

CHAPTER 6

CONCLUSIONS

The objectives of the thesis have been achieved, the main contributions being: 1) the development and validation of a new method, which is based on low-cost temperature sensors, to determine the occurrence and duration of combined sewer overflows; 2) the evaluation of the performance of a CSS and the provision of maintenance support by using the data on the occurrence and duration of CSOs obtained with the temperature sensors; and 3) the demonstration that it is possible to accurately calibrate a hydrodynamic model with data from low-cost sensors.

For the first contribution, the following conclusions can be drawn:

- A new methodology to quantify the occurrence and duration of CSO events using low-cost temperature sensors was developed.
- The methodology was validated in La Garriga CSS where high effectiveness in detecting the CSOs (higher than 80%) was obtained in most cases.
- The effectiveness of the method was affected by specific physical characteristics of some structures, which influenced the signal-to-noise ratio of temperature. Contrary, the effectiveness was not affected by seasonal temperature variations.
- Several options were also proposed to improve the effectiveness of the method. First, the use of two temperature sensors instead of one; and second, using a conductivity sensor which is also a low-cost solution which provides similar results. Also, an algorithm was proposed to automatically detect CSO events from the analysis of the temperature signals.

For the second contribution, the following conclusions can be drawn:

- In order to assess, improve, and maintain CSSs, it was developed a comprehensive methodology to analyze data collected from the low-cost monitoring of CSO structures. Monitoring was in the form of measuring rainfall data and the occurrence and duration of CSOs using temperature sensors.
- In the studied case, the La Garriga CSS was found to have a capacity in which overflows occur with rain volumes as little as 2 mm.
- To characterize the performance of each structure within a CSS, a statistical analysis was used. Through the statistical analysis, it was determined the overflow probability and ranking index (among other parameters) of each structure in the La Garriga CSS, which highlighted the structures that were most

problematic. To evaluate compliance with legislation, the measured number of overflows for each CSO structure was compared to the annual permitted number of overflows per structure recommended by government-issued guidelines.

- Finally, to predict which structures in a CSS will overflow after a rain episode, it was constructed a predictive model using decision trees, which can be used to optimize post-rainfall maintenance of CSSs. The decision trees for the La Garriga CSS had accuracies ranging from 70 to 83%, with two exceptions—one tree with an accuracy of 91% and another with 57%.
- Highly valuable data was obtained for 13 CSO structures for 11 months with an investment of less than 1000 €.
- The methodology presented is an effective and affordable package for municipalities and companies that manage sewer systems, as well as for engineers and scientists who need to gain a better understanding of the CSSs they are providing services for or in which they are conducting studies. Each of the analyses included in the methodology was based on the direct, simultaneous measurements of overflows in all of the CSO structures within a CSS.

For the third contribution, the following conclusions can be drawn:

- Data obtained from low-cost monitoring CSO duration were successfully integrated into the calibration of a hydrodynamic sewer model.
- A sensitivity analysis was conducted to identify the most influencing model parameters. The *Max* parameter was the most sensitive parameter for small episodes whereas the *N* and *Lss* parameters were for the medium and large episodes.
- With regards to the definition of objective functions for automatic calibration of the model by using optimization the Mean Average Error was the best option.
- The calibration of the CSO structure model was especially relevant for small episodes to properly simulate CSO flow. Whereas the default model (calibrated only based on the flow in the main trunk) did not show any overflow, the calibrated model (which also included the CSO structure) did.
- For medium and large rain episodes, similar accuracy (less than 12% difference) was obtained in the calibration when using duration of CSOs or flow measurements at the CSO discharge. However, the model calibrated with the

duration of CSOs always described better the simulated duration but worse volume and peak.

- For the small rain episodes the volume and peak of the CSOs were significantly better represented through the overflow approach calibration (especially in volume, with errors below 1%, compared to 40% with the duration approach).
- The model for medium rain episodes was successfully validated, with error differences on CSO volume, peak and duration of less than 10% between the *duration* and the *overflow* approach.

CHAPTER 7

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APPENDIX I - Installation and verification

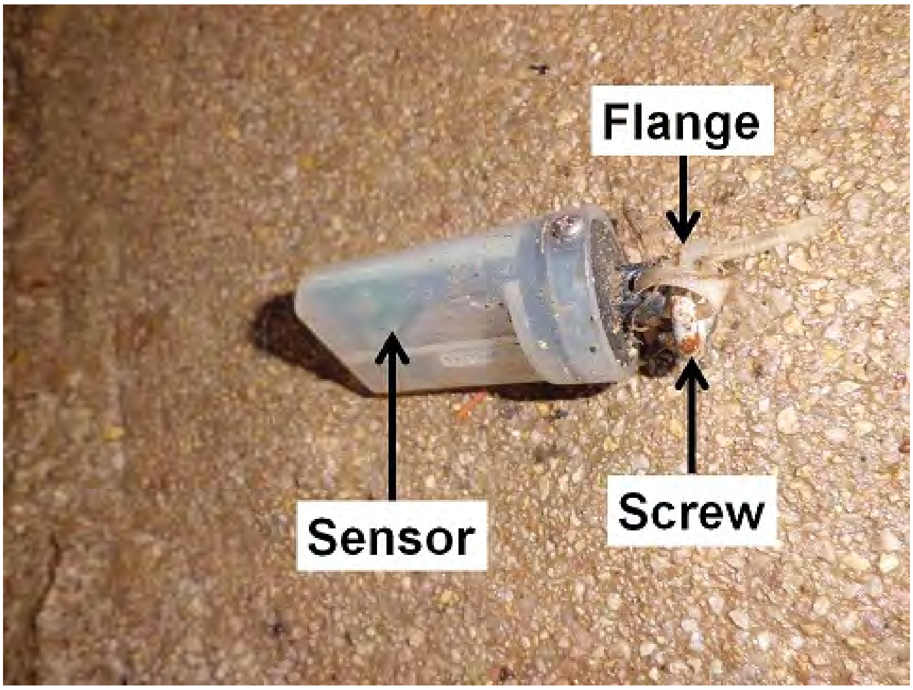


Figure AI-1. Detail of the sensor attachment to the CSO structure.

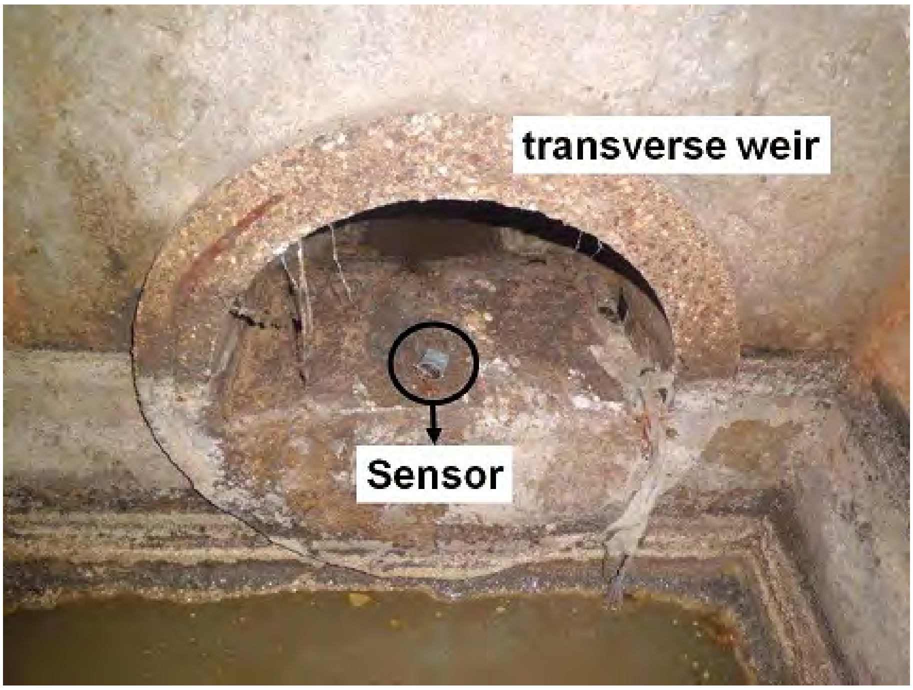


Figure AI-2. Detail of the sensor installation at the bottom center of a transverse weir.

