Universitat Politècnica de Catalunya
Barcelona Tech
Escola Tècnica Superior d'Enginyeria de Camins, Canals I Ports de Barcelona
Departament d'Enginyeria Hidràulica, Marítima i Ambiental

Civil Engineering Doctoral Programme

In-sewer organic sediment transport

Study of the release of sediments during wet-weather from combined sewer systems in the Mediterranean region in Spain

by

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PhD dissertation submitted in partial fulfilment of the requirements for the award of the degree of

Doctor of Philosophy by the Universitat Politècnica de Catalunya

Barcelona, October 2014

To my family with love

"Tell me, and I will forget.

Show me, and I may remember.

Involve me, and I will understand."

Confucius 450 BC

Abstract

The accumulation of sediments in combined sewer systems may give rise to significant quality problems, which sometimes are overlooked. Solids deposited in the network may lead to more frequent overflows into natural waters, where are often discharged without treatment during the beginning of storms events. When organic solids, released from in-sewer deposits, reach natural receiving waters, may produce serious impacts. Waters environments are degraded due mainly to the high oxygen biochemical demand, the ammonia contribution and other pollutants.

This study focuses on the release of highly-organic sediments having being accumulated inside a combined sewer network. After prolonged dry-periods, typical in Mediterranean region, sediments are re-suspended and conveyed when storm runoff appears. The aim of the research is to develop a methodology able to predict their potential erosion and subsequent mobilization through the network. To achieve that goal, it is needed to improve the knowledge on the processes occurring during long dry-periods, and analyse the variables involved that might affect the erodibility of the deposits. To achieve reliable results in water quality modelling, it is essential the availability of consistent and detailed field data.

Highly-organic non-homogeneous sediment samples collected from a combined sewer system were used for the laboratory assessment of the characteristics and the behaviour regarding erosion. Varying strength of the bed with depth allow for a more appropriate representation of the movement of solids in sewerage by introducing in the model a more realistic behaviour.

The results obtained have shown that the prediction of organic sediment mobilization and transport is complex but possible to accomplish. However, more effort is needed to ensure the transferability of the results for a more general application of the predictive model obtained.

This research has mainly contributed in a more detailed knowledge of the organic sediment bed structure regarding strength to erosion. The acquired knowledge can be applied for improvements in the prediction of pollutant loads that can reach watercourses, pursuing the receiving waters protection as a final goal.

Key words: *quality modelling; organic sediments; in-sewer sediment transport.*

Resumen

Los depósitos de sedimentos en sistemas unitarios de alcantarillado pueden dar lugar a importantes problemas de calidad de aguas, muchas veces ignorados. La acumulación de sedimentos en estos sistemas puede generar el aumento en la frecuencia de vertidos a medios naturales receptores durante una tormenta. La presencia de sólidos de origen orgánico en los vertidos de aguas sin tratar puede producir impactos perjudiciales en las aguas receptoras. Los medioambientes acuáticos son afectados principalmente por las altas demandas de oxígeno y las contribuciones de nitrógeno originados en los sedimentos orgánicos.

Este estudio se centra en los procesos de re-suspensión de sedimentos altamente orgánicos que se han acumulado en las redes de alcantarillado unitario. Luego de largos períodos secos típicos en la región Mediterránea, los depósitos de sedimentos son re-movilizados y transportados a través del sistema por la escorrentía producida por una tormenta. El objetivo de la investigación es desarrollar una metodología que sea capaz de predecir el potencial de erosión y posterior movilización de los sedimentos orgánicos a través del sistema. Para ello, es necesario mejorar el conocimiento que se tiene sobre los procesos que ocurren durante largos períodos sin lluvias y analizar las variables involucradas que puedan influir en la erosión de los depósitos. Contar con la disponibilidad de datos de campo confiables es esencial en el logro de resultados válido en un modelo de calidad de aguas.

Muestras de sedimento no homogéneo y altamente orgánico se recogieron en un sistema de alcantarillado unitario. A través de ensayos en laboratorio, estos sedimentos se utilizaron para la evaluación de sus características y comportamiento vinculado a la erosión. La introducción en el modelo de una ley de tensión crítica de arrastre más realista permite una mejor representación de la movilización de los sedimentos.

Los resultados obtenidos muestran que la predicción del transporte de sedimentos orgánicos de alcantarillado es posible de realizar aunque es un tema muy complejo. Mayores esfuerzos son aún necesarios para lograr la transferencia directa de los resultados para una aplicación más generalizada del modelo predictivo obtenido.

Una de las principales contribuciones de esta investigación está vinculada al logro de un conocimiento más detallado de la estructura de los depósitos de sedimento orgánico en relación a su resistencia a la erosión. El conocimiento adquirido podría ser aplicado en la mejora en las predicciones de cargas contaminantes que llegan a cursos de agua naturales durante vertidos. Todo ello, siguiendo como objetivo final, la protección de las aguas naturales receptoras.

Palabras claves: *modelos de calidad, sedimento orgánico, transporte de sedimento en alcantarillado.*

Acknowledgements

Foremost, I would like to thanks my Ph.D. advisor Prof. Manuel Gómez Valentín (UPC), for giving me the possibility and encouraging me to carry out this Ph.D. on this very special topic with strong commitment to water resources. Thanks go for all the dedication, personal support and the confidence given to let me work independently. Thanks also go for providing the funding needed for completing this project and for participating in conferences. I will always appreciate his own personal effort for this achievement.

During this doctorate project I had the possibility of carrying out a research stay in the UK in two occasions. Firstly at the University of Bradford in 2012 and then at the University of Sheffield in 2013, both times with the Pennine Water Group. During these stays, it has been my privilege to meet Prof. Simon Tait and Dr. Alma Schellat. I have enjoyed the opportunity to learn from their knowledge and experience. Thanks for the useful advices, for reinforcing my critical evaluation of scientific production. Many thanks also to Dr. Henriette Jensen (PWG) for her assistance with biochemical analysis and interesting ideas.

I would like to acknowledge the managers from Consorci per a la Defensa de la conca del Besòs and the technical staff from Drenatges Urbans del Besòs for their funding and collaboration in the fieldwork. Thanks to Josep Navarro, Ivan, Francesc, Jesús, Carlos, Montse, Llum, Oscar, Antonio, and Joan. Also to the technical staff of the University of Bradford and Sheffield in the UK, for the help and the everyday smiles I received, which made more joyful the hard days work. I must acknowledge also to Rafael Bartolí and Xavier Querol from the Instituto de Diagnóstico Ambiental y Estudios del Agua at the CSIC, who assisted in the performance of the sediment size characterization. Thanks to all of them for providing the facilities to carry out the field and laboratory work from where the results reported in this study were obtained.

Thanks go also to the proffesor from the Master of Water Resources at the UPC. Special thanks to Prof. Rafael Mujeriego Sahuquillo, who inspired me and broadened my worldview in the water quality and environmental fields. Thanks also to Pof. Joan García Serrano, for the support and assistance in the environmental laboratory.

Thanks to all the technical and adminstrative staff of Department of Hydraulic, Maritime and Environmental Engineering at the Universitat Politècnica de Catalunya. Special thanks to Eduardo y Javier from the environmental laboratory. And special thanks to the proffesors, collegues and staff at the Institut Flumen.

I must dedicate very special thanks to my friends and colleagues in the D1 and Campus Nord: Belén, Marina, Geor, Sole, Jeanne, Klaudia, Cesca, Hans, Eduard G., Eduardo, Úrsula, Rodrigo, Martí, Anaïs, José Luis, Jordi, Carlos, Jackson, Gonzalo, Chiara, Eduard R., Esteban, Cefe, Laura C., Laura S. and Ana and for creating such a close connection and friendly atmosphere that was a pleasure to go to work every day. Thanks for listening to me so many times, for sharing interesting discussions, and for the sincere friendship that they gave me. Thanks Belén, Marina and Georgina also for their reviews, comments, and support from the beginning to the end of this dissertation.

Thanks to Affifa, for sharing this strange enthusiasm in analysing sediments and for her lovely company during the long (and cold) periods of isolation in the laboratory in Sheffiled. I also enjoyed meeting friendly people there that alliviated the loneliness of being away from home: Isabel, Christian, Giulio, Martina, Jevgenija and Bestun thanks for their support and for so many cups of tea.

I would also like to thank to my friends in Barcelona, who since coming to "the other side of the world" have been a constant support, have shared joys and sorrows, but more importantly, they have given me their friendship and smiles. Thanks to: Virgina, Miguel, Ricardo, Héctor, Xung, Mónica also to Miriam, Marta, Sandra, Davide and Sonia for their support through the last months, for encouraging me to put an end point to this chapter. I also sincerely acknowledge also to Alejandro, who always supported me and with whom I shared so many good times. I also thank him for his reviews and sometime harsh criticism.

Thanks to my friends in Argentina: Caro, Sole, Myr, Pichi, my friends since and for ever, but always so much close. To Alejandra, Juan, Alicia, Víctor, Flavio, Juan, Roberto and so many others from Argentina, who supported and encouraged me to continue.

The last and deepest thanks are for my family. To my sisters, brother and brothers in-law: Laura, Paula, Javier, Diego, Rodrigo. Thanks for being there any time I needed you, for giving me the energy to go on. Of course many thanks to my so beloved nephews: Igna, Nahu and Agu, for their never-ending sweet love. And especially thanks to my parents Mirtha y Carlos. Thanks for guiding and teaching me, for giving me the chance to study and continue studying… and for giving me so much encouragement throughout my life. All these years away from home have not been easy, however they have always been close to me, and the achievement of this work is also their success.

Thanks to everyone that gave me his and her support and helped me enriches my professional and scientific career during these years.

This Ph.D. project was founded by a pre-doctoral research grant for the recruitment of new research personnel AGAUR-FI No. IUE/2644/2010 from October 2011 to September 2014, and a pre-doctoral grant for research stays abroad AGAUR-BE01053. I would like to thanks Agència de Gestió d'Ajuts Universitaris i de Recerca (AGAUR) for the financial support. I also acknowledge to Institut Flumen which has also economically supported this thesis work.

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Notation

Parameters

	variable	units
A	Area, wetted area	m^2
$A_{[ha]}$	area	ha
$A_{a\ sub\text{-}c}$	artificial sub-catchment area	m^2
A_b	bed cross section	m^2
A_{gr}	value of F_{gr} at threshold of movement	
A_s	sediment cross sectional area	m^2
$A_{s\text{-}e}$	sediment deposit superficial area	m^2
A_w	water cross sectional area	m^2
b	bed strength variation profile coefficient	-
B	sediment surface width	m
c	wash-off exponent	-
C'	Chezy coefficient	
$C_{SS,m}$	suspended sediment concentration measured	$mg\ l^{-1}$ $g\ l^{-1}$
$C_{SS,s}$	suspended sediment concentration simulated	$mg\ l^{-1}$
C_{SSc}	suspended sediment concentration corrected	$mg\ l^{-1}$
C_v	volumetric sediment concentration	$m^3\ m^{-3}$
c_w	weight correction factor	-
d	cumulative depth of erosion	m
D	pipe diameter	m
D^*	dimensionless grain size	-
d'	upper layer depth	m
d''	superficial layer depth	m
d_{10}, d_{90}	particle diameter (percentile 10 and 90)	m
d_{50}	particle diameter (percentile 50)	m , mm
d_e	eroded sediment depth	m
D_{gr}	dimensionless particle size parameter	-
D_m	hydraulic mean depth	m
d_{min} , d_{max}	particle diameter minimum, maximum	mm
d_s	sediment mean particle size or representative particle size	m
e	quadratic error	
E	erosion rate	$g\ m^{-2}\ s^{-1}$

	variable	units
E_c , E_m	erosion rate calculated / measured	$g\ m^{-2}\ s^{-1}$
F_d	Froude number	-
F_{gr}	dimensionless sediment mobility parameter	-
F_s	effective mobility parameter	-
f_{sb}	friction factor	
g	gravity acceleration constant ($g = 9.81\ m^2/s$)	$m^2\ s^{-1}$
G_{gr}	dimensionless transport rate parameter	-
h	water level	m
h_s	sediment height	m
i	rainfall intensity	$mm\ h^{-1}$
J	slope of energy	-
k_e	wash-off coefficient	mm-1
L	total length of a pipe	m
M	transport parameter (surface erosion rate when $\tau b = 2\ \tau c$)	$kg\ s^{-1}$
M_a	accumulated mass of pollutants over the surface	kg
m_e	mass of sediment eroded	kg
m_s	mass of sediment sampled	g
n_b	Manning's roughness coefficient for sediment bed	-
n_p	Manning's roughness coefficient for the pipe	-
n_w	Manning's roughness coefficient for the pipe walls	-
p	porosity of the sediment deposit	-
P_b	bed wetted perimeter	m
PE	percent peak error	%
p_s	percentage of cohesive matter parameter	%
P_w	wetted perimeter	m
q	average erosion rate	$g\ m^{-2}\ s^{-1}$
Q	water flow rate	$m^3\ s^{-1}$
q_b	volumetric bed load transport rate per unit width	$m^3\ s^{-1}\ m^{-1}$
q_b*	dimensionless solid flow rate	-
q_r	per capita wastewater rate flow	$m^3 cap^{-1} d^{-1}$
QWW	wastewater flow rate	$m^3\ s^{-1}$
r	pipe radius	m

	variable	units
Re	Reynolds' number	-
Re^*	Reynolds' number for the particle	-
R_h	hydraulic radius	m
Rh_b	hydraulic radius (sediment bed)	-
Rh_w	hydraulic radius (pipe walls)	-
s	specific gravity or relative sediment density	-
S_0	slope of the pipe	m/m
S_b	slope of the sediment layer	m/m
SD	standard deviation	-
SSE	sum of squared errors	
t	time	s , day
T	transport dimensionless parameter van Rijn	-
TS	daily total solid load	kg d^{-1}
u^*	bed shear velocity	m s^{-1}
$u^{*'}$	effective shear stress velocity	m s^{-1}
u^*_{cr}	critical bed shear velocity	m s^{-1}
v	average flow velocity	m s^{-1}
V , V_w	water volume	m^3
VE	percent volume error	%
v_m	sample volume	m^3
$V_{m,i}$ $V_{s,i}$	measured simulated volume	m^3
V_s	sample volume	
w_{50}	average settling velocity	m h^{-1}
W_b	sediment bed width	m
W_{max}	maximum sediment bed width	m
y	water depth	m
Z	percentage of suspended solids deposited along a pipe	%
μ	kinematic density	kg m^{-1} s^{-1}
Δm_s	error in mass sampling	g
Δt	temporal step	s
Δv_m	error in volume sampling	g
η	transport parameter (May relationship)	-
θ	mobility parameter	-
θ_{cr}	critical mobility parameter	-
κ	von karman constant ($\kappa \sim 0.4$)	-
λ	Darcy-Weisbach friction factor	-
λb	roughness sediment bed	-
λw	roughness of the pipe walls	-
ν	kinematic viscosity	m2 s-1
ρb	bulk density (or dry density)	kg m-3
ρm	density of sediment – water mixture	kg m-3

	variable	Units
ρ_s	density of sediments	kg m^{-3}
ρ_w	density of water ($\rho w = 1000$ kg/m^3 at 4ºC)	kg m^{-3}
τ_0	average bed-shear stress	N m^{-2}
τ_{0cr}	critical bed-shear stress	N m^{-2}
τ_b	applied bed shear stress	N m^{-2}
τ_c	critical bed-shear stress	N m^{-2}
τ_{cs}	surface layer critical shear stress	N m^{-2}
τ_{cu}	upper layer critical shear stress	N m^{-2}
τ_{DW}	dry-weather applied shear stress	N m^{-2}
τ_{s0}	initial superficial layer bed shear stress	N m^{-2}
ω	particle settling velocity	m s^{-1}
Φ	repose angle	rad

Pollutant parameters

BOD_5	biochemical oxygen demand (5-days)
Cd	cadmium
COD	chemical oxygen demand
Cu	copper
DO	dissolved oxygen
$FOGs$	fat, oil and greases
FS	fixed solids
H_2S	sulphide gas
NH^{+4}	ammonium
OM	organic matter
$PAHs$	polycyclic aromatic hydrocarbons
Pb	lead
$PCBs$	polychlorinated biphenyls
SS	suspended solids
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TSS	total suspended solids
VS	volatile solids
Zn	zinc

Nomenclature

A number of key terms are used throughout this document and are defined below:

Abbreviations

BMPs	Best management practices
CAD	comupeter aider design
CDCB	Consorci per a la Defensa de la Conca del riu Besòs
CIRIA	Construction Industry Research and Information Association from UK
CSO , CSOs	Combined Sewer Overflow / Overflows
DUB	Drenatges Urbans del Besòs
DWF	Dry weather flow
EMC	Even Mean Concentration
EPA	US Environmental Protection Agency
EXP	exponential function
F_D, F_L, F_C	drag, lift and cohesive forces
F_w	submerged weight of the grain
GPRS	General packet radio service
ICC	Institut Cartogràfic i Geològic de Catalunya
MPM	Meyer and Peter, and Müller method
NBS	Neaar-bed solids
NURP	US Nationwide Urban Runoff Program
OUR	oxygen uptake rate
POW	power function
SFGL	surficial fine-grained lamina
SSO , SSOs	separated sewer overflow / overflows
SWMM5	Storm Water Management Model version 5
TGA	thermal gravimetric analysis
WWF	Wet weather flow
WWTP	Wastewater treatment plant

Chapter 1
Introduction

Sediment deposits are an intrinsic problem in sewer system operation, and so are for the receiving water environment where they are often discharged without treatment at the beginning of storms events. The reduction of the pollution that arrives to natural waters originated in the combined or separated sewers systems has become a major concern in the last years in Europe, somehow driven by the need to comply with the European Water Framework Directive (Directive 2000/60/EC).