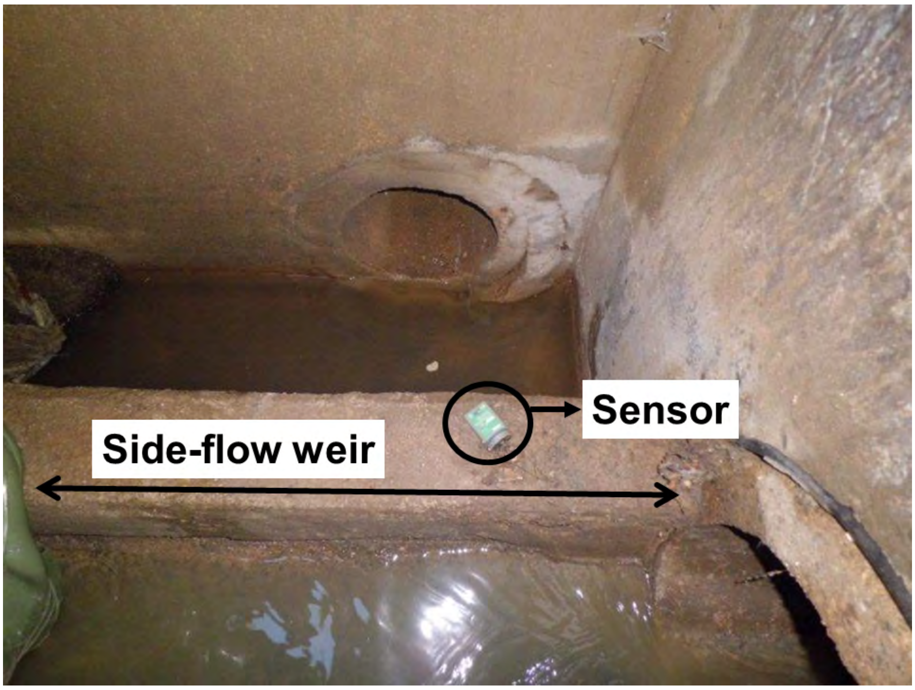


Figure AI-3. Detail of the sensor installation on the crest of a side weir.

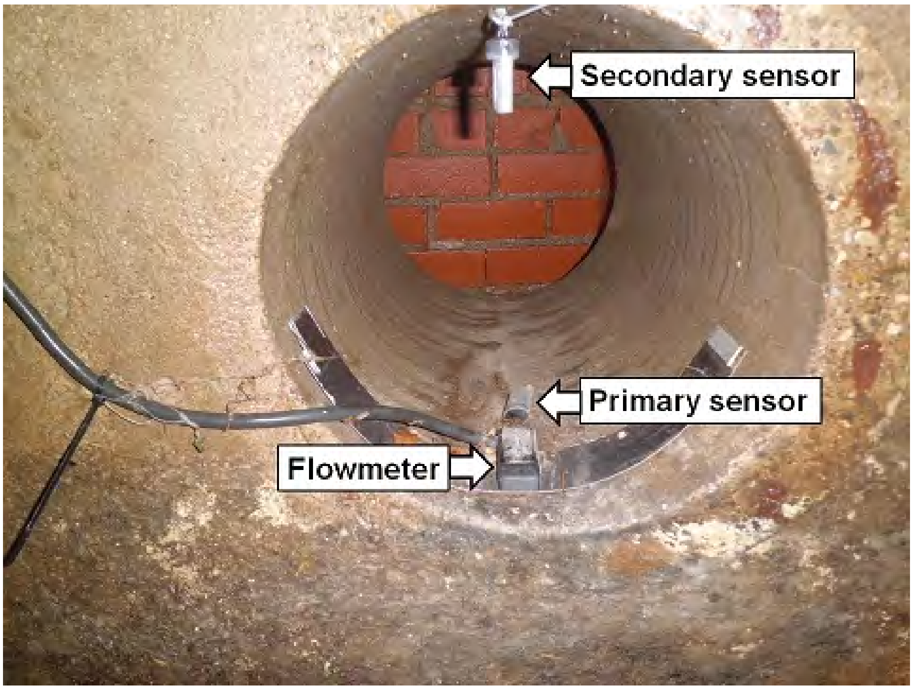


Figure AI-4. Installation setup for the verification of the method consisting on a flowmeter, a primary and a secondary temperature sensors.

APPENDIX II – Physical limitations

Figure AII-1. Detail of the CSO Structure 9. It can be appreciated the water turbulence created by a drop structure.

Figure AII-2. Detail of the CSO Structure 11. It can be appreciated stagnant water in the channel of the side weir during dry weather conditions.

Figure AII-3. Detail of the CSO Structure 13. As in the case of Structure 11, part of the CSO remains in the channel of the side weir during dry weather conditions.

APPENDIX III – Alternative approaches for CSO monitoring

<u>Double temperature-sensor approach</u>

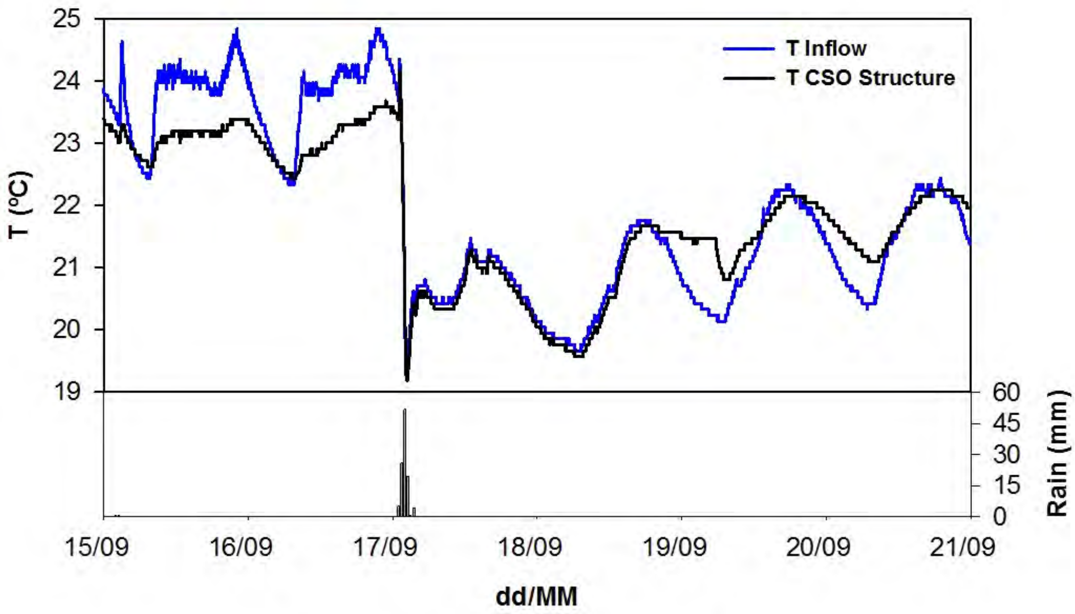


Figure AIII-1. Prolonged temperature convergence after the CSO event due to solids attached on the sensor in the inflow channel.

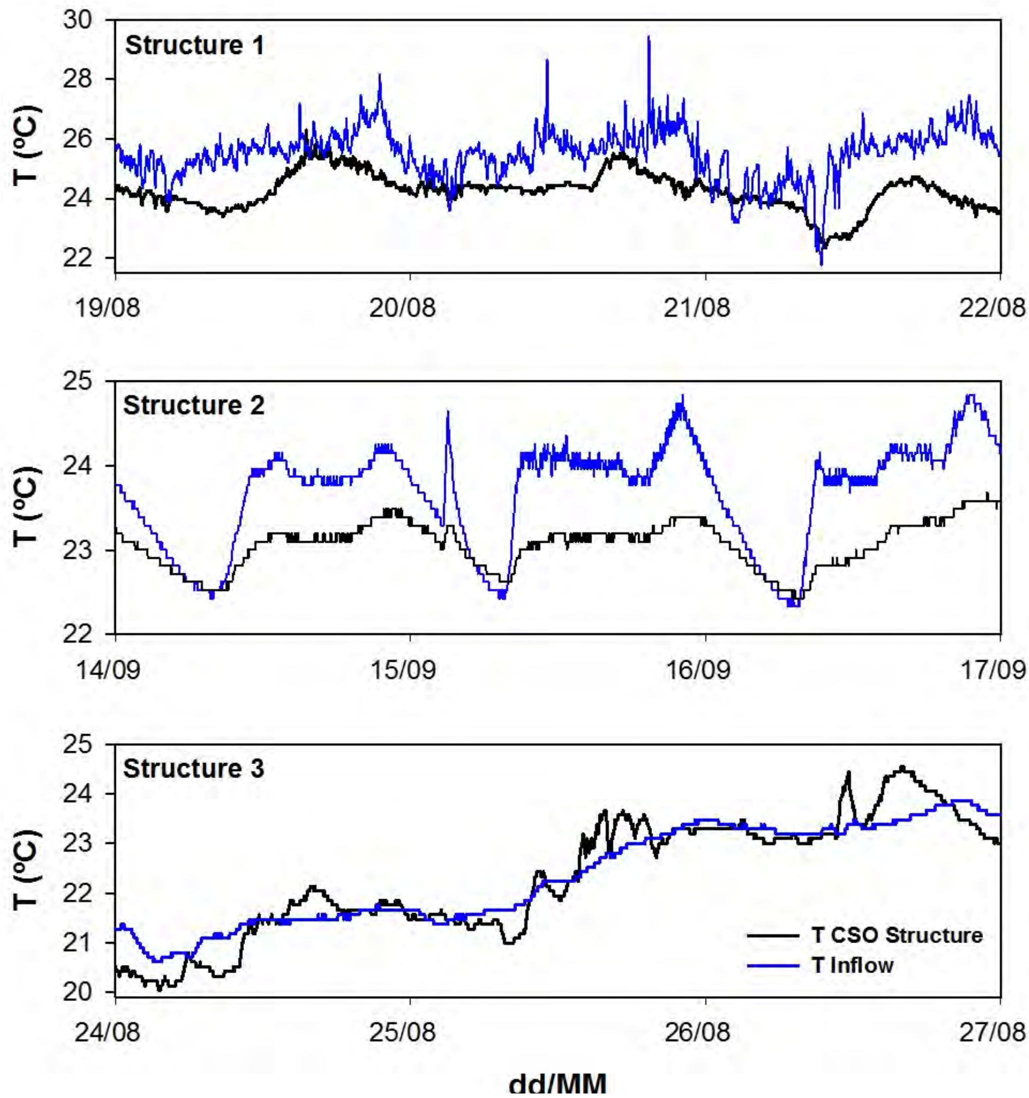


Figure AIII-2. Temperatures overlapping in dry weather condition.

Conductivity approach

Figure AIII-3 below shows results from the monitoring period from 08 to 24 November 2011 During this period occurred four CSO events on 10, 11, 17 and 19 November, according to the flow measurements. It can be seen how for the event of 10 November, the conductivity sensor correctly detect the CSO event, but this is prolonged until 16 November, thus masking the event occurred afterwards on the day 11. The same phenomenon occurred with the event of the day 17, which lasts until 21 masking the event occurred on 19. This was related to the deposition of solids on the sensor produced during the CSO event. Figures AIII-4 and AIII-5 (showing solids around the sensor), were taken on 16 and 21 November respectively, days in which the solids were removed, which led to the restoration of the conductivity signal.

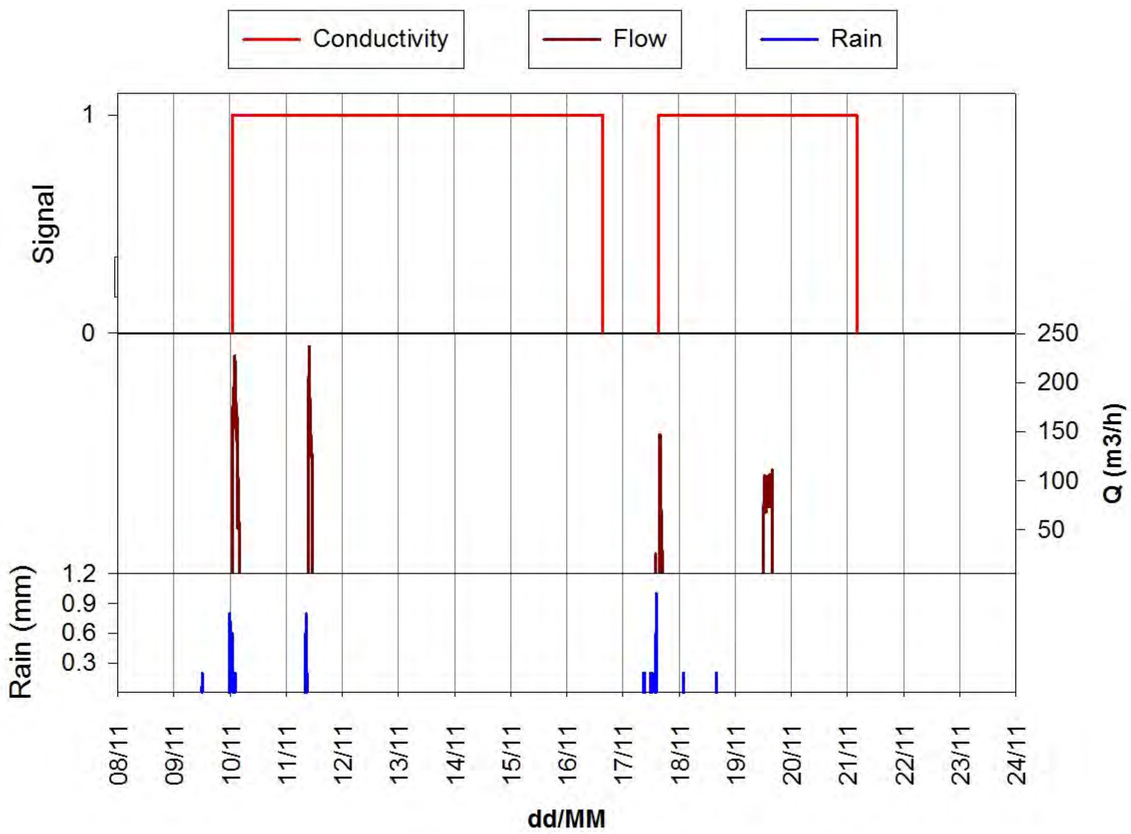


Figure AIII-3. Monitoring period from 08 to 24 November 2012 in the CSO Structure 14 (CSS of La Garriga). Four CSO events were detected with the flowmeter. The conductivity sensor only detected two events because of solids attached on the sensor, which produced a prolongation of the conductivity signal.