Under time varying flow conditions during storms in the combined sewer system (the usual type of drainage network in Spain), and with highly-impervious urban catchments, *first-flush* polluting phenomenon is typically observed in our Mediterranean environments. The high variability of the river flow regime in the region, strongly dependent on the seasonal rainfall, results in a quite limited dilution capacity of the natural waters in front of these urban waters discharges. Additionally the reductions in circulating flows in the rivers during some periods, leads to a substantial risk of biochemical degradation caused by the high concentrations of sediments and nutrients that can arrive through combined sewer overflows (CSOs).

Sewer solids consist of organic and inorganic material. Although, it is also known that in highly impervious densely populated urban areas, which is the pattern of many cities in Spain (and in Europe), the availability of sources that can provide coarse inorganic particles to the sewer system are quite few, if not inexistent. With this urban pattern, the wastewaters might become almost exclusively the only source of solids. Therefore, solids will have mainly an organic nature.

Throughout the research conducted in the last decade, it was evidenced the significant contribution to the pollution phenomena of the sediments released and re-suspended from in-sewer deposits during storms.

The organic solids released from in-sewer deposits might impact on the receiving waters causing the major detrimental in the water environment mainly because the biological demand and the ammonia contribution.

In the Mediterranean region it is therefore significant to achieve a good adjustment in the prediction of sediment and attached pollutants loads. They can reach natural receiving waters during storms and generate high oxygen demand and ammonia pollution in the receiving waters. A better prediction might allow clear benefits to the environmental management of natural streams.

The focus should be now directed toward the improvements in the prediction of the sediments (with organic content and cohesive-like behaviour) eroded and subsequently transported through the combined sewer systems.

To reach solutions in front to the described problems of urban pollution into receiving natural waters, it is certainly necessary to progress in the knowledge and the better understanding on the variables that affect the organic sediment behaviour and specially their erosion.

1.1 Motivation

Many researches have agreed about what is the main source of pollutants discharged during CSOs. There is a wide consensus that significant contributions come from the sediments and pollutants deposited within the combined sewer systems. Initiatives were taken in the past for analysing the nature and behaviour of the sewer sediments deposits, and even in some countries, the results of the researches were incorporated in design procedures. In Spain there are just a few studies conducted in the area of water quality in sewerage systems, and there are no regulations or directives regarding sewer sediment deposits for the design or operation of these systems. But even in countries where there is a deeper awareness on environmental protection, the quality problem related to the combined sewer system discharges is not yet fully solved.

Hydrodynamic modelling performance arrived the last years to really well prediction capacity. In contrast, the quality modelling that considers the erosion from in sewer deposits has received much less attention and pollutant loads cannot actually be reliably predicted. Limitation in the current knowledge is significant and leads to uncertainties in the results obtained. Sewer quality modules from commercial software packages models require a lot of data for calibration and verification, and availability of water quality data is quite limited. Given the high variability observed in the characteristics of the sediment, local data is needed for calibrating water quality models.

With all the research findings up to date, it is well known that being the deposited sediments the main source of pollutants during CSOs, to lead to a realistic representation, the quality modelling should include their re-suspension and transport.

On the other hand, the cohesive-like nature of the sediments associated to the organic content was identified in several previous researches in the field. Due to their nature, biological transformations might have an effect of the consolidation of the deposits that may affect the sediment bed structure and erodibility potential. Nevertheless, studies on organic solids erodibility have so far been limited, and many of them based on the study of synthetic cohesive-like sediments. Several gaps in the knowledge about cohesive and organic sediment behaviour currently increase the difficulties to predict their erodibility and mobilization. The reasons for the apparent omission in its analysis might be associated with the large number of variables that interact in the biochemical and physical interactions and generate a complex environment to perform studies and analyse results.

Additionally, quality in urban drainage is not well understood by many professionals in the area and water managers. Apparently many sewerage managers in Spain see the sediments deposited in sewers just as a cleaning cost problem or as a reduction of nuisance odour problems, both related to the maintenance of the system. Designers might go a little further and concern about the hydraulic capacity reduction that the sediment deposits can cause. In general it was seen that the organic composition of these sediments and their potential pollution problems in the receiving waters are somehow forgotten (or avoided) to be considered and analysed in the management of the systems. Investments seem to be preferably oriented to the construction of new infrastructures but sometimes with a general lack of information. Data concerning the type of sediment (organic or inorganic), the spatial distribution along the network or the full characterization of the sediment properties, which definitely would reduce uncertainties in the water quality modelling, even for the same new infrastructures built, is generally not considered.

The CSOs discharges of highly organic sediment to the natural receiving waters during storm events should be managed, not just for environmental protection but also for human health reasons.

1.2 Aim of the study

The aim of the conducted research is to develop a methodology able to predict the potential erosion / re-suspension and mobilization of highly-organic sediments previously deposited in combined sewer systems. It is intended to emphasize the need for a better understanding of the process occurring during long dry-periods and for the characterization of the variables involved in the process that might affect the erodibility of the deposited bed.

1.3 Contributions expected and scope

The improvement in the prediction of the organic sediment and attached pollutant loads is required to better manage the pollution episodes related with the CSOs from densely populated urban areas. A better description of the physical and biochemical properties of the organic sediments from combined sewer systems and its behaviour is worth to be considered in water quality models. The more realistic behaviour that could be introduced in a model will allow to represent more appropriately the movement of these organic solids in pipes and predict more accurately the changes in pollutant concentration.

Additionally, the analysis of the erosional behaviour of real organic sediments will enable the verification of the performance of sediment transport theories developed in laboratory scale tests with synthetic sediments.

On this basis, the proposed methodology is intended to be applicable in combined sewer systems in the Mediterranean region for further improvement in the quantification of the pollutant problem in watercourses during CSOs events.

1.4 Thesis structure

The rest of this dissertation is organised as follows:

Chapter 2 presents the state-of-the-art on the current sediment transport methods and software packages, and makes a review on the sewer sediment characteristics, as the basis for this study. The sediment deposition process in combined sewers systems is briefly introduced.

In Chapter 3, the study site is presented. A monitoring station for the collection of water quantity and quality data was installed in the outlet of the studied catchment. The hydraulics and quality aspects in the combined sewer network during storm events and dry-weather periods are identified through a continuous monitoring. The methodology implemented for the collection and analysis of the characteristics of sediment deposited in-pipes is also detailed.

Chapter 4 is related to the laboratory experiments for the identification and quantification of the main variables influencing the erosional resistance of the sediment deposited at the invert of the sewer pipes during dry-weather conditions.

Chapter 5 describes the design and implementation of a simplistic conceptual methodology based on SWMM5 intended to raise a first assessment of the pollutant loads mobilised from in-sewers.

Chapter 6 describes the implementation of a coupled model that integrates the hydraulic information with the erosion and transport of previously deposited highly organic sediments. The coupled methodology is implemented in the study case for the validation of the proposed method.

Chapter 7 ends this dissertation reviewing the work undertaken and summarizing the main conclusions. Finally in this chapter, future work directions are suggested

Chapter 2
Literature review

This chapter discusses about the in-sewer sediment transport state-of-the-art, and about the current knowledge on related topics believed necessary for a comprehensive perspective. This review is made for obtaining the current knowledge as an initial state for the herein research departure.

The significance of the dry-weather sediment deposition in-sewer pipes together with the subsequent sediment release, re-erosion and transport during rainfall has been studied by several researchers in the field. Even, the in-sewer sediment mobilization during time varying flows is recognized as constituting one of the leading causes of the first flush pollution phenomenon at the start of a storm event. Consequently, sediment deposits in-pipes are considered a significant cause of the quality detriment in natural receiving waters nearby urban catchments.

Despite the hydrodynamic aspects of erosion and transport of non-cohesive sediment is overall well understood, the influence of cohesive behaviour and biochemical transformations displayed by highly organic sediments from sewers are still under study. This chapter will review on the up-to-date findings about all aspects that influence on the propensity of cohesive sediments to be eroded, to provide a background for a more suitable application of transport formulations on which the herein dissertation focus.

The review presented in this chapter serves several purposes. Firstly, it was wished to identify the significance of the problems caused by combined sewer overflows into natural water courses focusing on the influence of semiarid Mediterranean climate (Section 2.1, 2.1.1). Secondly it was intended to establish the basis for the transport of sediment particles (Section 0) for what initially is necessary understand the characteristics of the sediments commonly found in combined sewer systems (Section 2.2), which will influence on the erodibility of the deposits. It is also useful reviewing on the knowledge of the deposition inside the pipes of a sewer network prior to a storm event occurs, which is made on Section 0. At Section 2.4.6.5 a brief introduction to commercial software for sewer flow-quality modelling is presented. Finally, Section 2.6 summarises the chapter review.

2.1 Quality problem in receiving waters during wet weather

In order to prevent the surcharging of the drainage system, or the arriving of flows above the capacity of the treatment plant during storm events, diverter devices are incorporated in the network. The Combined Sewer Overflows (CSOs) and Separated Sewer Overflows (SSOs) basically operate limiting the water flow passing towards pipes downstream the overflow structure. The diverted excess water flow is sent, usually untreated, directly into watercourses nearby (commonly termed "natural receiving waters").

Overflows from runoff of urban storm and combined sewer systems are widely recognised as one of the major causes of degradation in the quality of receiving waters (fluvial, marines or lacustrine environments). They contain significant amounts of pollutants, generating great impact in natural waters quality.

Previous research findings conclude that the main source of pollutants discharged from Combined Sewer Overflows (CSOs) is associated to the release of sediments from previously formed in-sewer deposits during dry-weather periods (Ashley and Crabtree, 1992; Ashley *et al.*, 2003, 2004; Chebbo *et al.*, 1995; Ahyerre, Oms, *et al.*, 2001; Gromaire-Mertz *et al.*, 2001; Tait, Chebbo, *et al.*, 2003; Sakrabani *et al.*, 2005; Gasperi *et al.*, 2010, 2012). Chebbo (1992) predicted that around 20% of the mass of pollutants discharged annually from CSOs is originated from the erosion from solids stored in deposits. Verbanck (1990) conclude that the most potentially detrimental effect of CSOs upon watercourses is due to the wash-out of finer organics from the sediment beds inside pipes, conclusion later supported by Ahyerre (2000) establishing the source of eroded pollution at the organic layer at water-bed interface.

Research based on a pollutant mass balance analysis carried out from a field study in Paris (Gromaire-Mertz *et al.*, 1999, 2001) found out between 30-80% of the TSS (total suspended solids), VS (volatile solids), COD (chemical oxygen demand) and BOD_5 (biochemical oxygen demand), originated from in-sewer deposits. These researches also conclude that the release of sediments previously deposited in-pipe mainly provide with TSS (total suspended solids), organic matter, Cu (copper) and PAHs (polycyclic aromatic hydrocarbons), meanwhile Zn (zinc) and heavy metals loads are originated mainly from the wash-off from impervious surfaces during rainfall.

Sedimentation in pipes occurs during decelerating flows linked both to dry-weather flows and when storm flows are receding. Apart of the flow conditions, the formation of sediment deposits in the inlets is associated to the characteristics of the sediments itself, the length of the dry-weather periods, the wastewaters sediment production conveyed, and to the frequency of the maintenance operations. More information about factors that have influence on sedimentation processes can be seen at Section 0

Due to temporal and spatial variations in the climate conditions and on the possible sources of sediments and pollutants, the characterization of the pollutants discharged during overflows from combined sewer systems is a complex problem.

Several studies also documented the detrimental of natural water quality in watercourses near urbanized areas, mainly after a heavy rain event (Deletic, 1998; Skipworth *et al.*, 2000; Lee *et al.*, 2002; Laplace *et al.*, 2003; McIlhatton *et al.*, 2005;

Bach *et al.*, 2010; Tippler *et al.*, 2012). The impacts on the receiving waters are manifested with reduction in dissolved oxygen and light transmission, nutrient enrichment and increment in the oxygen demand that can potentially produce anaerobic conditions. These effects, altogether with raise in toxics often leads to eutrophication of natural waters, besides the aesthetic impact on the environment and the alterations on the aquatic wildlife.

Both, the sedimentation in-pipes and the release and transport during rainfall are strongly dependent on the available sediments and flow conditions in the systems. Therefore, dependent on the population habits, the duration of dry-periods and rainfall events main characteristics. Because the climate conditions for dry-wet periods are different from one geographical area to another, the measures that need to be adopted to reduce the pollution problems caused by overflows from combined systems to preserve the quality in natural water courses should consider the specific particularities of the climate of the region.

Particularly, in the Mediterranean region, smallest watercourses are more sensitive to the untreated waters from CSOs because the spill volume is usually higher than common watercourse circulating flows during the same period of discharges (Karlavičienė *et al.*, 2009). In these conditions, the dilution capacity can be significantly reduced. The recovery of the biological and chemical quality in natural waters downstream a spill outlet is complex. The complexity is even higher when the watercourse has a limited base flow because particularities in the climatic conditions or an intensive use or the water resources (Prat *et al.*, 2000), as commonly happen in the Mediterranean region.

2.1.1 Particularities of the climate in the Mediterranean region in Spain and related problems

As it was mentioned before, and regarding the objectives of this dissertation, it is necessary to take into account the particularities of the Mediterranean climate conditions that have a strong influence on the sedimentation and re-mobilization of pollutants accumulated in the sewer systems.

The data that will be presented along this dissertation was registered in an urban catchment and sewer system located in Granollers (Barcelona), in the south-east of Catalonia, Spain. The urban area selected is crossed by the Congost River, a tributary of the Besòs River.

Total precipitation oscillates around 500-700 mm a year in the area where the catchment under study is situated. Nevertheless, the climate of the Mediterranean region presents a quite irregular distributed rainfall along the year. For instance, in the studied area, 33% of storm events recorded between May 2010 and May 2012 (total events are 123) showed a cumulative precipitation higher than 10 mm, from which 23% occur with an antecedent dry period longer than a week and a maximum of 70 days without rainfall was registered. More detail about the storm events measured along the research work will be presented in Chapter 3.