Figure AIII-4. Solids attached on the conductivity sensor (16-Nov-2012).

Figure AIII-5. Solids attached on the conductivity sensor (21-Nov-2012).

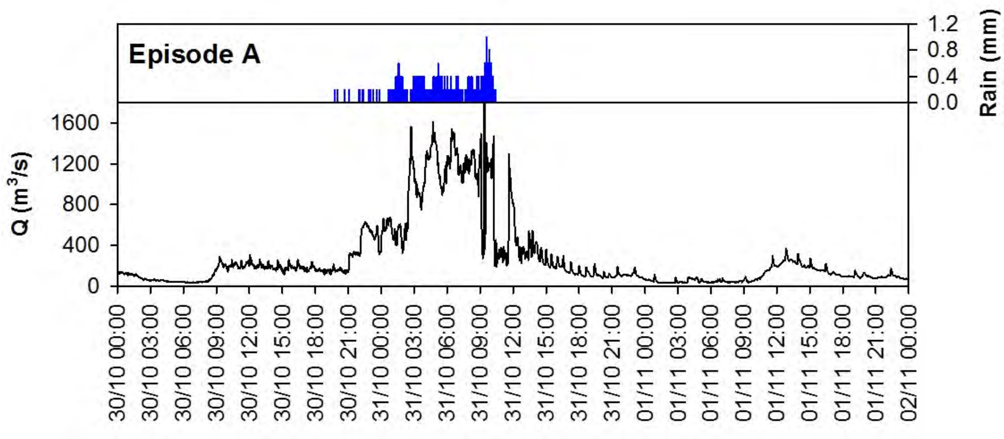
APPENDIX IV – Rain inter-episode time (La Garriga CSS)

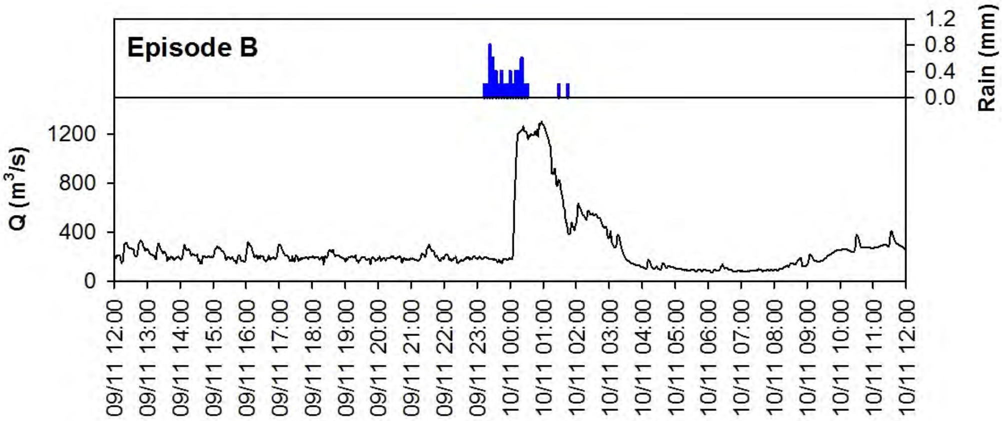
The inter-episode time for the rain episodes used in this study was set at 6 hours. This was obtained based on the time needed to get back to dry weather conditions after a rain episode. It was used data on the flow discharge measured at the end of the combined sewer system from 5 measured rain episodes, from which the average inter-episode time was calculated (Table AIV-1).

Episode	Date	Volume (mm)	Duration (min)	Max. Intensity (mm/5min)	Time to dwf (h)
A	**30-Oct-2012**	34.6	885	1	16
B	**09-Nov-2012**	6	150	0.8	4
C	**11-Nov-2012**	4	45	0.8	3
D	**28-May-2013**	2.6	20	1.2	2
E	**08-June-2013**	8.1	65	2.2	3
				Average	**5.6**

Table AIV-1. Characteristics of the rain episodes and the time to dry weather conditions based on flow measurements

On the following are shown the figures of the flow measurements taken at the end of the CSS (just before the WWTP) for that 5 rain episodes:




Episode B
Rain (mm)
1.2
0.8
0.4
0.0
Q (m³/s)
1200
800
400
0
09/11 12:00
09/11 13:00
09/11 14:00
09/11 15:00
09/11 16:00
09/11 17:00
09/11 18:00
09/11 19:00
09/11 20:00
09/11 21:00
09/11 22:00
09/11 23:00
10/11 00:00
10/11 01:00
10/11 02:00
10/11 03:00
10/11 04:00
10/11 05:00
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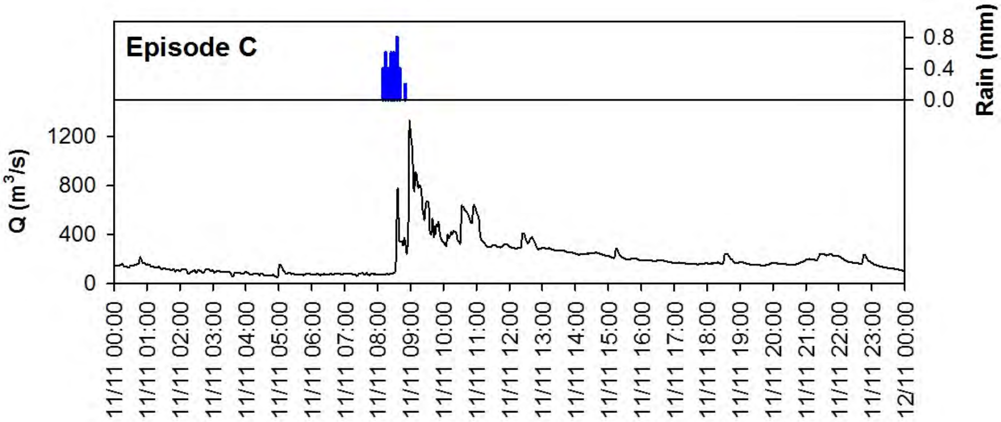
10/11 11:00
10/11 12:00