The Mediterranean irregular rainfall regime results in long dry-weather periods, during which the relatively low dry-weather foul flow combined with a not proper design of the sewer system, allows in-sewer sedimentation and the accumulation of deposits with high organic content. These long dry periods are typically followed by intense precipitation events that erode the in-sewer deposits and as a consequence high concentrations and amounts of pollutants can be released into natural receiving waters through combined sewer overflows (CSO).

Due also to the Mediterranean weather, most of the tributaries of the Congost River dry up during summer (Prat *et al.*, 2000). Congost River mean monthly flow in the last 10 years is 0.26 m^3/s (*Catalan Water Agency*, from the flow measurements in fluvial systems section at http://aca-web.gencat.cat, for the period from July 2004 to July-2014) see Figure 2-1. The flow regime is directly influenced by the irregular rainfall regime. The water fluctuation can reach significantly low flows. For instance, in the same mentioned period from 2004 to 2014 it was registered a minimum flow of 0.00208 m^3/s (in August 2009), and Prat *et al.* (2000) in their research referred to a minimum flow of 0.0014 m^3/s measured in the river in July 1996.

Hence, this additional circumstance of high variability of the flow regime of the rivers in the region, strongly dependent on the seasonal rainfall, turns in a quite limited dilution capacity of the natural waters in front of urban waters discharges.

Significant ecological impact can occur as consequence of the release of the sediments and pollutants built-up during the mentioned prolonged dry periods. Having this in mind, it is therefore significant in this region to achieve a good adjustment in the prediction of pollutants loads that can reach natural receiving waters through combined sewer overflows (CSOs) in the course of rainfall events.

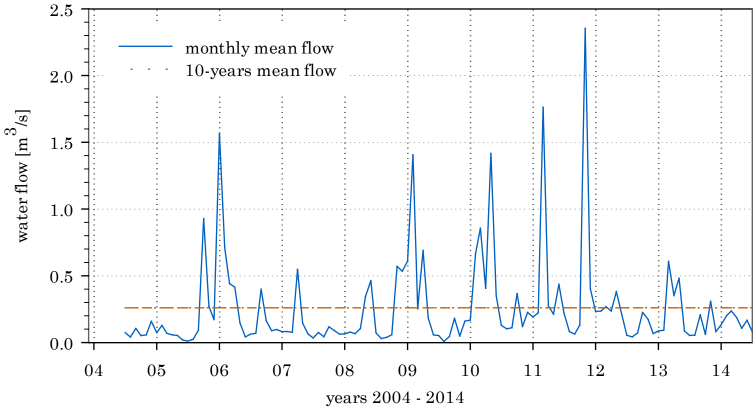


Figure 2-1 Average monthly flow in the last 10 years in the Congost River. (Source: Catalan Water Agency (ACA))

2.1.2 First flush

Strong pollutants first flushes are frequently observed in small impervious catchments (Bertrand-Krajewski *et al.*, 1993; Lee *et al.*, 2002; Kang *et al.*, 2006). Nevertheless the actual existence of the first flush phenomenon was discussed by many researchers, it is generally agreed that the initial stage of storm runoff through the combined sewer network usually convey higher pollutant concentration rates than the later period

(Saul *et al.*, 1989; Bertrand-Krajewski *et al.*, 1998; Deletic, 1998; Skipworth *et al.*, 2000; Lee *et al.*, 2002).

This effect is termed as first flush pollutant phenomenon. Its occurrence might be dependent, aside from the size of the catchment, on specific rainfall patterns of duration and intensity (Kang *et al.*, 2006), on the duration of the dry-weather period, as well as on the pollutant characteristics itself.

There has been a great number of research works aimed to define when the first flush occurs and its magnitude. Geiger (1987) defined the first flush as occurring at the first portion of the runoff volume based on the analysis of the dimensionless curves of cumulative pollutant mass versus cumulative discharged volume. Geiger considered that exists a significant first flush when the slope of this normalized cumulative mass emission plotted against normalized cumulative volume is greater than 45º. This mean that the first portion of the runoff volume related to the storm event, accounts the major pollutant load. Later, Bertrand-Krajewski et al. (1998) quantify the runoff volume based on *in situ* measurements. In their research conclude that there is a significant first flush when during a storm, experiencing accumulated only the 30% of the circulating volume, the pollutant mass discharged is at least the 80%, which is termed 30/80 first flush.

The increment of the bed shear stress that occurs during the runoff inside the system may cause the release and re-entrained of sewer sediment deposits into the water flow. The re-suspension of sediment previously deposited in pipes might be significant and was reported as the main source of pollutant loads during the first flush pollutant phenomenon. For instance, Saul *et al.* (1989) reported up to 90% of the sediments discharged during first flush released from the in-sewer deposits.

In Mediterranean catchments, under time varying flow conditions first-flush polluting phenomenon is typically observed (Deletic, 1998; Obermann et al., 2009). In this region, the singular weather conditions described above in previous section, characterized by long dry-weather period followed by storm events with high intensities has a strong influence on the phenomenon occurrence. Together with the reduction in circulating flows of the rivers during some periods, there is a substantial risk of biochemical degradation caused by the high concentrations of sediments and nutrients that can arrive to these natural water bodies through CSOs.

First flush evidence on the field study site is later exposed in Section 3.2.4

2.1.3 Design and management of sewerage

The problem of designing and operating urban sewer systems was thought for the early period, as a problem of transporting water flows. Initial sewer design does not consider the influence that the particles moving in these waters can have on the same network system or in the environment indeed. Even today, some urban drainage master plans intended to prevent floods are mostly developed without considering quality issues in drainage.

In the Mediterranean region in Spain, most of the sewer systems are combined and are still nowadays designed follow standard guidelines that do not consider for instance the sediment properties or behaviour (density and particle size, cohesive properties, etc.) to avoid sedimentation. Design criteria for defining cross section and slope of the conduits in most cases just consider the stormwater flows. Often, self-cleaning network design does not consider the assessment of the threshold of motion of the sediment as one of the basic parameters that is necessary to know to analyse the re-suspension of sediments.

Nevertheless, despite most of the operating managers are still more concerned about convey reduction and hydraulic problems caused by the sedimentation or cleaning techniques, in the last years management plans are more concerned from a quality point of view, on the influence of the pollutants conveyance and overflow effects over receiving waters.

Encouraged by the accomplishment of the Water Framework Directive requirements regarding chemical and ecological status of water bodies that need to be achieve by 2015, governmental agencies are now concerned in the management of solids within a sewer systems as integrated models including river basin management, wastewater treatment plants and receiving water bodies. There is also a general agreement to consider the management of pollutants in the design and operation of the sewer and drainage systems.

An integrated modelling will require the accurate knowledge of the pollutants that will arrive to the receiving natural waters during CSOs. Therefore in an attempt to better predict the evolution of the sediments and attached pollutants discharged, it is necessary to improve the knowledge on the sediment behaviour and the mechanisms that will have influence on the release and re-suspension during a rain event.

2.2 Sewer sediments overview

Despite the widely use of the terms “sediments” or “particles” when solids transport issues are addressed, these words are probably not the most appropriate terms to name the wide range of particulate matter that can be mobilized in sewerage and urban drainage systems. Nevertheless, as it was declared some time ago in the *International workshop of origin, occurrence and behaviour of sediments in sewer systems* (Verbanck *et al.*, 1994), until the adoption of a more appropriated word, both “sediment” and “particles”, will continue being using to refer to the solids in sewers.

Sediment particles within a sewer system can vary widely in character and composition and show an agglomerated structure, as it has a variety of sources. Some are essentially inorganic and others have a significant organic fraction; some display a non-cohesive behaviour and therefore, readily transported along sewers, whilst others are cohesive and less amenable to movement by hydraulic forces. A considerable spatial variation in the inputs of sewer sediments (even in the same catchment and along the network), and time dependent sources (Ashley and Crabtree, 1992) leads to difficulties when assess properties addressed to characterize the particles.

The erodibility (and previous deposition) of sediments will depend on the internal forces and on forces between particles (gravity, friction, cohesion and adhesion) and these, on the sediment properties itself. Addressing the hydrodynamic aspects of sediment erosion and transport, the knowledge of properties and behaviour of these sediments are relevant.

While the non-cohesive particles behaviour against erosion is currently well understood, the cohesive way of behaving is more difficult to assess and is not so extensively studied.

In the present section emphasis will be made on the sediment properties which are considered to have influence on the erodibility of sediments from sewers. Physical characteristics, biochemical properties and biological aspects are the main issues that influence on threshold of motion over cohesive sediment deposits, and affect their erodibility as Grabowski *et al.* (2011) summarized.

2.2.1 Sewer sediment sources

Sewer sediments are a complex mixture of inorganic and organic matter displaying agglomerated structure when form deposits.

Because it exists a variety of sources for sediment that arrives to a sewer system, sediments deposits in-sewer are highly nonhomogeneous (De Sutter et al., 2003) and enclose a wide range of particles with various size, forms, chemical composition, and exhibiting various physical and biological properties.

Ashley *et al.* (2004) detail the following sources for urban sewer sediments (Figure 2-2):

- atmosphere, contributing with the finest fraction of sediment (dust and aerosols);

- impervious surfaces in the catchment, where solids are accumulated during dry-weather conditions;
- domestic wastewaters, contributing with the highest proportion of organic solids;
- commercial and industrial effluent;
- areas under construction;
- other sources, like infiltration from surrounded soils or degradation of the pipe material itself

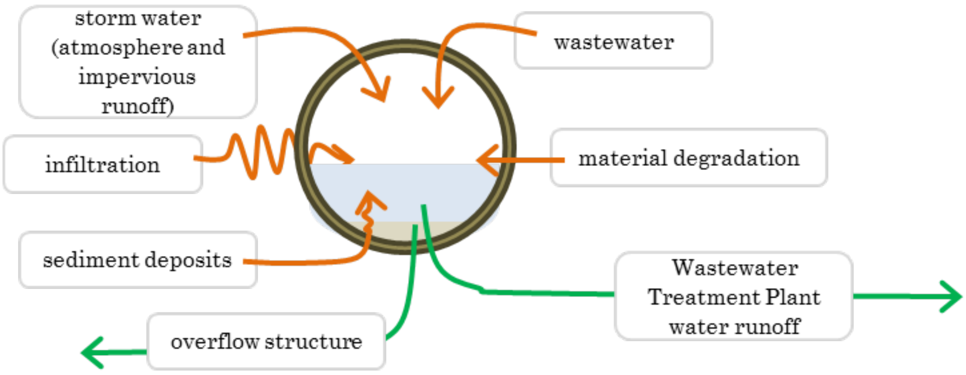


Figure 2-2 Inputs and outputs of sediments in a combined sewer system.

Various sources give a wide range of variation in composition around the urban catchments although; the characteristics of the sediments are mainly conditioned by the characteristics of the wastewater sediments. The wastewater sediment, also highly variable, are the main contributors to the deposits formation in-sewers (Arthur, 1996).

2.2.1.1 Solid particles accumulated in the surfaces of the catchment

The impervious areas that contribute with pollutants loads to the water runoff during rainfall events can be summarized in streets, highways and paved areas, parkings, and roofs. Solids accumulated in dry-time on these surfaces are originated, for instance, from the dust deposition, the erosion of the concrete and asphalt surfaces itself, the wear of the tires, the physical and chemical degradation of roofs and terraces, the accumulation of atmospheric solids, the build-up of tree leaves, animal wastes and other municipal wastes (like cigarette butts, etc.).

In agreement with several research conclusions (Ashley and Crabtree, 1992; Ashley et al., 2004; Gromaire-Mertz *et al.*, 2001; Puertas *et al.*, 2008), the sediments released from these surfaces are mainly inorganic. The main pollutants associated with these solids are heavy metals, aromatic hydrocarbons and mineral oils whose build-up rate depends on the traffic density, catchment characteristics and cleaning techniques. Nevertheless it is basically inorganic matter; an organic fraction can be present.

Additionally, pervious areas like green surfaces and those areas under construction, might contribute to the runoff pollutants loads with sediment particles originated in the erosion of the ground. Although areas under construction might produce a significant but localised contribution in the amount of solids of the runoff water during rainfall (increments in the TSS up to 300% according findings detail by Ashley *et al.* (2004)), their contribution is occasional.

Previous research carried out in Europe about sewer sediment characteristics are summarised in Table 2-3 and Table 2-4 presented later. Despite the variability in composition and characteristics of the sediments, it can be observed that the sediments wash-off from the surfaces of the catchments have a particle size between 20 µm and 1 mm, with a characteristic diameter d_{50} = 300-400 µm. Regarding density, it can be noticed similarity with sand particles, with a maximum specific density of about 2.6.

2.2.1.2 Solid particles from wastewaters

The solid particles contribution from wastewater can be initially distinguished between those ones originated from domestic wastewaters (residential source) and those originated in industrial and commercial areas.

Sediments from domestic wastewaters are themselves classified as coarse solids and sanitary solids. Sanitary solids are mainly organic in nature, constituted by fine particles originated in the physical and chemical-biological degradation of the domestic waste. These sediments are transported mostly in suspension or as a bed load.

The composition of sanitary solids can be highly variable, spatially and temporarily, because wastewater flow and concentration fluctuations, subject on cultural habits and activity of the population (Ashley and Crabtree, 1992). Even though the variability, the organic fraction is relevant (65 and 85 % of the total solids).

Composed mainly by fine particles (around a 25% of the sediments with a size less than 125 µm), with characteristic diameter in the range of $30 < d_{50} < 38$ µm. Regarding specific density, sanitary solids are usually lighter than those contributed from the impervious surfaces, displaying values lesser than 1.6. Consequently, the particles show slow settling velocity in the range of 1.4 to 1.8 m/h (Verbanck et al., 1994; Gromaire-Mertz *et al.*, 1999; Ashley *et al.*, 2004; Puertas *et al.*, 2008).

Big solids like paper, sanitary towels and other miscellaneous sewerage litter are considered coarse solids. These solids are transported as floating material or as bed-load (Verbanck *et al.*, 1994; Ashley *et al.*, 2004). The coarse solids can cause blockage problems in the network, and also significant “aesthetic” pollution problems when are discharged through outfalls of the combined sewer system into the receiving natural waters.

Sediment particles originated from commercial and industrial discharges are difficult to characterize due it high variable composition depending on the commercial/industrial activity.

2.2.1.3 Solid particles from infiltration and sewer degradation

Groundwater infiltration along the length of sewer pipes might also occur. The generated water streams through displaced joints and fissures on the conduits material can allow the entrance of fine solids from the surrounded soil. The fluctuations of the groundwater level might cause the increment of the amount of solids that can reach water inside the conduits. The characteristics of the sediments will depend therefore on the nature of the surrounded soil.

Despite the fine sediment conveyance by infiltration can be locally relevant; it does not constitute a significant problem in the majority of sewer systems.

The degradation of the material of the sewer conduits itself can be established as another source of solid particles. The sediment from the material decay is mainly inorganic in composition and can be considered as fine solids. The decay of the material can be caused by chemical effects originated in the anaerobic conditions inside some conduits, and because of the generation of sulphide gas (H_2S). Concrete decay may also take place due to other toxic compounds and high water temperatures in areas where industrial discharges occur.

Physical degradation in conduits material can also occur linked to structural problems (e.g. sections with high water velocity) or failures of the material.

2.2.2 Sewer sediment classification

For the purpose of the sediment transport analysis and the consideration on the hydraulics conditions inside sewer pipes, several authors proposed various classifications to identify the sediment types. The usual classifications are based on the particles physical characteristics, origin and ways of transport in the water mass.