Episode C
Rain (mm)
0.8
0.4
0.0
Q (m³/s)
1200
800
400
0
11/11 00:00
11/11 01:00
11/11 02:00
11/11 03:00
11/11 04:00
11/11 05:00
11/11 06:00
11/11 07:00
11/11 08:00
11/11 09:00
11/11 10:00
11/11 11:00
11/11 12:00
11/11 13:00
11/11 14:00
11/11 15:00
11/11 16:00
11/11 17:00
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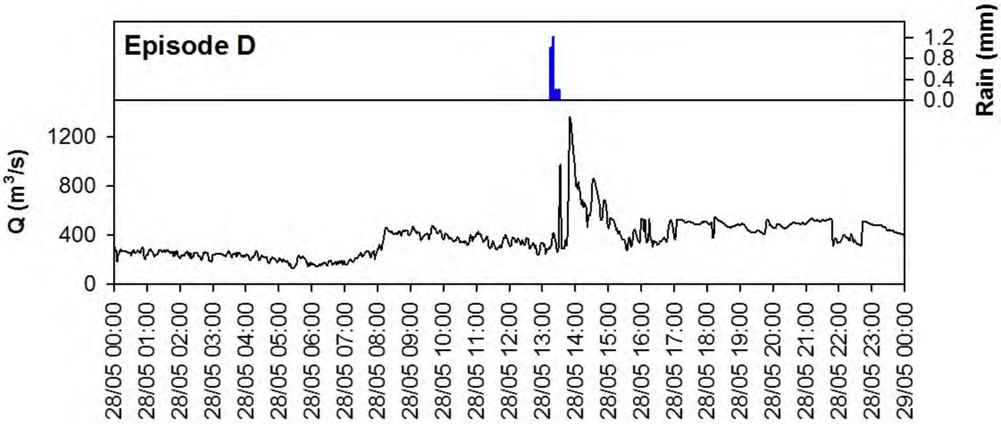
11/11 23:00
12/11 00:00


Episode D
Rain (mm)
1.2
0.8
0.4
0.0
Q (m³/s)
1200
800
400
0
28/05 00:00
28/05 01:00
28/05 02:00
28/05 03:00
28/05 04:00
28/05 05:00
28/05 06:00
28/05 07:00
28/05 08:00
28/05 09:00
28/05 10:00
28/05 11:00
28/05 12:00
28/05 13:00
28/05 14:00
28/05 15:00
28/05 16:00
28/05 17:00
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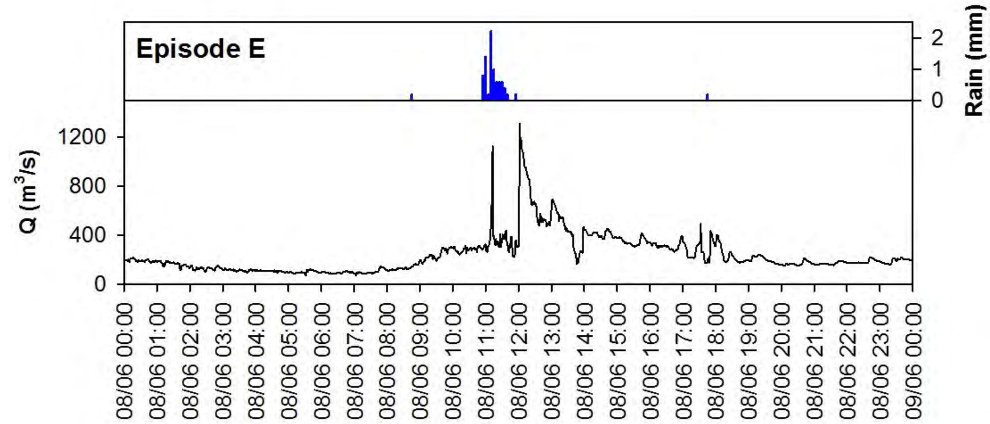
28/05 23:00
29/05 00:00


Episode E
Rain (mm)
2
1
0
Q (m³/s)
1200
800
400
0
08/06 00:00
08/06 01:00
08/06 02:00
08/06 03:00
08/06 04:00
08/06 05:00
08/06 06:00
08/06 07:00
08/06 08:00
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08/06 15:00
08/06 16:00
08/06 17:00
08/06 18:00
08/06 19:00
08/06 20:00
08/06 21:00
08/06 22:00
08/06 23:00
09/06 00:00

APPENDIX V – Model development and CSO duration-rain volume curves

Assessing the capacity of a CSS

The relationship between CSO duration in each CSO structure and rain volume were obtained based on the results from a numerical rainfall-runoff model. The model, set in the SWMM5.0 modelling software, consisted of a well-delimited catchment area (24.5 ha) from the La Garriga CSS with one CSO structure at the outlet of the catchment. The modelled CSO structure was calibrated against flow data measured in the CSO structure during a rain episode that occurred in May/2012. The calibration was performed under an automatic scheme using the NSGA-II as the optimization algorithm, and the Nash-Sutcliff coefficient as the objective function.

The selected calibration parameters (and their values limits) were selected under expert knowledge. The parameters and limits were, from the catchments: the imperviousness, width, depression storage and the curve number; from the conduits: the pipe roughness and the maximum flow at the conduit after the CSO structure; and from the CSO structure: the weir discharge coefficient. The calibration results are presented in Figure AV-1.

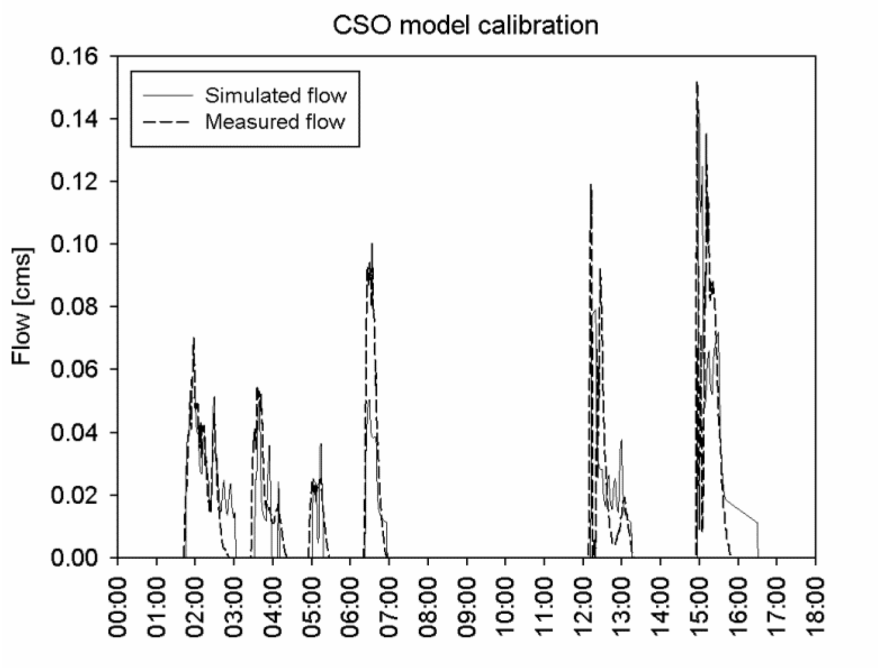


Figure AV-1. Simulated and measured flow profiles from the CSO structure calibration.

Following calibration of the model, two case scenarios were evaluated: a poorly-designed and a well-designed system. First, the calibrated model was run for 61 rain episodes that occurred between July/2011 and October/2012. The characteristics of the rain episodes are summarized in Table AV-1. After all the simulations, 71 CSOs were obtained, whose duration was annotated. This case served as an example of a poorly-designed system.