One of the widely used classification system for the sediment deposited in-pipes was developed by Crabtree (1989), based on descriptive observations of the sediment appearance made over sediments collected from in-pipes deposits in UK sewer networks. Five categories are suggested. Each category shows distinctive characteristics in terms of appearance, composition, nature and polluting potential. A typical location of each sediment deposit category proposed by Crabtree (1989) is shown in Figure 2-3 and are listed in The aim of the conducted research is to develop a methodology able to predict the potential erosion / re-suspension and mobilization of highly-organic sediments previously deposited in combined sewer systems. It is intended to emphasize the need for a better understanding of the process occurring during long dry-periods and for the characterization of the variables involved in the process that might affect the erodibility of the deposited bed.

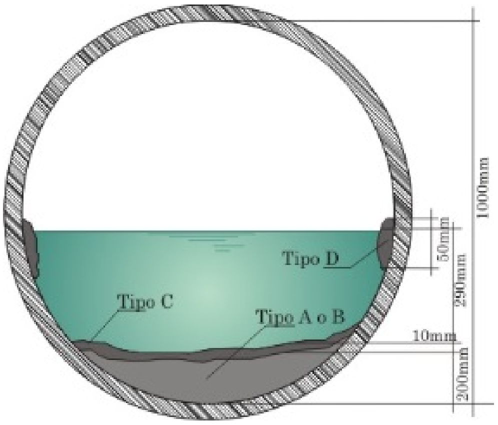


Figure 2-3 Typical location of sediments in a sewer pipe cross section. Classification of sediment deposits proposed by Crabtree (1989).

The Type A sediments are coarse and granular material. Sediment of the Type A displayed non-cohesive behaviour and therefore, readily transported along sewers. This type of sediments is the most significant in terms of mass, so that as consequence, the Type A sediment is linked with problems of reduction of the water conveyance in pipes (Crabtree, 1989; De Sutter *et al.*, 2003). Nevertheless, since it is mostly formed by inorganic materials (Ahyerre *et al.*, 2000)., Type A is the less significant regarding pollution impact once is released and discharged into natural water streams.

The term granular, is used to describe a material composited by discrete non-cohesive particles, regardless of particles size.

Table 2-1: Classification of sediment deposited in sewer propossed by Crabtree. Aapted from (Crabtree, 1989)

sediment type	description and location	percentage of particle size			Density (kg/m^3) mean	O.M. content (%) mean	COD (g of pollutant/kg of dry sediment) mean
		silt and clay (<0.063 mm)	sand (0.063-2 mm)	gravel (2.0-50 mm)			
A	coarse, loose, granular, predominantly mineral material found in the inverts of pipes	6	61	33	1720	7	23
B	as A but concreted by addition of fat, bitumen, cement, etc. into a solid mass						
C	mobile, fine grained deposits found in slack flow zones, either in isolation or above Type A material	45	55	0	1170	50	76
D	organic pipe wall slimes and zoogloeal biofilms around the mean flow level	32	62	6	1210	61	193
E	fine-grained mineral and organic deposits found in SSO storage tanks	22	69	9	1460	1.5	48

Type C sediment (usually termed “organic layer”) and the biofilm (Type D) in contrast, have the higher potential of pollution during storm periods because are constituted mostly by organic matter (Ahyerre *et al.*, 2000). Their cohesive behaviour converts this type of sediment in less amenable to movement by hydraulic forces.

The significant organic matter fraction with cohesive characteristics found in sediment deposits analysed in the herein study, allows to suggest the presence of a relevant layer of Type C sediments. This organic layer is believed that represents the main sediment composition in deposits found in combined sewer systems in the Mediterranean region, due to similarities in catchment characteristics, habits of the population and length of dry-weather time for accumulation.

2.2.3 Sediment properties affecting erodibility

Sediment threshold of motion and transport process depend on the properties of the sediment itself, on the characteristics of the sediment bed and on the hydraulic of the circulating flow.

Sediment transport formulations largely focus on the mobilization of non-cohesive sediment. Classical transport equations (Section 2.4.4) used even in urban drainage modelling, were developed for river sediments that display a non-cohesive behaviour. The application of these general transport formulations requires the knowledge of at least three sediment physical characteristics that will condition their mobilization in the water flow. The three main characteristics usually needed are: the characteristic size and sediment size distribution, the specific density and the settling velocity.

As it has been explaining throughout this chapter, sewer sediments exhibit cohesive properties and that influences the way in which these are mobilized. The sediments from combined sewer systems display complex chemical and biological composition and distinctive physical characteristics when comparing against purely non-cohesive sediments from rivers. The application of the general transport formulations without considering the complex composition and interaction between particles that occurs with cohesive sediment, can be inadequate for it application in urban sewer and drainage systems (Ashley *et al.*, 2003). Processes occurring within sewer systems depend on the properties of the sediment and deposited bed, and on the dynamic of the water flows. Both the hydraulic conditions and the properties of sediments are displayed with highly spatial and temporal variation, which also influence on the release and transport of particles.

The following sub-sections (2.2.4 and 2.2.5) give an overview on the relevant properties useful to characterize cohesive-like sediments. The techniques for the assessment of the sediment properties values, as well as sampling procedures will be outlined in more detail in the following chapter (Chapter 3. Section 3.3), where the specific values assessed for the sediment collected during the present research study are reported.

The high variability over time and space, and the difficulties in sampling besides the complexity in assessing the contribution of sediments from the various sources, make the characterization of these sediments from combined sewer systems a complex task.

2.2.4 Physical characteristics

The wide diversity of sources and origins in combined sewerage have a relevant influence on the properties of the sediments accumulated within the system. The physical properties were the most comprehensively studied.

The physical characteristics of the sediments are highly variable and dependent on the nature of the catchment, the population habits and the sewer system type and local characteristics (Verbanck *et al.*, 1990; Ashley and Crabtree, 1992; Chebbo, 1992; Ristenpart, 1995; Gromaire-Mertz *et al.*, 1999). Besides, it is also necessary to consider the cleaning techniques on the surfaces, the local sewer operating practices for maintenance, and the length of the dry period that altogether will influence on the sediments available to enter and to be accumulated in deposits in the system. As well there exist time dependent processes that will lead to changes along the sediments bed influencing into the physical properties of the deposited sediments (Ristenpart, 1995)

When considering a potential for re-suspension from in-sewer deposits, variations in the physical properties values are relevant. The most concerned properties influencing on the erodibility and transport are the particle size and distribution, the density, water content (De Sutter *et al.*, 2003; Grabowski *et al.*, 2011).

2.2.4.1 Particle size distribution

The particle size is commonly used parameter involved in the assessment of deposition and transport. There is a common link between the sediment size and the minimum water velocity needed for settling, or moving because the effect of flushing flows.

The size of sediment particles is usually considered through a "characteristic particle diameter" or "mean particle size" (d_s) in the sediment transport equations, and is the diameter expressed frequently in millimetre (mm) or microns (µm). For cohesive sediments d_s represent the axe of an idealized particle thought as an ellipsoid.

Aside from the mean particle size, it is convenient to better describe the structure of a sediment deposit, considering the distribution of the particle sizes by ranges, especially when dealing with cohesive-like sediment. For this case, the relative proportion of each size fraction might significant affect the sediment bed erodibility (Grabowski *et al.*, 2011).

The sediment particle distribution by size can be found through a sieving analysis of the material. Once the distribution by size is obtained, it can be represented in a frequency curve or in a distribution curve, from where the standard parameters d_{10}, d_{50} and d_{90} can be obtained (percentiles 10, 50 and 90 respectively).

Since the '90s several researchers worked in the assessment of a size distribution of the sewer sediments. Summarizing the obtained results, the sewer particle diameters vary from colloidal particles with $d_s < 1$ µm (in the range of clays) until coarse solids with $d_s > 4750$ µm (in the range of gravel).

Comparing the results obtained in several research works, it can be observed a wide variability in the size distribution from catchment to catchment. The wide variation range is associated with the diversity of sources of the sediments. It can be found in-sewer deposits formed mainly by fine cohesive particles, and on the other side, even in the same network, it can be observed granular particles in the range of sand or gravel (Arthur, 1996; Ashley *et al.*, 2004; Bertrand-Krajewski, 2006; Piro *et al.*, 2009; Almedeij *et al.*, 2010). Table 2-2 shows values presented by Chebbo (1992) for particle sizes of suspended solids mobilized during rain events.

Sediment particles size distribution also varies along the sewer network, and temporally. The high spatial and temporal variability is directly dependent on the water velocity. Generally, pipes found at the upstream part of the network system will show the coarser material in the bed deposits meanwhile the sediments become finer towards the outlet of the system (Ashley *et al.*, 2004; Bertrand-Krajewski, 2006) (see Figure 2-4). There can also be a variation in the sediment particle distribution with time.

Despite the variation in particle size over the network, has been also found that the size distribution may be also dependent on both, the method for measure the gravimetric size, and the cross section point within the conduit from where the sediment is sampled. In that regard Bertrand-Krajewski *et al.* (1996) show that the characteristic particle size parameters d_{10}, d_{50} and d_{90} decrease to both sides of the central axis of the pipe.

Furthermore, it will be seen later in section 2.2.6.1, that sediment size distribution will also be influenced by the cohesive nature of the sediments. Sediments from combined sewers are susceptible to flocculate and agglomerate; then, an apparent sediment floc diameter may become relevant when assessing sediment transport and the typical d_{50} use in most of the transport formulas may not be an appropriate parameter.

Although it is not possible to establish a typical particle size or representative percentile diameter, particles mainly involved in in-sewer re-suspension and transport processes are reported in the literature as being in a range of average diameter between 0.01 and 2 mm (diameters comparable to clay and silt), with a typical d_{50} = 0.04 mm (40 μm) (Chebbo, 1992).

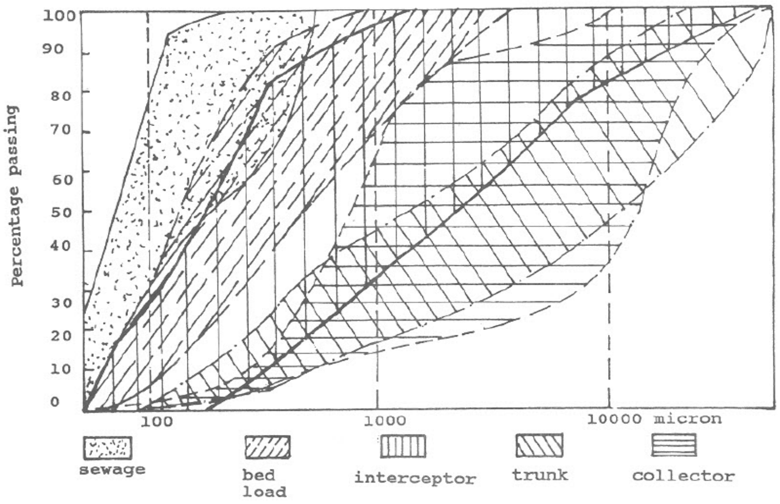


Figure 2-4 Particle size distribution range for various location in the sewer system (after (Ashley and Crabtree, 1992).

Table 2-2: Particle sizes for suspended solids mobilized during rain events (reproduced from Chebbo, 1992)

	sewer type	d_{10}[μm]	d_{50}[μm]	d_{90}[μm]	% < *100*[μm]
combined sewer	average	6.78	34.1	331	75
	standard deviation (SD)	3.25	6.4	112	5.5
storm water	average	7.4	32.1	617	81
	standard deviation (SD)	1.1	3.5	442	3.3

2.2.4.2 Density

Sediment density (ρ_s) is another sediment property that will be strongly influenced by the heterogeneity of sediments in beds caused by the wide diversity of sources.

In general, sediment deposits characterized by relevant organic composition have lowest average density than the sediment beds with highest inorganic content. Even the average density in sediment deposits with high organic composition could reach to values less than 1000 kg/m^3.

In a literature review it is noteworthy the great variation in density values found in the several sewer systems studied. However there is also a trend regarding the position in the system from where the sediment deposits were sampled. In this regards, greatest densities were found in sediment deposits upstream of the system (remember the mentioned highest average particle size and it will be seen below about the highest inorganic content of the sediments deposits, characteristics directly linked with the density). For instance, in the framework of sewer sediments studies carried out in France by Lin (1993) referenced by Arthur (1996), sediment deposit density was found to vary from 1500 kg/m^3 (downstream of the network), to 2655 kg/m^3 upstream. In interceptors in Dundee, Scotland (Arthur, 1996), densities in header pipes deposits display an average value of about 1800 kg/m^3, significantly lower than the one presented by Lin, with an average density of 1580 kg/m^3. Similar values were previously found in Germany with a mean value of 1560 kg/m^3 (maximum 1820, minimum 1350) in deposits from interceptors (Ristenpart, 1995). Ristenpart (1995) also conclude that there are an increasing density variation over time because in-sewer biochemical processes. In studies conducted in Brussels, the average value found is also in the same order of magnitude, with a value of 1510 kg/m^3.

During experimentation in real sewer in France (Ahyerre *et al.*, 2000), it was assessed an average density of about 1309 kg/m^3 for particles deposited during a previous dry-weather flows, despite was also conclude that the sediments eroded during flushing tests become denser (up to 1538 kg/m^3) at each flow increment, which may be related with the more inorganic composition in deeper sediment layers.

The *specific gravity* or *relative sediment density* (s) is another parameter that can be found in sediment transport formulations. In fluid mechanics is defined like a dimensionless parameter calculated as the relation between the sediment density, and the density of clean water measured at 4 ºC (ρ_w).

$$s = {}^{\rho_s}/_{\rho_w} \qquad \textit{2-1}$$

In the study of solids with major organic content, the average value of the specific gravity is in the range of 1.01 and 1.5 found by Butler (2001) and Delleur (2001).

On the other hand, the parameter termed as *bulk density* or *dry density* (ρ_b) that can be also found in the definition of some sediment transport formulations, is the dried mass per unit volume of a sediment bed. This parameter considers therefore the porosity of the deposit and has units of mass/volume.

$$\rho_b = (1-p)\rho_s \qquad \textit{2-2}$$

2.2.4.3 Porosity

An important consideration in sediment transport from previous deposited sediments is the relative volume displayed by particles when remain agglomerated in the deposit structure. This relative volume can be quantified using a parameter named porosity (p). This means the volume of the pore-space within the unit volume of bed.

Porosity is usually independent on the sediment particle size but the heterogeneity in the distribution of sediment size in a deposit has a significant influence because fine grains can fill voids left by the larger grains, decreasing the values attained by the porosity. So then, porosity might be related with particle size distribution.

Studies on real sewer sediments conducted in UK and in the Netherlands (Schellart *et al.*, 2005), found average value of porosity around 0.22 (London), and 0.30 (Loenen). Meanwhile porosity of non-cohesive sediments in a bed is often assumed to around 0.4 (dimensionless) porosity in cohesive beds is lower and may vary widely. In Section 2.2.5.2 values of porosity for deposits containing high amount of fat and greases is reported in the rage of 0.10 to 0.24.

2.2.4.4 Water content or moisture content

This last reported physical parameter, together with the bulk density and porosity (for submerged sediment), provides an idea of the proportion between solids and liquid in the sediment deposit.

Achievements from laboratory and field studies with estuarine and riverine muds show that water content is inversely correlated with erodibility. This mean a higher consolidation degree in cohesive sediments when display a lower water content (Grabowski *et al.*, 2011).

2.2.4.5 Reported sediment parameter values

The report 141 from CIRIA (Construction Industry Research and Information Association from UK) (Ackers *et al.*, 1996), provide with typical values of sediments properties by source for the characterization of transport in sewer systems, which are shown in Table 2-3). Table 2-4 summarize values properties in sewer sediments reported in several reviewed literature.

2.2.5 Sewer sediment biochemical properties

The sediment bed stability to erosion or erosion resistance is directly linked with the critical shear stress. By applying experimental based formulations, the critical shear stress value can be addressed by characterising the sediment properties. It was mentioned before that especially for non-cohesive sediments; most formulations are based on the physical parameters only. The influence of biological properties on sewer sediment stability has not been longer investigated, however it is known that biological factors display a weighty impact on the sediment bed resistance to erosion (Sakrabani *et al.*, 2005; Hitved-Jacobsenv *et al.*, 2013).