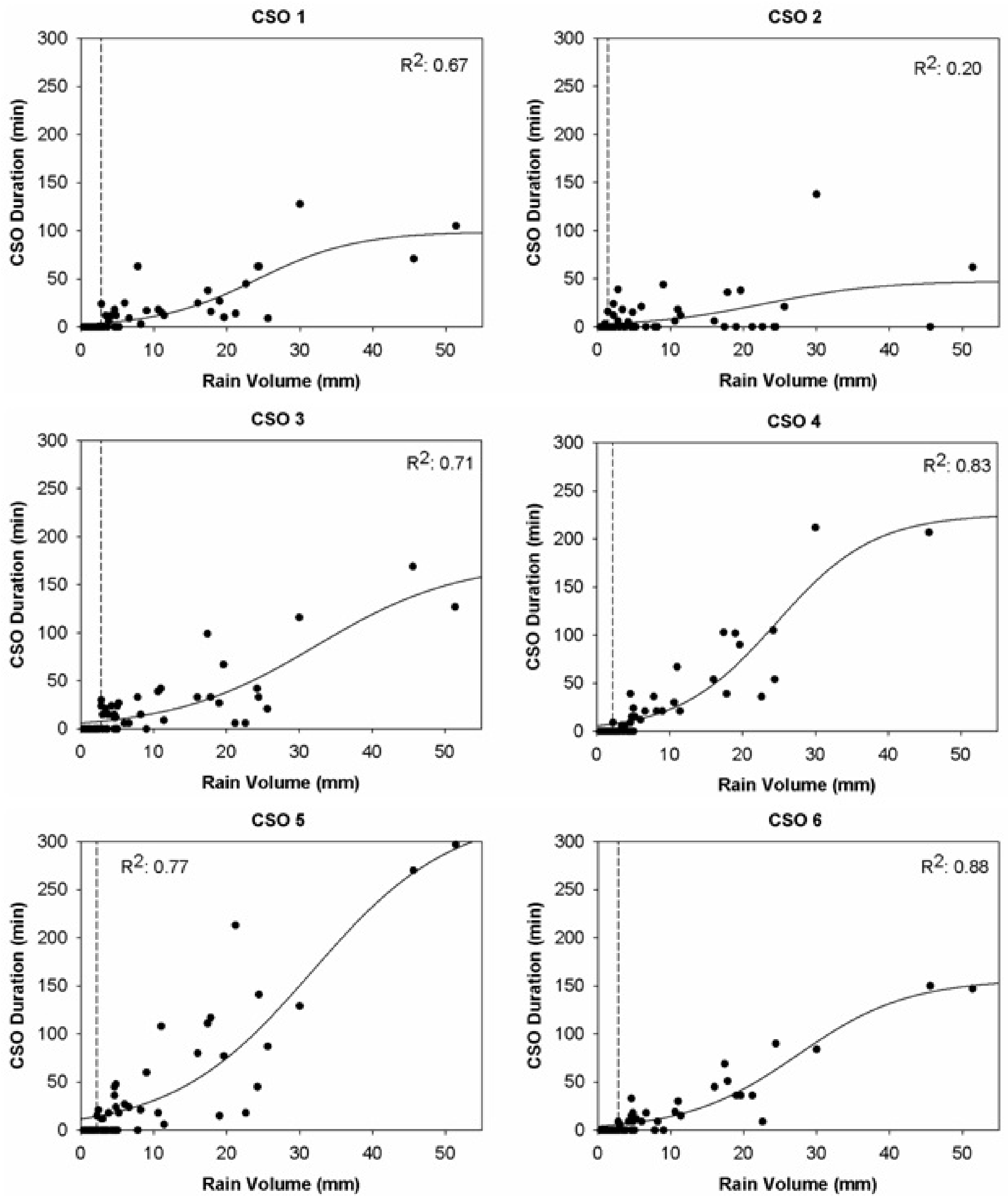
The case representing the well-designed system was obtained by re-calibrating the model, this time considering the number of overflows as the calibration objective. We considered a 90% reduction of the number of CSO events (i.e. 7 CSO events). The calibration parameters in this case were the conduit and junction maximum depth, the weir crest height and the weir length. Such parameters meant that physical modifications on the modeled system were made in order to achieve the considered number of CSO events.

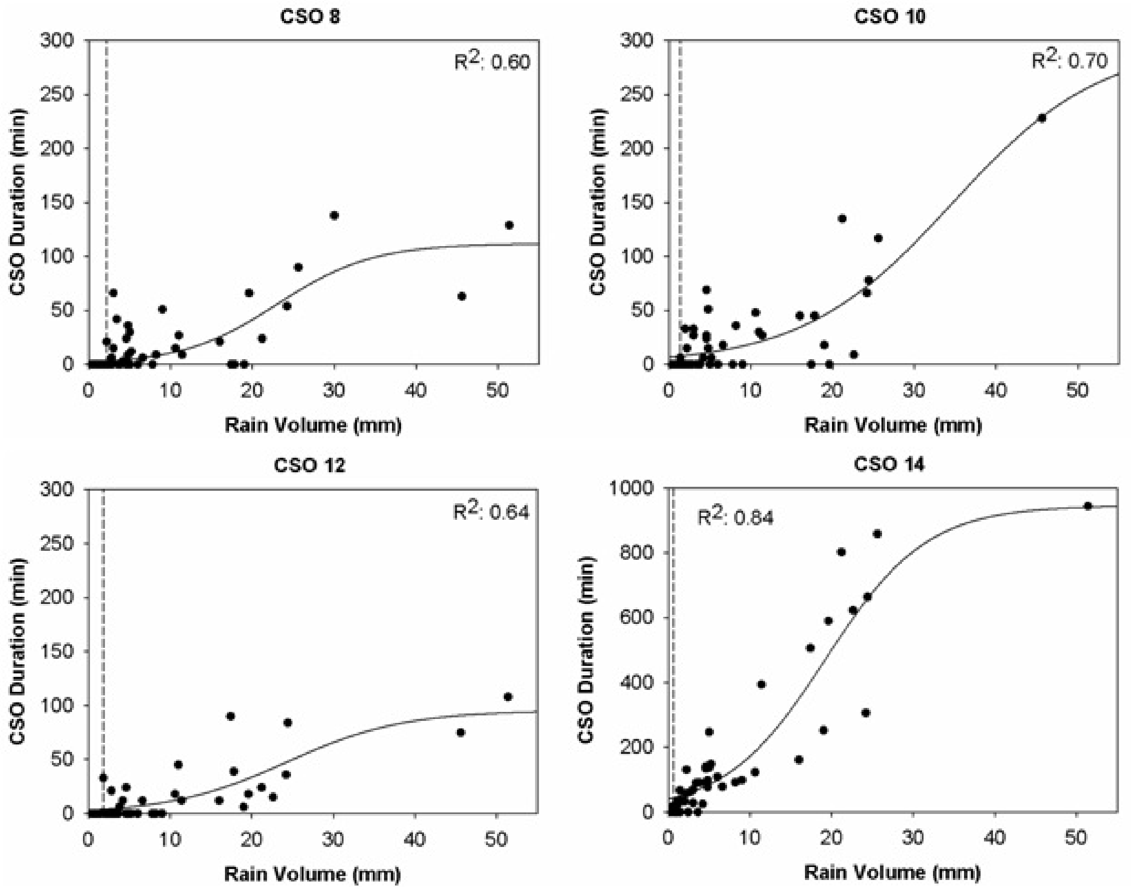
	Volume (mm)	**Duration (min)**	**Max intensity (mm/5min)**
Min.	0.6	10	0.2
Max.	82.8	1510	9.0
Avg.	10.7	284	1.4

Table AV-1. Summary (i.e. minimum, maximum, and average) of the characteristics of the 61 rain episodes used to obtain the relationship between rain volume and CSO duration.