Despite physical parameters affect the consolidation of sediment deposits, changes in the cohesive sediment deposits structure are also dependent on biochemical properties, and most of these processes are time dependent.

The biological and chemical compositions that have influence on the propensity of the sediments to be eroded include the organic and the fatty compounds content mainly.

Table 2-3 Summary of the typical sewer sediment characteristics proposed by CIRIA report 141 based on source and way of transport.

Type	normal transport mode	sewer system	parameters	sediment load		
				low	medium	high
wastewater solids	suspension	separate and combined	concentration (mg/l)	100	350	500
			d_{50} (µm)	10	40	60
			specific gravity (-)	1.01	1.4	1.6
stormwater solids	suspension	separate and combined	concentration (mg/l)	50	350	1000
			d_{50} (µm)	20	60	100
			specific gravity (-)	1.1	2	2.5
grit	bedload	separate and combined	concentration (mg/l)	10	50	200
			d_{50} (µm)	300	750	750
			specific gravity (-)	2.3	2.6	2.6

Table 2-4 Summary of typical values for physical parameters of sediments found in combined sewer systems. Source: (Ashley et al.*, 2004; Bertrand-Krajewski, 2006)*

source in literature	location	parameters			
		d_{50} (µm)	specific gravity (-)	organic fraction (%)	settling velocities (m/h)
(Bertrand-Krajewski, 2006)	domestic wastewater solids	30 - 40	1.5		
(Delleur, 2001)		10 -60	1.01 – 1.6		
(Chebbo *et al.* 1990) after (Ashley *et al.*, 2004)		30 – 38	< 1.0 – 1.2		
(Verbanck *et al.*, 1994) after (Ashley *et al.*, 2004)				70 – 85 (VS/SS)	
(Peavy *et al.* 1986) after (Ashley *et al.*, 2004)					1.0 – 2.5
(Chebbo *et al.* 1990) after (Ashley *et al.*, 2004)					0.34 – 30
(Michelbach and Wöhrle 1992) after (Ashley *et al.*, 2004)					15
(Bertrand-Krajewski, 2006)	stormwater runoff solids	30 - 40	2.4		
(Delleur, 2001)		20 – 100	2.0 – 2.5		
(Ashley *et al.*, 2004)			1.83 – 2.6	10 – 20	
(Bertrand-Krajewski, 2006)	in-sewer sediments	200 – 1000	2.6		
(Ahyerre, Chebbo, *et al.*, 2001)			1.31	54 – 86 (VS/SS)	
(McIlhatton *et al.*, 2005)		180	1.61(bulk); 1.15 (dry)	6.8 (VS/SS)	

2.2.5.1 Organic content

According to Ristenpart (1995), the organic content has the strongest influence over all the other observed properties in sediments from sewers. Organic content can be one of the most critical factors influencing on the erodibility of sediments. This statement was also supported by field and laboratory studies performed on riverine muds (Grabowski *et al.*, 2011).

Sanitary solids are the main source of sediments deposited in-sewer pipes. Then, the in-sewer sediment bed characteristics are directly dependent on the wastewater nature, which is essentially organic (Bertrand-Krajewski *et al.*, 1993; Verbanck *et al.*, 1994; Ashley *et al.*, 2004) because of their origin.

Organic matter in sewer sediments is composite by carbohydrate, protein and lipids. There is not a direct measure of the organic content, nevertheless the parameters BOD_5 (biochemical oxygen demand), COD (chemical oxygen demand) and TOC (total organic carbon), as well as volatile solid content (VS) are indicators of the organic matter present. The volatile solid determination is often used as an overall assessment of the organic matter in sediment transport research studies.

Verbanck et al. (1990) show VS ranging between 70 to 85 % of the total SS. The volatile solid content assessed in combined sewer pipes in Paris was VS = 54 – 86% (Ahyerre, Oms, *et al.*, 2001). Regarding the organic matter in various layers in the deposits, the average values found were: 68 % for the organic layer (type C), 58 % for biofilm layer and between 9.6 and 32 for the type A layer. Average BOD_5 value of 0.25 (g/g) was assessed for the organic layer. (Ahyerre *et al.*, 2000)

The organic fraction in sediments is not homogeneously distributed among the various sized of particles ranges. Verbanck et al. (1990) conclude that the finest fraction of sediments is mainly constitute by light (densities close or even lower to 1000 kg/m^3) and highly organic (90 % of VS/SS ratio) particles. In that regard later research carried out in combined sewer in France by Bertrand-Krajewski (1996), suggests a link between particle size of sediments and organic content, proposing that as finer the sediment particles, the bigger organic fraction.

Another parameter related with the organic matter and commonly used in judging the pollution impact is the total Kjeldahl nitrogen value (Kjeldahl-N), also called organic nitrogen or ammoniacal nitrogen. The ammoniacal nitrogen is a widely used method for assessing proteins content.

The knowledge of the organic composition of sediments that can be released from sewers and spilled into receiving waters is moreover relevant because the potential pollution. The discharged compounds with organic origin usually give rise to dramatic reductions in the dissolved oxygen availability. Dissolved oxygen levels in natural waters are significant in preserving a health water environment.

2.2.5.2 Fat, Oil and Grease (FOG)

The presence of fat, oil and grease (FOG) in-pipe deposits of combined sewers, directly linked with the wastewater sediments source, might constitute a major impact regarding pollution arriving to natural receiving waters. The emission of FOGs into natural waters may result in serious biological degradation of the environment and in health problems caused by the increase in the level of pathogens in water.

FOG deposits may also be the main reason of blockage problems in the network because their natural insolubility in water that, together with an adhesive character can make the aggregate structure highly resistant to detachment and erosion (Keener *et al.*, 2008; Williams *et al.*, 2012; Dirksen *et al.*, 2013).

The amount of fat and organic greases in sediments from wastewaters may have a quite significant effect also on the settling properties. In that regards, Raunkjær et al. (1994) found that a high lipid content in flocs deteriorate the settling properties.

Greases and oils enter to the system mainly from kitchens in residential areas, catering and food commercial and industrial establishments in general. Fat and oil intake vary along the day hence, the deposition in-pipes is a discontinuous process. Despite the important input from kitchens, deposits composed by FOGs are generally softer than common solid fat (Williams *et al.*, 2012) because of transformation processes occurring during dry periods.

Certainly related with the high organic content in FOG deposits, high percentage of the fatty solids are volatile (94% was found by Williams et al. 2012). The main component of FOG was found as saturated fatty acids (commonly termed as *soaps*), triglycerides, calcium, and high concentration of lipids with a similar profile to the cooking oils (Keener *et al.*, 2008; Williams *et al.*, 2012).

Deposits formed by FOG displays porosities lower than common sewer deposits, in the range of 10 to 24%, values found in EEUU in separated sewers by Keener (2008). Highly variability regarding moisture content is displayed by deposits with high amounts of FOG. Values of water content in between 10 to 60% was reported from separated sewers in EEUU (Keener *et al.*, 2008) and also ranging between 15 to 95% in combined sewer deposits in UK (Williams *et al.*, 2012). Maturation in sewer possibly influence on moisture content.

2.2.6 Structure of cohesive sediment deposits. Attributes affecting erodibility

2.2.6.1 Flocculation and settling velocity for cohesive-like sediments

In general, individual sanitary solids particles (excluding grit and gross solids), have small settling velocities because their organic composition and small average particle size. The organic composition of the sewer sediment is one of the parameters that enhance flocculation (because biological processes), promoting increases in floc size (Hoeft *et al.*, 2011) and hence in the sedimentation velocity and the deposition rate.

Because to the development of attractive superficial forces, fine particles in suspension in the water mass tend to agglomerate. The increment in weight caused by the particles cluster (flocs formation's process) lead the increment of the settling velocity. Hence flocs may settle towards the bottom faster than individual particles.

Taking into account the possibly high variation in the values of sediment settling velocity for heterogeneous sediment, some authors agree in the adoption of a value of medium settling velocity (w_{50}) (Verbanck *et al.*, 1994; Ashley *et al.*, 2004; Puertas et al., 2008). This value implies that the 50% of the particles have a settling velocity lesser than that value.

Research carried out in France by Lucas-Aiguier *et al.* (1998) conclude that the particles transported by wet-weather flows have a settling velocity higher than the ones transported by the dry-weather flows. Nevertheless because the cohesive nature of sewer sediment, the flocculation might occur and the flocs settle out regardless whether flow conditions reduce below a certain level or not. (Lau *et al.*, 2000)

Field studies also in France carried out by Chebbo (1992) determined the w_{50} velocity ranging from 4 to 11 m/h for combined sewer (Chebbo *et al.*, 1995), and later Ahyerre et al. (2000), found values of w_{50} = 0.01 - 0.072 m/h for particles in dry-weather flow, and w_{50} = 1.8 – 4.32 m/h during runoff.

Settling experiments using sewerage sediment confirm that solids do not behave as discrete, granular particles (Verbanck *et al.*, 1994). It is also necessary to highlight that the assessment of the settling velocity parameter is highly influenced on the measurement technique. So then, the determination of settling velocities may become a complex process which needs to consider the agglometation/floc and the break-up during circulating flows.

The agglomerate structure formed by flocs has an effect also on the porosity of the deposit bed, property involved in the transport rate.

2.2.6.2 Cohesion, consolidation and armouring effects. Significance

Apart from mechanical forces, the cohesive features in sediments have a significant effect on the initiation of motion conditions.

From the analysis of existing non-cohesive sediment transport formulations, it is clear that the movement of the coarse particles is mainly dependent on the physical characteristics (particle size, density, friction angle or shape of particles) some of them briefly explained above. Nevertheless, in analysing cohesive sediment movement, it is necessary to take into consideration for instance: the organic composition and fat content, in addition to density, water content and degree of saturation, that all are involved in the resistance to erosion in front to an increasing flow. The better prediction of the sediment release from sediments deposited in-sewers, as they frequently showed a cohesive behaviour, will require taking into account cohesion as the interaction between fine particles.

Cohesion and adhesion generate depending on composition of sediments. Organic matter and fine size particles presence have the greatest influence on these mechanisms. Sediments found in sewers are heterogeneous mixtures of particles, but because their organic nature, the presence of biological sludge and greases, sediments in combined sewers generally exhibit cohesive-like strength (Nalluri *et al.*, 1992; De Sutter, 2000a; Delleur, 2001). Sediments from storm drainage systems in contrast, are mainly inorganics and non-cohesive.

Organic cohesion together with microbiological activity in sewer sediments can develop strong bonding forces between particles, influencing the structure of the surface of the bed (Mehta *et al.*, 1997; Banasiak *et al.*, 2005). Increasing erosion resistance is displayed as higher the percentage of cohesive material (Berlamont *et al.*, 1996). This can have a significant influence on the behaviour of a sewer sediment deposit regarding its resistance to erosion. This 'bonding' behaviour adds additional difficulties to the prediction of the rate of erosion and the modelling of sediment transport in sewers, which already involves considerable uncertainty even when this behaviour is not taken into account (Schellart *et al.*, 2010).

For cohesive sediments, density is shown as an indicator of the level of consolidation. The importance of bulk density into the cohesive sediment erodibility was intensively studied in estuarine sediment transport literature. In general it was conclude that the bulk density is inverse correlated with erodibility, which means higher erosion thresholds for less dense sediment deposits (references of this can be found in Grabowski *et al.* (2011)).

The formation of a bed with cohesive structure is a complex process that involves consolidation, dehydration, chemical interactions between the particles of organic content, biological degradation or decomposition of the organic matter over time. These rheological changes were studied by Risternpart (1995) who indicates the existence of an increase in density and a reduction in the volatile solids over time. The higher the dry period between rainfall events, the higher the probability of the generation of a top layer in the solid deposit with a greater erosion resistance (Nalluri *et al.*, 1992).

On the other hand, the deposit might gains in strength against erosion as a result of consolidation. The consolidation process that take place over the deposited sediment in beds in-pipes can be produced under the influence of physical gravity (due for example to the weight of the water column above it), or because biochemical reactions between particles in sediments with high organic composition. During this compaction process, water accommodated in the pore of the deposit structure is expelled.

Fine sediments suspended in water column are continuously interacting and flocculating. During changes in flow conditions (hydrograph receding), velocity can reach magnitudes below the requires for break-up the flocs, and they can be deposited (Lau *et al.*, 2000). These upper layers are known as surficial fine-grained lamina (SFGL) (Droppo and Stone, 1994), and can be related with Type C classification (Table 2-1). This upper structure lying over the Type A or B sediment shows a time-dependent cohesive behaviour. Because the increase on the strength against erosion in this layer, it is usually termed in the literature as “armour” or “crust”, and to its formation process as “armouring”.

This armouring effect could be responsible for the main differences on the initiation of motion comparing deposits formed by cohesive or non-cohesive sediments, but also regarding differences in maturation of cohesive sediment (related with biochemical transformations) and length of the dry-weather periods.

Despite the weighty influence of the cohesive behaviour on the mobilization of the deposited sediments, research carried out by Nalluri and Alvarez (1992) suggest that the influence of the cohesion is relevant just until exceed the strength to break the bonds between particles of the cohesive consolidated structure. Once the critical shear stress is exceeded, occurs a sudden collapse of the structure of the consolidated deposit (Nalluri *et al.*, 1992; Butler *et al.*, 2003; Bertrand-Krajewski, 2006). Since the initiation of motion, the particles are re-suspended and transported in a similar way as they were non-cohesive

2.2.6.3 Biological transformation process. Effects

Beyond the physical properties, the influence of chemical and biological characteristic on cohesion and adhesion mechanisms, and therefore on erosion resistance, becomes evident when analysing the behaviour of cohesive-organic sediments.

There is a wide variety of microorganism inhabiting in the sewer sediment deposits. As Grabowski *et al.* (2011) remark, the contribution of these organism to the sediment behaviour is more complex and varied than that represented by the simple measure of organic content.

The microorganism activity can affect the erodibility of a deposit by transforming the sediment properties during their living cycle, disaggregating particles for instance or generating changes in the sediment chemistry. Organic cohesion together with microbiological activity in sewer sediment can develop strong bonding forces between particles, influencing the structure of the surface of the bed (Mehta *et al.*, 1997; Banasiak *et al.*, 2005) which may lead to an increment on the erosion resistance. Additional adhesive force might be generated by the presence of microbial biofilm growth influencing on the boundary shear stress of the deposit (Fang *et al.*, 2014).

In studies on the erosion of in-sewer sediment, Tait *et al.* (2003) and Schellart *et al.* (2005) concluded that microbiological activity had an effect on the strength of sewer sediment bed. Vollertsen and Hvitved-Jacobsen (2000) and Banasiak and Tait (2008), also concluded that biochemical properties and changes in deposit composition are of importance in sediment transport behaviour.

Biodegradation processes because microorganism activity also lead to transformation in chemical composition. Processes like saponification may occur in sediment deposits with high FOG content (Keener *et al.*, 2008; Williams *et al.*, 2012). Ristenpart (1995) found a vertical variation trend in sediment properties, concluding that are related with anaerobic degradation processes near the invert in the sediment beds.

During deposition and storage of bed-deposits in sewer systems in the course of the dry-period, sediments are exposed to complex and aged dependent transformation processes. Biological and chemical degradation of the organic matter and the and microorganisms growth are strong influenced by temperature, residence time length (Raunkjær et al., 1994; Hoeft *et al.*, 2011) and oxygen availability (Rudelle *et al.*, 2011). Re-aeration and biofilm processes must be taken into account.

Dependent on the dissolved oxygen (DO) concentration available and the microorganisms' types, transformation of organic matter might occur under aerobic or anaerobic conditions. In gravity sewer for instance, it is possible to have re-aeration of the water mass through the network incrementing the levels of DO and allowing the growth of aerobic organism community, which in turn will cause oxygen consumption.

Under anoxic conditions, bonding forces between particles may become stronger. Consequently the resistance to erosion increases. One additional problem in pipes with anoxic environment is regarding the pollution impact on receiving waters. Once the anaerobic sediment deposits release, the pollution discharged into natural waters might be toxic (Vollertsen *et al.*, 2000; Sakrabani *et al.*, 2009; Grabowski *et al.*, 2011).

It is also important the amount oxygen depletion in receiving water after a combined sewer overflow, because of the spill of matter readily to biodegradation (Sakrabani *et al.*, 2005, 2009). The quality of water and sediment under anaerobic conditions can be significantly affected. Large amount of readily biodegradable substrate production, biofilm develop on the surface of the sediment layer, and sulphur-related processes occur (Vollertsen *et al.*, 2000; Rudelle *et al.*, 2011). Hydrogen sulphide formed under anaerobic environment in sewer biofilms, generate both, malodorous and toxic discharges problems (Jensen *et al.*, 2008) when released to receiving waters. Bacterial attachment and biofilm growth is limited based on a nutrient concept (Clegg *et al.*, 1992).

Organic matter is usually characterized based on the BOD_5, COD and TOC parameters. Ahyerre et al. (2000) observed that the most biodegradable particles are found in the organic layer. The highest biodegradability was found in deposits with the lowest COD/BOD_5 ratio: Type C (organic layer) $COD/BOD_5 = 4$ (Ahyerre *et al.*, 2000), $COD/BOD_5 = 3$ for DWF particles (Gasperi *et al.*, 2008); and for Type D (biofilm) the ratio was found around 4.8. To improve the knowledge about biological transformations occurring in sewers is necessary a more detail characterization of organic matter (Raunkjær *et al.*, 1994, 1995).

Information about the in-sewer processes associated with the evolution of deposits is very difficult to obtain because the processes are continually interacting (Raunkjær *et al.*, 1995) and hence increase the difficulties in assessing the temporal change in deposit strength when predicting sewer sediment transport. As part of an integrated operation of drainage systems, improvements in the knowledge of biotransformation processes will benefit the better prediction of pollutant erosion and transport mechanism and consequently improve the management of discharges into natural receiving waters, wastewater input into treatment plants and might also help in assessing the feasibility of the in organic matter potential for pre-treatment in-sewers.

2.2.7 Pollutants attached to solids

Most of the pollutants usually found in combined sewer overflows episodes during rainfall might be considered attached to the solid particles convey through the network (Kleijwegt, 1992; Delleur, 2001; Gasperi *et al.*, 2010).

Sewer sediments, due to an absorbent nature, commonly accumulate nutrients and contaminants (Mehta *et al.*, 1997). Extensive research developed in Europe verifies the existence of patterns that relates the mobilized solid fraction and the concentration of termed “sediment-attached” pollutants (Delleur, 2001; Gromaire-Mertz *et al.*, 2001; Ashley *et al.*, 2004). Suspended solids, SS, are in quantity, the most important insoluble pollutant discharged during a CSOs episode, and can be related with other pollutants concentrations (Deletic, 1998).

It was also found that each size fraction of particulate solids exhibit certain affinities with pollutants. A strong link was shown between the fine sediment particles and the highest proportion of pollutants loads (see Table 2-5 and Table 2-6). From experimental observations, it was found that the smaller the particle, the more important the pollutant load attached (Bertrand-Krajewski *et al.*, 1993). Pollutants such as heavy metals, organic matter and nutrients in general are usually associated with these finest size fractions (Verbanck *et al.*, 1994). Thus, fine sewer sediment particles act as stores of these other pollutants until the deposited bed is released by changes in the hydraulic conditions in the pipe system.

Table 2-5 shows usual pollutants attached to the solid fraction found in combined sewer systems, and the percent relation assessed by Sartor, J. and Boyd, G., Chebbo, G.; Gromaire-Metz, M.C.; Holgland, W. and others, information complied by Bertrand-Krajewski *et al.* (1993)

Regarding modelling, several researchers agree that a reliable analysis of the pollutant loads evolution can be made through the assumption that suspended solids, SS, act like stores of other pollutants (Crabtree *et al.*, 1995; Ashley et al., 2003). Observed sediment-attached pollutant can be introduced in existing commercial models (SWMM, InforWorks and MikeUrban) as potency factors associated with fine and coarse sediment fractions (Crabtree *et al.*, 1995). Nevertheless, the assessment of these relations involves the collection of field data. Establishing adequate relationships (site dependents values) between the solid fraction and attached pollutants it is possible to get a more reliable assessment of the pollutant loads through modelling the quality in sewer systems.

For the study case herein, in the Mediterranean area near Barcelona, fractions of SS that provide a relation between them and the pollutants compounds BOD_5 and Ammonium (NH_4^+), were found for the application of quality modelling using SWMM5 (Seco *et al.*, 2013). The established relations are 85% for BOD_5 and 1.3% for ammonium.

Table 2-5 Percentage of pollutants mass attached to the solid fraction in combined sewer systems (reproduced from (Bertrand-Krajewski et al.*, 1993)*

pollutant		% of the solid fraction
Chemical oxygen demand(COD)		83 - 90
Biochemical oxygen demand (BOD_5)		77 - 95
Total Kjeldahl nitrogen (TKN)		57 - 82
Heavy metals	(Cd)	> 95
	(Pb)	68- 96
	(Zn)	> 95
Hydrocarbons		80 -90
Polycyclic aromatic hydrocarbons (PAHs)		79 – 97
Polychlorinated biphenyls (PCBs)		90 - 93

Table 2-6 Percentage of pollutants mass attached to the solid fraction from the release of sewer sediment beds (adapted from (Ashley et al.*, 2003)*

	pollutant	Attached to coarse % of the solid fraction	Attached to fine % of the solid fraction
Bulk sediments	Chemical oxygen demand(COD)	5.2	1.3
	Biochemical oxygen demand (BOD_5)	97.5	1.5
Near-bed sediments	Chemical oxygen demand(COD)	97	2.5
	Biochemical oxygen demand (BOD_5)	95.8	3.7

2.3 Sedimentation in combined sewer systems

The application of current guidelines for the design and dimensioning of combined sewer systems, can promote wastewater flow with insufficient energy during dry-weather periods. As a result, water velocities might be kept temporally under the particles settling velocity limit, generating thus the progressive accumulation of sediment in the pipes during periods between rainfall events.

Sediments accumulated as a bed inside pipes are one of the leading problems regarding reduction on the flow capacity of the network. The progressive accumulation of sediments may consequently lead to the surcharging of the systems, flooding problems and overflow discharges.

Moreover the transport problems caused by the accumulation of sediments in pipes, the release of the deposited sediments contributing to increase the pollution in receiving natural water bodies. During storm events, sediments and associated pollutants may be sent to a river through Combined Sewer Overflows (CSOs) without any previous treatment, compromising the quality standards of the receiving watercourses.

2.3.1 Significance of sedimentation in pipes during dry-weather

In previous sections we highlight that various researches results conclude that in-sewer deposits constitute the leading source sediments and associated pollutants found in overflows during storm events.

Sediment deposits build-up intermittently inside the combined sewerage systems because the daily and temporal fluctuations in wastewater flows and changes in the solids concentrations. As a function of the velocity linked with the shear stress it is possible the re-erosion of particles in between or along a day. In this sense, the daily wastewater peak or punctual flow entrances exceeding the daily diurnal variations may be responsible for declining in height of the bed-deposits.

The length of the dry-weather period influence on dynamics of the sediment deposition. Nevertheless an equilibrium state between the deposition and re-suspension of sediments can be established, and the time required that balance is site specific (Mannina *et al.*, 2012; Lange *et al.*, 2013). The cleaning techniques on the urban surfaces and the maintenance operating practices within the sewerage system influence on the accumulation process as well.

The amount of sediments accumulated in pipes is variable between sites, time, season, and dependent on the amount of sediment supplied from the various sources. The deposition of sediments varies also along the network system and over time. The main characteristics of the particles and the depth of the accumulated bed of sediments are space and temporally dependent, directly link with the water velocity. In consequence, as was mentioned before in the analysis of sediment properties, upstream pipes storage the coarser sediments with highest density meanwhile the downstream deposits have been found to be lighter and finer and with cohesive behaviour.

The accumulation of sediments in the combined sewer may negatively affect the performance of sewer systems. Difficulties in the operation of the system because blockage problems and also because the reduction of the conveyance capacity, disturbing the dynamic of the circulating flow are related with sediment accumulation in the system. The sediment deposits have also a significant effect on the hydraulic resistance due to the increment in the roughness at the inside the pipes, (Butler *et al.*, 2003), which in turns causes the increment of the water level and the reduction on the water velocity. Changes on the hydraulic conditions because the presence of sediments in-pipes might generates surcharging, flooding, and premature operation of overflows (Pisano *et al.*, 1981; De Sutter *et al.*, 2003).

Moreover, the high organic composition of the solids found in combined sewerage contributes to the development of biochemical transformations on the water-sediment interface and in the sediment deposit itself. These chemical and biological processes promote the formation and release of hydrogen sulphide gases causing malodour and toxic (Jensen *et al.*, 2008) during overflow events into receiving waters.

The quantitative evaluation and the analysis of solutions to pollution problems originated because overflows from combined sewer systems (CSO) required the assessment of the volume of solids previously deposited in the sewer network. Additionally, the knowledge of the distribution of the sediments in the whole system is necessary for the achievement of a better evaluation of the sediment transport during rainfall.

2.3.1.1 Problems caused by sewer sediments in pipes

Sediments deposited inside pipes can cause difficulties in the operation of the sewer system as was introduced above. The main reasons of difficulties in managing are related with the following problems:

- blockage problems
- reduction of the capacity of water conveyance (hydraulic capacity), surcharging flooding and premature overflows' operation
    - because of the progressive accumulation of sediment at the inlets that reduce the cross-sectional area of the conduits
    - because of the increment in the hydraulic roughness related with the roughness of the sediment bed built inside the pipes
- Overflow pollutant events, malodour and toxic problems
    - because organic compounds biochemical transformation occurring during accumulation periods

Large solids (sanitary cloth, trash, etc.) and build-up of smaller solids may cause progressive blockage problems mainly inside the lowest diameter sewer pipes. The reduction of sewer conveyance was investigated and reported by Ackers *et al.* (1996) as reaching until 10 and 20% of the full pipe capacity, while the roughness might also be incremented in a 10% of the value of the material of the pipe due the sediment deposition. Both problems here exposed might lead to the surcharging of pipes and manholes of the system, flooding events occurrence as well as the increment on the frequency of operation of the overflows structures.

From a quality point of view, the solids from the deposits in pipes might be released during strong rainfall events. Thus the water discharged through the overflow structures conduct to the environment large amounts of pollutants. This pollution success, which occurs mainly at the start of a storm event, is known as *first-flush* and was previously described in section 2.1.2. Spills from CSOs cause detrimental environment impacts on natural receiving waters.

A further problem might be caused by the sediments accumulated in-sewer, because their organic composition. The influence of anaerobic environment at which are exposed; promote the formation of hydrogen sulphide. The build-up of hydrogen sulphide gas in sewer systems is a well-known problem resulting in odour nuisance and may cause sewer a long term corrosion and deterioration in the pipe's walls (Hvitved-Jacobsen *et al.*, 2013) which may lead the collapse of the conduit affected.

2.3.1.2 Sedimentation processes

If the water velocity and/or the level of turbulence are reduced by any circumstance, there will be a clear fall in the amount of sediment that can be maintained in suspension.

Structural and hydraulic discontinuities of the network system (like abrupt changes of slope, changes in diameter and pipes cross section, divider structures, etc.) are the main contributors to the deceleration of the water flows, promoting sedimentation of the solids transported in suspension (from Chebbo *et al.*, 1995 cited by Ashley *et al.*, 2000). In turn, if flow increases for instance in a circular cross section pipe, the water depth, the velocity and the hydraulic radius change, resulting in higher shear stresses and as consequence, less sedimentation.

The identified factors that influence on the sedimentation processes can be summarized in the following list showed in Table 2-3 (Ashley and Crabtree, 1992; Ashley, Wotherspoon, *et al.*, 1992; Chebbo *et al.*, 1995; Butler *et al.*, 2003).

The actual shear stress linked to the flow regime; the length of the dry period (build-up time) and the wastewater sediment suspended load appear to have the higher influence on the sedimentation processes (Ashley, Wotherspoon, *et al.*, 1992).

The length of the dry-weather period influence on dynamics of the sediment deposition, nevertheless, equilibrium between erosion and deposition might be established. The time required to establish the mentioned equilibrium is site specific (Mannina *et al.*, 2012; Lange *et al.*, 2013) and might do not be reached (Banasiak *et al.*, 2005) because highly variable flow conditions during dry-periods. About this time evaluation, for instance, Larson *et al.* (1990) cited by Ashley, Wotherspoon, *et al.* (1992) found a 15-20 days period to achieved a state of equilibrium depth of deposited sediments in-pipes, meanwhile a recent laboratory experimentation carried out by Lange *et al.* (2013) found 50 days under constant conditions.

Regarding the sediment transported in the water mass, research carried out in United Kingdom (Butler *et al.*, 2003) show as results that the most significant variable that has influence on sedimentation in pipes is the sediment concentration. Meanwhile, the size of the particles is less influent. This meant that if the sediment concentration increases in a 100% (for instance going from 50 mg/l to 100 mg/l) an increment of the 20% of the velocity is required in order to avoid particles deposition. In this sense, in the assessment of sedimentation processes, it is important a good estimation of the sediments supplied from domestic sources and contributions from industrial a/or commercial sources.

Table 2 4 Summary of factors that influence on the sedimentation processes

location	factor
sewer system	slope, length, cross section shape and dimensions of pipes
	material (roughness, age of the material)
	maintenance and cleaning operations
	location of the pipe within the network
sediment	sediment characteristics and composition
	sediment concentration in wastewater
	bed roughness
hydraulic regime	wastewater flow/velocity range and daily/seasonal fluctuations
	actual shear stress
	sediment transport capacity
	local effects on the flow (discontinuities of the sewer network)
meteorological	length of dry-weather period

Furthermore during design it is important considering that the water velocity at which sedimentation occurs is usually smaller than the required for the re-suspension of the particles (Butler *et al.*, 2003).

2.3.1.3 Total depth/volume and distribution of sediment deposits along a combined sewer network

One of the major problems for operating tasks in sewerage is predicting where the sediment will be deposited (Ashley *et al.*, 2000). Regarding quality problems, it is also of interest the sediment volume accumulated along the system, available to be release and discharged thorough overflows structures.

From the observation made in combined sewer sedimentation studies it is widely agreed that the finest particles and the sediment with the highest organic composition are deposited downstream of the sewer network (mainly in interceptors), meanwhile the biggest particles settle upstream at the heads of the network at the smaller diameter pipes (Verbanck, 1990; Ashley, Wotherspoon, *et al.*, 1992; Ashley *et al.*, 2004). Table 2-7 show the commonly found distribution of sediments in a combined sewer network.

Another finding to highlight is related to the daily rate at which sediments are deposited. Lange *et al.* (2013) in laboratory experiments in Germany assess an average growth of the sediment depth in-pipes around 0.75 mm/d during the 30 first days, meanwhile 4 mm/year (0.011 mm/d) was found by Dirksen *et al* (2011) in the Netherland sewerag. The rate of sedimentation during dry-weather periods was found (Ashley, Wotherspoon, *et al.*, 1992) to be lower in interceptors because the highest velocity of the water associated with their design.