APPENDIX VI – CSO duration-rain volume curves (results)

Following are shown the plots of CSO duration Vs Rain volume obtained for each single CSO structure, with the vertical dashed line indicating the rain volume *breaking point* (the plots corresponding to Structures 7 and 11 are shown in Chapter 4.2). Table AVI-1 indicates the *breaking point* for each structure.





Structure #	***Breaking point* (mm)**
CSO 1	2.8
CSO 2	1.4
CSO 3	2.8
CSO 4	2.2
CSO 5	2.2
CSO 6	2.8
CSO 8	2.2
CSO 10	1.4
CSO 12	1.8
CSO 14	0.6

Table AVI-1. Rain volume *breaking point* for each CSO structure.

APPENDIX VII – Support for CSS maintenance (decision trees)

CSO structure	Explanatory variables				Nº branches	Internal nodes	Leaves	Accuracy (%)
	Total volume	Rain duration	Max intensity	Time since last rain				
1	■	■	■		8	4	5	81.1
2			■	■	4	2	3	56.6
3	■				2	1	2	83.0
4	■		■		4	2	3	83.0
5		■	■	■	10	5	6	75.5
6	■		■		4	2	3	77.4
7	■				8	4	5	81.1
8			■		2	1	2	69.8
10			■		2	1	2	75.5
11	■		■	■	6	3	4	73.6
12	■	■	■		6	3	4	75.5
14	■		■		4	2	3	90.6

Table AVII-1. Summary of the characteristics of the obtained trees for each CSO structure.

As an example, the decision tree created for CSO structure 14 is depicted in Figure AVII-1. In this case, the tree consisted of 2 internal nodes, the *Max. Intensity* and the *Total Volume*. Each branch extending from the nodes are decision values. For instance, for a rain episode with maximum intensity less than or equal to 0.4mm/5min and total volume greater than 1mm, an overflow for structure 14 is predicted with 90.6% accuracy. Within each leaf (the terminal nodes), the number of rain episodes that meet the value of its corresponding branch is noted in parentheses, along with the number of rain episodes that the tree predicted incorrectly, if incorrect predictions were made. In the tree presented in Figure AVII-1, there are 40 rain episodes with a max. intensity greater than 0.4mm/5min, and the model predicted overflow successfully in all 40 cases. For the 9 episodes with a total rain volume greater than 1mm, 1 episode was predicted incorrectly, and for the remaining 4 episodes, the model's prediction was wrong in 1 episode.

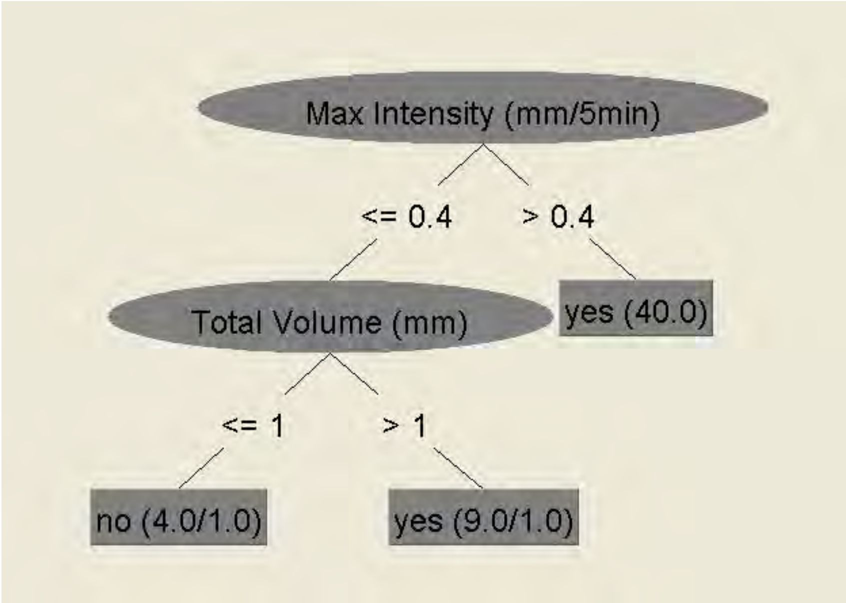


Figure AVII-1. Decision tree constructed for the CSO Structure 14.

<u>"La Garriga CSO Network Simulator"</u>

In the main screen of the La Garriga CSO Network Simulator (Figure AVII-2), the user inputs rain characteristic data (total volume, duration, maximum intensity, and the time since the last rain episode) into boxes on the left side of the screen. After the user introduces the rain data and runs the model, the results (predictions about whether or not overflow occurred) of the model appear in the middle of the screen. Finally, the user can select a CSO structure and its decision tree will appear on the right side of the screen.

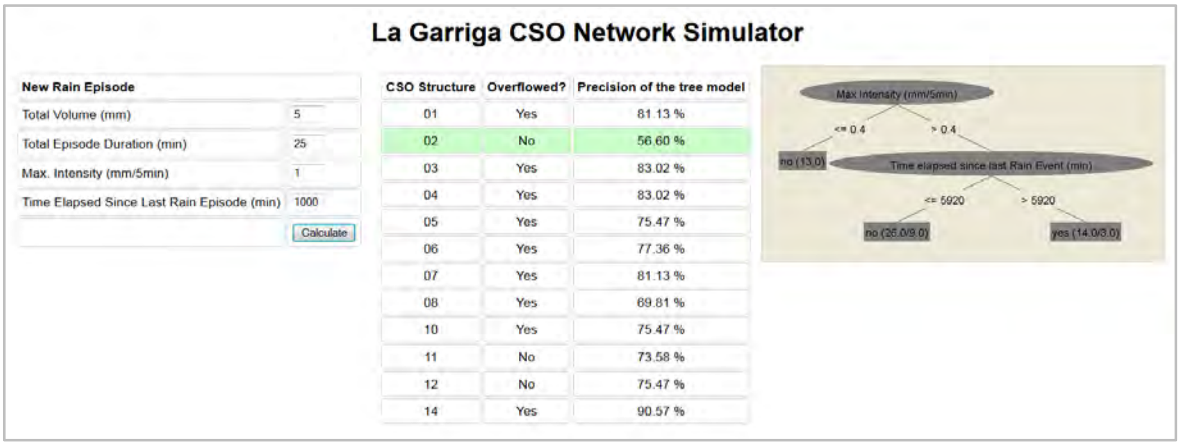


Figure AVII-2. The *La Garriga CSO Network Simulator* interface, with an example of the overflow predictions made for a rain episode with user-input characteristics; an overflow prediction is made for each CSO structure (with CSO structure 2 highlighted and its tree shown in the image).

APPENDIX VIII – Modified SWMM (SWMM_CSO)

Computation of the CSO duration in the modified SWMM

The original SWWM5 after a simulation generates by default two types of files, 1) a binary file containing the value of each time series for each chosen time step defined in the input file, and 2) a report file containing summary information of the simulation. No information regarding the duration of the CSO events can be extracted directly from either of these files. Thus the code was modified so that two additional files are generated:

- A report file containing summary information about the overflow events produced for each modeled weir (nº of overflows, total and average overflowing duration, and total and average overflow volume).
- A time series file containing for each simulated time step and each weir two different values, '1' or '2', depending whether overflow occurred at each evaluated time step ('1' meaning 'no overflow' and '2' meaning 'overflow'), based on the condition 'overflow discharge > 0'.