Table 2-7 Sediment accumulation potential location and characteritics in combined sewer networks, adapted from (Ashley, Wotherspoon, et al., 1992; Ashley et al., 2004).

sewer system type	sediment deposit location	geometric characteristics	sediment deposit nature	pollutant concentration
small collector sewer	at discontinuities*, otherwise randomly located in discrete 'lumps'	smallest diameter	mainly organics, sand and gravel	lower pollutant concentration
trunk sewer	at discontinuities*, otherwise only larger, denser particles deposited	steeper gradients (connect collectors to outfalls or interceptors)	large granular particles, some intermixed organics	
interceptor sewer	at discontinuities*, otherwise where gradients slack	largest diameters, slackest gradients greatest potential for sedimentation	fewer large organics than above, plus finer granular particles than above	

*structural or hydraulic discontinuities

Table 2-8 gives values of sediment build-up compiled by Ashley, Wotherspoon, *et al.* (1992) from reported measured values found in various combined sewers.

Table 2-8 Sediment deposition rate in combined sewer (Ashley, Wotherspoon, et al., 1992).

sewer pipe diameter [mm]	sewer gradient	population or sewer length	sediment deposition rate [g/m/d]	comments
300	0.005 – 0.003	69 – 75 m	9 – 65	flushing results on collector sewers
375	0.005 – 0.003	41 – 57 m	16 – 29	
500	0.0042		30	collector sewer (vigorous flush)
1500	0.00069	14590 inh.	34 - 128	interceptor sewer

Research findings presented by Verbanck (1990) suggested that a bed of finest particles that present more organic composition (type C from Crabtree, 1989) might be built over a coarser bed deposits in the upstream sewer conduits, but are possibly daily released due to the scouring action of the dry-weather peak flow. Later research finding suggested that this fine-grained sediment (organic layer or biofilm) has usually lower resistance to erosion and may be continuously changing not only because flow fluctuations, but for the biological transformations (Ahyerre, Chebbo, *et al.*, 2001; Banasiak *et al.*, 2005).

The sediment depth accumulation or sediment mass deposited is hardly complex to be assessed and generalized. Because of the high fluctuations in sediment concentrations, nature of the particles, hydraulic conditions, cleaning operations, etc. influence on the amount and on the way at which sediment settle, the determination of a sediment bed depth is complex. Previous research in Europe evaluate the accumulation of sediment in combined sewer networks found: between 100 to 200mm depth in interceptors in Dundee (Arthur, 1996), average bed depth of 250 mm in trunk sewers between 600 to 600 mm diameter also in Dundee (Fraser *et al.*, 2002), and in between 370 to 424 mm in London (Schellart, 2007).

Despite the mentioned sediment depth values and deposition rates, it is significant emphasize that the determination of a sediment bed depth accumulated in-pies during the dry-weather period is strongly site dependent.

2.3.2 Assessment of sedimentation in sewerage

As was previously highlighted, sedimentation process and the amount of sediment accumulated in-pipes during dry-weather depend upon various factors. The factors are related not just with the characteristics of the sewer network itself (nature of the sewer system, diameters and slopes of the network, discontinuities), but also with climate factors (length of dry period, intensity of rainfall), and human activity (sources of sediments, concentration loads). Additionally, all these factors may also vary temporally and spatially, in a catchment and a possible sedimentation rate is site specific.

Evaluate the thickness of sediment deposited on a particular conduit/network, and at a specific time is not a simple task. Thus, mathematical relationships or models that enable the evaluation of the accumulated deposits might ever be possible to be generalized and site independent.

Although the evaluation of the sediment deposited in a sewer system is not the purpose of the work develop in the present doctoral research, it is necessary to identify sediment patterns of distribution in the sewer network, as well as assess the volume of sediment accumulated during the dry-weather period as initial condition in order to implement a sediment transport model. It is clear that the release, re-suspension and particles transport processes will be dependent on the amount of sediment initially available as a deposit, as well as on the length of the accumulation period during which physical and biological consolidation processes are possible.

Sedimentation prediction methods consider in general, sediment particles as ideal solids. This meant, small particles, non-cohesive and with conservatives properties. It is also hypostatised that deposition-erosion arrive to an equilibrium with time (Ashley *et al.*, 2004). Although these characteristics are not satisfied in real sewer systems, the results that can be obtained by the application of some of these methodologies are considered sufficient approximate for the purpose in the herein research.

In that respect, an approach methodology for the assessment of the sedimentation in combined sewer systems are briefly presented at the following section. The Pisano methodology (1981) was chosen for the purpose of assessing the initial depth of sediment in a sewer network after a dry-weather period. This method gave reasonable agreement with observations based on the findings by Ashley and Goodison (1991) referred by Ashley, Wotherspoon *et al.* (1992). A modified relationship based on Pisano's method is developed by Fraser and Ashley (1999) referred at (Ashley *et al.*, 2000)

We will see later at Chapter 5 the estimation of the sediment deposit formed in a combined sewer network under analysis, based on the distribution trend suggested by Pisano (Pisano *et al.*, 1977, 1979; Fan, 2004) explained here below.

2.3.2.1 Pisano (1981) EPA’s methodology

A simplified approach develop by William Pisano for the U.S. Environmental Protection Agency (US-EPA), allows the estimation of the volume of sediments deposited in a combined sewer system (Pisano *et al.*, 1977, 1979, 1981; Fan, 2004). The methodology form part of a series of studies carried out in USA in the 1970’s to improve the design of sewers to minimise deposition.

Pisano (1979, 1981) based the prediction on the hypothesis that the propensity for sediment deposition might be associated to the location of the pipe in the network as well as their size, slope and sediment concentration in wastewater.

The predictive model considers the daily peak of wastewater flow. On the other hand, in order to evaluate the limiting particle diameter that can settle in a conduit, proposes the utilization of the Shields’ criteria. This method allows in a relatively simple way, the assessment of the rate of sediments mass deposited daily in combined sewer pipes.

Pisano (1979, 1981) proposed four alternatives power equations for the prediction of the total daily sediment load deposited within sewer pipes. The simplest equation (2-6) requires the lesser amount of data but consequently, has the lower reliability, whereas the first model approach (2-3) requires greater data providing the better estimation of the sedimentation rate. From the proposed equations we will utilise the intermediate approach (equation 2-4) that is considered for our case, the more adequate for the application since the parameters involved in the method are known or can be calculated.

The chosen equation for the estimation of the sediment deposit depth is the following.

$$TS = 2.64\ 10^{-4}\ L^{0.814}\ S_{PD}^{-0.819}\ S_{PD/4}^{-0.108}\ q^{-0.51}\ (R^2 = 0.949) \qquad 2\text{-}3$$

$$TS = 10.91\ 10^{-4}\ L^{1.18}\ A_{[ha]}^{-0.178}\ S_0{}^{-0.418}\ D^{0.604}\ q^{-0.51}\ (R^2 = 0.852) \qquad 2\text{-}4$$

$$TS = 3.69\ 10^{-4}\ L^{1.22}\ A_{[ha]}^{-0.178}\ S_0{}^{-0.434}\ q^{-0.51}\ (R^2 = 0.848) \qquad 2\text{-}5$$

$$TS = 7.09\ 10^{-4}\ L^{1.063}\ S_0{}^{-0.438}\ q^{-0.51}\ (R^2 = 0.845) \qquad 2\text{-}6$$

where the parameters used for the assessment of the total daily sediment load deposited (*TS*) expressed in kg/d are:

L: total length of the sewer system [m]

$A_{[ha]}$: area of the catchment [ha]

S_0: average slope of the pipes in the sewer system [m/m]

D: average diameter of the pipes in the sewer system [m]

q_r: wastewater flow rate per capita [m^3/cap/d]

L_{PD}: length of a conduit corresponding to the deposition of the 80% of the solids of the system in volume [m]

S_{PD}: slope corresponding to L_{PD}

$S_{PD/4}$: slope corresponding to ¼ of the percentage of pipe length L_{PD}

S_{PD} and $S_{PD/4}$ are experimental assessed parameters. Their values allow a better definition of a slope distribution function. In order to evaluate them, the curve shown at Figure 2-5 is needed.

The equations 2-3 to 2-6 were derived from deposition data analysis under the assumption of clean pipes, with non-sediment bed deposit previous to the storm event, and good maintenance practices. The consideration of these issues will lead to increases in the deposited sediments. The impact of the age of the sewerage and a possible poorly maintenance practices can be also considered in the prediction by applying a multiplicative correction factor on the results given by the application of the previous equations for clean pipes (Pisano *et al.*, 1977).

Equation 2-7 can be applied to consider an intermediate degree of maintenance (under assumption of initial deposit depth ranging from 25.4 to 76.2 mm). Equation 2-8 gives the correction factor to consider under poor maintenance (initial deposit depth ranging from 76.2 to 152.4 mm).

$$TS_{corrected} = 1.68\ q^{-0.076}\, TS_{clean}\ \ (R^2 = 0.988) \qquad \textit{2-7}$$

$$TS_{corrected} = 1.79\ q^{-0.084}\, TS_{clean}\ \ (R^2 = 0.999) \qquad \textit{2-8}$$

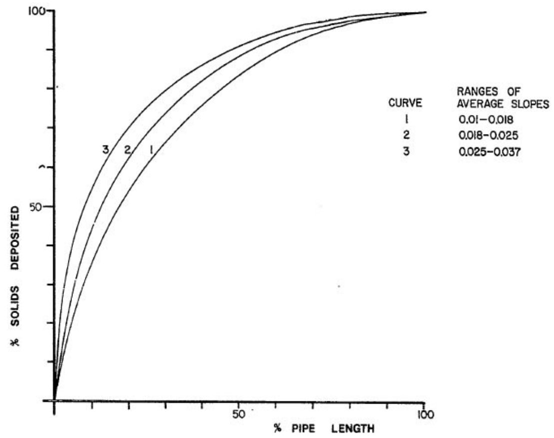


Figure 2-5 Cumulative distribution of deposited sediments against length of the conduits (after (Pisano et al., 1981).

Pisano (Pisano *et al.*, 1977; Fan, 2004) had also performed a regression analysis on the fraction of other pollutants and TSS data. The analysed pollutants include BOD_5, COD, TKN, NH^{+4}, P and VS. The assessment of solids-attached pollutant loads can be made under the assumption of the reliability of these relations (see Section 2.2.7) through the application of the equations showed at Table 2-9.

Table 2-9: Regression equations for the assessment of pollutants mass attached loads to the solid fraction prior deposited in sewer as sediment beds (adapted from (Pisano et al., 1977)

pollutant	% of the solid fraction deposited in-pipe
Chemical oxygen demand(COD)	$COD = 0.875\ TS^{1.04}$
Biochemical oxygen demand (BOD_5)	$BOD_5 = 0.344\ TS^{1.308}$
Total Kjeldahl nitrogen (TKN)	$TKN = 0.039\ TS^{1.135}$
volatile solids (VS)	$VS = 0.689\ TS^{1.033}$

The application of the methodology to a real network is shown later at Chapter 5, Section 5.3.1.3.

2.3.2.2 Other related methodologies

The equation found by Pisano *et al.* (1979) can be expressed as a function of the bed shear stress as follow, where Z is the percentage of suspended solids deposited along the pipe length.

$$\begin{aligned} Z &= 40\left(\frac{\tau_b}{\tau_c}\right)^{-1.2} && for\,\tau_b > \tau_c \\ Z &= 40 && for\,\tau_b \le \tau_c \end{aligned} \qquad 2\text{-}9$$

Fraser and Ashley (1999) referred at (Ashley *et al.*, 2000) perform a modification of these equations shown at equation 2-10 which allows the estimation of long-term deposition.

$$Z = 0.899\left(\frac{\tau_b}{\tau_c}\right)^{-1.2}.\left(\frac{W_b}{W_{max}}\right) \qquad 2\text{-}10$$

where W_b and W_{max} are the sediment bed width and maximum sediment bed width respectively.

2.4 Transport of sediments

The assessment of the sediment transport under the water flushing effect constitutes a significant and complex problem for the hydraulic engineering in general. The complexity on the sediment movement is given by the wide range of the mechanisms involved. Deposition, release and re-suspension, and subsequent transport are affected by mechanical and biochemical interaction between particles, but also by the hydraulic conditions and dynamic of water flows. Adding complexity to the process, all of them are manifested in combined sewers with significant temporal and spatial variability, even at a catchment scale.

The movement of sediment can be described in three basic phases: the deposition, the entrainment or initiation of motion, and the transport itself. In Section 0, a basic review on general deposition for cohesive sediments in sewers was presented. In Section 2.2.3 some sediment characteristics that will affect the entrainment of sediment in the flow by erosion were showed.

A wide amount of research was carried out in the past decades on sediment transport. Research was mainly focus in the study of the transport of granular sediment in open canals and natural streams, developing predictive formulations and methodologies.

The goodness of the results obtained in computing sediment transport capacity using these physic based models, have driven their later application in sewage systems based on an assumed similarity between the sediment transport conditions. Nevertheless, despite the formulations are useful for the understanding of the solid movement principles, the results obtained from their application in sewerage (especially with cohesive sediment) are not conclusive and might be inappropriate. Moreover, there are uncertainties in the application of formulations developed for rivers when they are intended to be applied in close conduits, with rigid boundaries and regular cross sections in a detail pipe by pipe scale. There exist also uncertainties because the dynamic of the water flow can be considerably different from flows in rivers. Regarding the sediment particles, there are substantial differences with particles found in rivers because the heterogeneity in size and composition, besides differences in the sediment nature and properties (Arthur, 1996; Delleur, 2001; Butler *et al.*, 2003).

All the mentioned conditions present in sewerage sediment transport give rise to difficulties the application of sediment transport general formulations (that have been based on experimental data from river sediment transport, or from laboratory studies using non-cohesive sediments).

We intend to overall review the concepts concerning sewer sediment transport. Despite the traditional formulations (at Section 2.4.4 below) were developed from experimental data using coarse sediment, they are frequently used by predictive tools in urban drainage for the assessment of the sediment and pollutants loads. Thus, the following sections will be focused in basic concepts about initiation of motion conditions and sediment transport formulation that have been applied in sewer sediment mobilization.

We will also report later at this section, about sediment transport formulations developed particularly for sewerage systems and for cohesive sediments.

2.4.1 Basic concepts of sediment transport

2.4.1.1 Initiation of motion

As water flows throughout the overlay sediment deposits, the hydrodynamic forces (lift and drag) are exerted on the particles. If the magnitude of these forced do not exceed the equilibrium forces (submerged weight of the particle, the interlocking forces and cohesive forces between particles if present) the grain remains steady. If exceeded, the start of movement occurs.

Depending on sediment composition, mechanical forces (cohesion and adhesion) can also be important in the fine size range (Mehta *et al.*, 1997).

Under a circulating flow, (see Figure 2-6) a prominent particle at the bed will experience a force proportional to the exposed area, named drag force (F_D). The other hydrodynamic force called lift force (F_L) will oppose to the addition of the submerged weight of the grain (F_W) with the cohesive force (F_C), this last, generated from the interaction between particles (Mehta *et al.*, 1997; Rushforth, 2001).

The instant at which a particle with determined characteristics is release from the deposit and mobilized by the water flow is named: *threshold of motion* or *incipient motion*.

The equilibrium condition will be established by mentioned forces by subtends a repose angle Φ. Thus, the condition for incipient motion is given in equation 2-11.

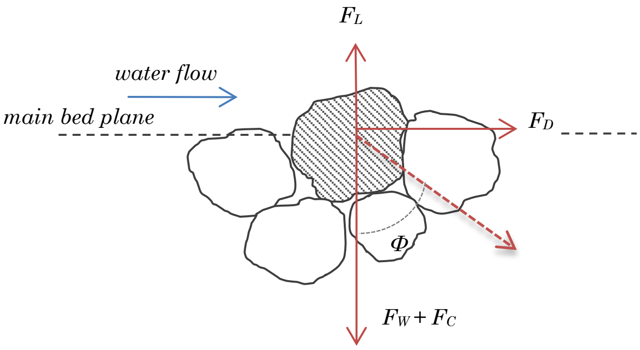


Figure 2-6 Forces acting on a prominent particle at the bed-deposit subject to steady water flow (after Mehta et al., 1997).

$$\tan\phi = \frac{F_D}{F_W + F_C - F_L} \qquad 2\text{-}11$$

2.4.1.2 Bed shear stress

The shear stress expresses the influence of the flow over the sediment deposit and is a concept used for describing the threshold of initiation of the particles motion.