For the 'duration approach' calibration the new time series file was used. To that end, an additional time series file is need, regarded as the calibration file in which is specified the observed overflow occurrence, using again the values '1' or '2'. Examples of both calibration and simulation files are shown in Figure AVIII-1.

```
******************
CSO CSV File
******************

Step (seconds);Weir_1
60.000000;1
120.000000;1
180.000000;1
240.000000;1
300.000000;1
360.000000;1
420.000000;1
480.000000;2
540.000000;2
600.000000;2
660.000000;2
720.000000;2
780.000000;2
840.000000;2
900.000000;2
960.000000;1
1020.000000;1
1080.000000;1
1140.000000;1
1200.000000;1
```

Date Time	Step (seconds)	Weir_1
15/08/2012 0:00	0.00	1
15/08/2012 0:01	60.00	1
15/08/2012 0:02	120.00	1
15/08/2012 0:03	180.00	1
15/08/2012 0:04	240.00	1
15/08/2012 0:05	300.00	1
15/08/2012 0:06	360.00	2
15/08/2012 0:07	420.00	2
15/08/2012 0:08	480.00	2
15/08/2012 0:09	540.00	2
15/08/2012 0:10	600.00	2
15/08/2012 0:11	660.00	2
15/08/2012 0:12	720.00	1
15/08/2012 0:13	780.00	1
15/08/2012 0:14	840.00	1
15/08/2012 0:15	900.00	1
15/08/2012 0:16	960.00	1
15/08/2012 0:17	1020.00	1
15/08/2012 0:18	1080.00	1
15/08/2012 0:19	1140.00	1
15/08/2012 0:20	1200.00	1

Figure AVIII-1. On the left is shown an example of file generated by the modified SWMM after a simulation. On the right is the calibration file in which is noted the overflow observations. In the simulated file (left) it can be observed an overflow event from second 480 to second 900 (8 minutes), while in the calibration file (right) the overflow event lasts 6 minutes.

APPENDIX IX – Sensitivity, hypothesis tests and calibration results

Sensitivity analysis results

	Small episode S1		
	CSO Volume R^2_{adj}: **0.82**	**CSO peak** R^2_{adj}: **0.91**	**CSO duration** R^2_{adj}: **0.90**
Parameter	**SRC**	**SRC**	**SRC**
Cd	0.03	0.02	-0.03
Max	-0.90	-0.95	-0.94
N	0.04	0.08	0.11
Lss	0.03	0.07	0.09

	Medium episode M1		
	CSO Volume R^2_{adj}: **0.96**	**CSO peak** R^2_{adj}: **0.95**	**CSO duration** R^2_{adj}: **0.99**
	SRC	**SRC**	**SRC**
Cd	0.12	0.16	-0.03
N	0.70	0.69	0.71
Lss	0.68	0.67	0.71

	Large episode L1		
	CSO Volume R^2_{adj}: **0.96**	**CSO peak** R^2_{adj}: **0.94**	**CSO duration** R^2_{adj}: **0.97**
	SRC	**SRC**	**SRC**
Cd	0.14	0.39	0.00
N	0.71	0.66	0.73
Lss	0.67	0.62	0.71

Table AIX-1. SRCs for the evaluated small, medium and large episodes.

Hypothesis test results

	Small episode *S1*								
	CSO Volume			CSO peak			CSO duration		
Parameter	T_0	T	H_0	T_0	T	H_0	T_0	T	H_0
C_d	1.78	1.96	Not rejected	1.63	1.96	Not rejected	1.80	1.96	Not rejected
Max	47.15	1.96	Rejected	71.59	1.96	Rejected	63.57	1.96	Rejected
N	2.18	1.96	Rejected	6.34	1.96	Rejected	7.09	1.96	Rejected
Lss	1.69	1.96	Not rejected	5.46	1.96	Rejected	6.24	1.96	Rejected

	Medium episode *M1*								
	CSO Volume			CSO peak			CSO duration		
Parameter	T_0	T	H_0	T_0	T	H_0	T_0	T	H_0
C_d	14.22	1.96	Rejected	15.59	1.96	Rejected	6.67	1.96	Rejected
N	83.94	1.96	Rejected	66.62	1.96	Rejected	138.23	1.96	Rejected
Lss	81.40	1.96	Rejected	64.24	1.96	Rejected	137.91	1.96	Rejected

	Large episode *L1*								
	CSO Volume			CSO peak			CSO duration		
Parameter	T_0	T	H_0	T_0	T	H_0	T_0	T	H_0
C_d	15.16	1.96	Rejected	34.69	1.96	Rejected	0.315	1.96	Not rejected
N	77.12	1.96	Rejected	58.44	1.96	Rejected	91.45	1.96	Rejected
Lss	72.49	1.96	Rejected	54.98	1.96	Rejected	89.19	1.96	Rejected

Table AIX-2. Hypothesis test results for the evaluated small, medium and large episodes. H_0 is the null hypothesis that the coefficient b_i is statistically not different to zero (b_i=0); if H_0 is not rejected then the coefficient b_i could be excluded from the model (and hence the parameter i).

Calibration results

Episode #	Criteria	Overflow Approach (MAE)	Overflow Approach (PVWE w:0.75)	Duration Approach (MAE)	Duration Approach (SSE)
S1	**Volume**	0.80%	37.10%	-39.4%	-83.5%
	Peak	-23.20%	-9.30%	-40.2%	-73.1%
	Duration	24.10%	43.50%	-7.4%	-43.5%
S2	**Volume**	0.00%	5.10%	-72.2%	-43.2%
	Peak	-33.90%	-26.60%	-64.7%	-49.2%
	Duration	56.60%	60.40%	13.2%	35.9%
M1	**Volume**	-0.80%	-48.30%	23.7%	23.4%
	Peak	47.80%	0.10%	67.8%	67.8%
	Duration	-17.50%	-41.60%	3.0%	2.4%
M2	**Volume**	0.50%	51.10%	12.2%	17.10%
	Peak	-27.70%	-0.30%	-20.1%	-17.70%
	Duration	3.10%	8.30%	7.1%	3.10%
L1	**Volume**	126.4%	126.50%	136.4%	141.2%
	Peak	22.5%	22.50%	26.2%	28.1%
	Duration	15.0%	15.20%	16.6%	14.6%

Table AIX-3. Volume, peak and duration errors obtained with the objective functions MAE and PVWE (*overflow approach*) and MAE and SSE (*duration approach*).

Episode #	Parameter	*Overflow Approach*	*Duration Approach*
S1	C_d	2.89	1.29
	Max	0.37	0.31
	N	0.02	0.01
	Lss	0.73	0.26
S2	C_d	2.34	1.27
	Max	0.36	0.43
	N	0.01	0.01
	Lss	0.95	0.26
M1	C_d	2.90	1.29
	N	0.02	0.02
	Lss	1.30	1.30
M2	C_d	1.20	2.68
	N	0.01	0.01
	Lss	0.25	0.26
L1	C_d	1.20	2.63
	N	0.01	0.01
	Lss	0.25	0.25

Table AIX-4. Values of the model parameters obtained in the calibrations.

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