The applied bed shear stress is generally calculated by hydraulic formulae (Oms *et al.*, 2008), where ρ_w is the water density, g is the gravitational acceleration, R_h the hydraulic radius and J the energy slope. It can be noticed that the water velocity is not directly included in the relationship, but is considered through the energy slope. The energy slope (J) can be replaced by the bed slope (S_b) when the flow is considerable steady uniform. Nevertheless, the replacement might introduce important errors, especially under rapidly varying flow conditions (Berlamont *et al.*, 2003), as happened in sewer systems.

$$\tau_b = \rho_w . g . R_h . J \qquad 2\text{-}12$$

The applied shear stress (τ_b) appears to be the most significant parameter in a sediment transport equation. The τ_b parameter incorporates the effects of the slope and reflects the action of a flow over a sediment bed.

Despite the significance of a reliable assessment of the applied shear stress over sediment deposits is a quite complicated task. The unsteady flow conditions, the presence of non-homogeneous sediments deposits, the influence of the wall roughness and the conditions inside sewers increment difficulties in the determination of the shear stress values. Moreover, in the analysis of a real case of erosion, mainly because the fluctuating hydraulic conditions in time and space, not all the particles with the same size located at the sediment-water interface will start moving at the same time.

The presence of a sediment bed at the inlet of a pipe has a significant effect on the shear stress distribution over the of the wetted perimeter (Berlamont *et al.*, 2003). The shear stresses values is not uniformly distributed over the wetted perimeter for pipes with sediment accumulated, meanwhile for clean pipes, the shear stress distribution is quite uniformly.

Past research was also made on determining the influence of the deposition conditions over the deposit stability against erosion (Lau *et al.*, 2000). The results suggest that critical shear stress values displayed are lesser for deposits formed under quiescent conditions than for disposition under flowing conditions.

The termed *critical bed-shear stress* or *boundary shear stress* referred to the lowest value of the shear stress that will produce the release and re-suspension of the particles laying on the superficial layer of the sediment deposit at the interface solid-water. It is therefore a relevant factor in erosion process modelling, and its accurate assessment is crucial because the movement of the particles depends basically on the excess of shear stress between the critical and the applied value.

Laboratory assessment with synthetic sediments under steady flows, and calculations based on the Shields' diagram (developed for non-cohesive sediments but widely used in sewer sediment transport models) are the more usual ways of estimation of the bed-shear stress (Skipworth *et al.*, 1996; Hrissanthou *et al.*, 1998; Berlamont *et al.*, 2003).

2.4.1.3 Effective settling velocity

A minimum flow is required to initiate the motion of particles accumulated in deposits in the inlet of the pipes. Several researches proposed the use of a bed shear stress criterion related to that flow, but other described the threshold of motion of the particles based on a "no deposition" criteria by using an effective settling velocity (w_s).

The results obtained from several researches indicate that the flow velocity for re-suspension of the previous settled particles is greater that the flow velocity at which the solids were settled (i.e. velocity for solids re-suspension > 0.44 m/s and velocity for solid settling < 0.27 m/s from (Fan *et al.*, 2003)).

Some of the sediment transport relationships that consider the use of a no-deposition criterion are Macke (1980, 1983) and Velikanov (1954) both for account total load transport. References to these formulations can be found in (Ashley *et al.*, 1996; Bertrand-Krajewski, 2006). However, the most widely approach is the based on the critical shear stress that is detailed below in the next section.

2.4.2 Establishing the threshold of motion

Due to continuous variations in the water flow conditions on the interface fluid-sediment, there are permanent variations in the mobilizing and restoring forces. Thus, in these conditions, it is difficult to establish the exact moment for the initiation of motion of the sediment particles on a deposit. The threshold of motion is even more complicated to establish if dealing with non-uniform particles sizes, and sediment deposits heterogeneous in composition.

There are two general criteria to establish the threshold for the incipient motion. One is based on a minimum transport rate reached once the critical shear stress or minimum erosional velocity is exceeded. The second way is following a design criterion based on experimental observations.

The former criterion, based on the minimum bed-shear stress is the most widely used. One of the approximations developed to establish the threshold of motion for particles is the one proposed by Shields in 1936. The Shields' approximation was defined based on the mobilization of uniform size and non-cohesive particles, stored as a bed-deposit with flat surface.

Shield (1936) established the equilibrium condition (given at equations 2-13) for the case when the average bed-shear stress (τ_0) (equation 2-14) is equal to the critical bed-shear stress value (τ_{0cr}). And the mobilization will occur when the bed-shear stress become greater than the critical value.

$$\begin{array}{ll} \textit{equilibrium condition} & \tau_0 = \tau_{0cr} \\ \textit{particle movement condition} & \tau_0 > \tau_{0cr} \end{array} \qquad 2\text{-}13$$

where the average bed-shear stress (τ_0) is calculated as a function of the shear velocity (u^*) and the water density (ρ_w).

$$\tau_0 = \rho_w \, . u^{*2} \qquad 2\text{-}14$$

and where shear velocity (u^*) is function of the hydraulic radio (R_h), the bed slope (S_b) and the gravitational acceleration (g).

$$u^* = \sqrt{g \, . R_h \, . S_b} \approx \sqrt{g \, . y.} \qquad 2\text{-}15$$

Shields (1936) express the critical shear stress in terms of a dimensionless parameter termed *mobility parameter* (θ) (equation 2-16).

$$\theta = \frac{u^{*2}}{(s-1) \, . g \, . d_{50}} = \frac{\tau_0}{(\rho_s - \rho_w) \, . g . d_{50}} = F_d^2 \qquad 2\text{-}16$$

Because of this relation, the mobility parameter can be used as well as a threshold of motion condition when becomes greater than a critical value ($\theta > \theta_{0cr}$).

The Shields' mobility parameter, also called *dimensionless shear stress*, establishes the relation between the mobilizing forces and the restoring on a particle.

From experimental data, Shields (1936) establish a relation between the *mobility parameter* (θ) with the Reynolds number for the particle (Re^*) from equation 2-17. Using the mobility parameter it is possible to assess a theoretical point for what a particle initiates the movement in the water mass, under particular conditions.

Shields proposed plotting θ against Re^* to obtain a diagram named later the Shields' curve (see Figure 2-7). Thus, this curve allows to evaluate the θ_{0cr} and τ_{0cr} as a function of Re^*, where the Reynolds' number for the particle is in turn calculated as function of the shear velocity (u^*), the particle diameter (d_s) and the kinematic viscosity (v) in m^2/s, whose value can be calculated by using the equation 2-18, as function of the kinematic density (μ) and the water density (ρ_w).

$$Re^* = \frac{u^*\,.\;d_s}{v} \tag{2-17}$$

$$v = {}^{\mu}/_{\rho_w} \tag{2-18}$$

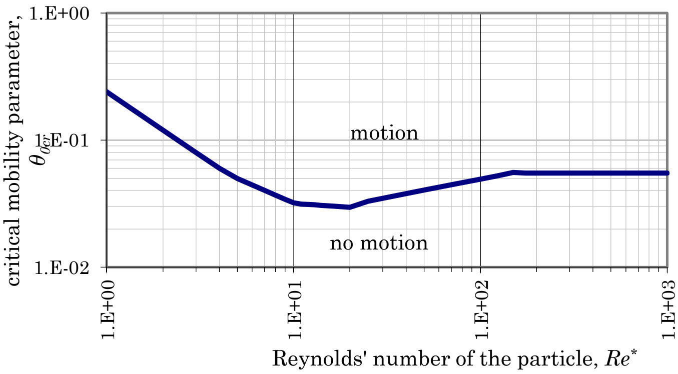


Figure 2-7 Shields' curve for the assessment of the critical bed-shear stress.

Despite the relevant significance of the diagram in sediment transport, there is a practical obstacle in using the Shields diagram in the way as appear at Figure 2-7. The major drawback is that the shear velocity (u^*) is parameter needed for calculated both axes θ and Re^*, and therefore the diagram cannot be used directly.

Later, to overcome the aforementioned problem, Bonnefille and Yalin (1963) (in van Rijn, 1984, 1993) worked in the development of a formulations that allow a more practical use of the Shields' diagram. The solution was established by the introduction of another dimensionless parameter called *dimensionless grain size* (D^*) shown in equation 2-19, which represent the influence between the gravity forces, the density and the viscosity over the mobilized particle.

$$D^* = \left(\frac{g\,.(s-1)\,.d_{50}{}^{3}}{v^2}\right)^{\frac{1}{3}} \tag{2-19}$$

Once the D* value is obtained, it is possible the calculation of the mobility parameter by using the set of equations shown at 2-20, also included in Figure 2-8, where the modified Shield's diagram is shown.

$$D^* \leq 4; \quad \theta_{cr} = 0.24\,.\,D^{*^{-1}}$$

$$4 < D^* \leq 10; \quad \theta_{cr} = 0.14\,.\,D^{*^{-0.64}}$$

$$10 < D^* \leq 20; \quad \theta_{cr} = 0.04\,.\,D^{*^{-0.10}} \qquad \textit{2-20}$$

$$20 < D^* \leq 150; \quad \theta_{cr} = 0.013\,.\,D^{*^{0.29}}$$

$$D^* > 150; \quad \theta_{cr} = 0.055$$

The Shields' diagram is up to date widely used as a base to the assessment of the threshold of motion shear stress in sediment transport studies.

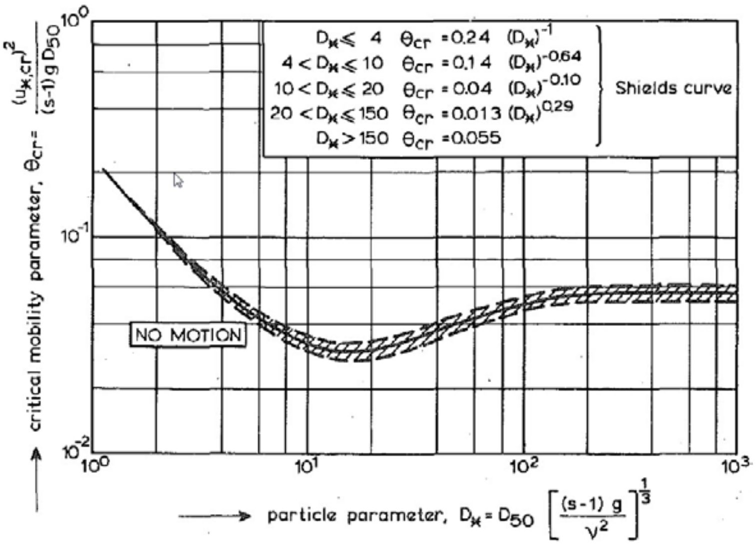


Figure 2 8 Adapted Shields' curve for the assessment of the critical bed-shear stress (reprinted from van Rijn, 1984).

Results obtained from experimental studies carried out by Nalluri and Álvarez (Nalluri *et al.*, 1992) reveal that the Shields criteria for the definition of the threshold of motion is valid and applicable to circular conduits in sewers, and that provide similar results to the measured values obtained for non-cohesive sediment.

The sediment particle stability at the sites could be also determined directly by measuring the critical shear stress that generates erosion. Nevertheless, the measures *in situ* are truly complicated due the uncontrolled conditions that may lead to significant uncertainties. Better results were obtained by *in situ* sampling and subsequent measures in the laboratory using appropriated devices.

In situ measurement of the applied shear stress was developed in the "Marais" catchment in France. The measurements of the water velocity were taken in sewer pipes with dry-weather flows and non in-pipe deposits, conditions chosen to closely replicate ideal steady flow conditions in laboratory facilities. From this study shear stress values are established in the range of about 0.06– 1.83 N/m^2 (Oms *et al.*, 2008), while the calculated values using the energy slope obtained from Manning formula (equation 2-12) evaluated for the same cross sections data and water flow conditions vary between 0.20 and 2.80 N/m^2. This research concludes that the classical methods for assessing the applied shear stress from hydraulic calculation might introduce large errors in the determined values.

2.4.3 Modes of transport

The mobilization of the particles by water is classified according to the area in the water column where the movement of sediment take place. In this way, the particles are transported in suspension (*suspended load)* or as *bed-load*. Both modes of transport can occur simultaneously.

The *bead-load* transport involves the displacement of the particles by rolling, sliding or jumping. The particles are transported nearby the surface of the bed of sediments along the pipe. In the case of the *suspended load* mode, the particles are transported in suspension, because the action of turbulent flow. In this way, the particles are released from the bed and lifted into the water volume where are distributed in the entire water column.

The mode of transport depends primarily on the size, shape and specific gravity of the particles and on the hydraulic flow conditions that will influence the movement (speed and turbulence).

Despite the transport mode is well defined from a theoretical point of view, the transition between one and the other in real conditions is not well limited. Although for the purposes of its mathematical representation, it is necessary to establish a boundary between both.

The limit will be given by the bed-shear stress value (τ_0) or the shear velocity (u^*) given in equations 2-14 and2-15. Both parameters can be related with equation 2-21, where λ is the Darcy-Weisbach friction factor.

$$\tau_0 = \frac{\rho \,.\, \lambda \,.\, u^{*2}}{8} \qquad \text{2-21}$$

When the value of the bed-shear stress (τ_0) exceeds the critical value for the initiation of the movement, the particles will move rolling or sliding, or both. For increasing shear stresses, the particles will move along the deposited bed, by more or less regular jumps. When the value of the shear velocity exceeds the settling velocity for particles, the released particles can be re-suspended until a level for what the turbulent forces are comparable or greater to the weight of the submerged particle. In this way, the particles are transported in suspension in the fluid mass. The higher the velocity of the flushing water, the greater the sizes of the bed-sediment particle which can be rise in suspension and transported on this mode.

Researchers in the field established limits for the modes of transport (Bertrand-Krajewski, 2006). Most of these limits are dependent on the relation between the settling velocity (ω) and the shear velocity (u^*) as are shown in equation 2-22 suggested by Raudkivi, A.J., 1998.

$$\begin{array}{ll} \textit{transport in suspension} & (\omega/u^*) < 0.6 \\ \textit{transport by saltation} & 0.6 < (\omega/u^*) < 2.0 \end{array} \qquad \text{2-22}$$

bed-load transport $2.0 < (\omega/u^{*}) < 6.0$

Previous research carried out in close pipes by Durand *et al.*, (1952) mentioned at (Bertrand-Krajewski, 2006) assess the same modes of transport for coarse and heterogeneous sediment, setting the limits between modes as a relation of the particles size.

transport in suspension $50\ \mu m < d_s < 200\ \mu m$

intermediate conditions $0.2\ mm < d_s < 2.0\ mm$ *2-23*

bed-load and saltation transport $2d_s > 2.0\ mm$

2.4.4 Sediment transport formulations

There is a broad range of predictive sediment transport loads formulations developed since several decades mainly for granular particles (Table 2-10).

Despite continuous improvements in the sediment mobilization assessment, there is so far no equation that can be universally applied to all cases. A model just gives a simplified representation of a complex phenomenon. So that there is not a better or more suitable transport method to applied. The selection of the more adequate formulation for each study case will depend on that the conditions (sediment characteristics and hydraulic conditions) for which the predictive formulation was developed, better suit on the study case conditions.

Table 2-10 Summary of of formulations developed mainly for estuarine, coastal and riverine sediment erosion by water and transport.

bed load sediment transport	sediment transport in suspension	total sediment transport
Meyer, Peter (1934), Meyer, Peter and Müller (1948)	Rouse (1937)	modified Einstein by Colby and Hembree (1964)
Einstein-Brown (1950)	Einstein (1942)	Banglod (1966)
Yalin (1963)	Smith-McLean (1977)	Engelund – Hansen (1972)
van Rijn (1984)	van Rijn (1984)	Yang (1972)
Engelund – Fredsøe (1976) modified by Deigaard (1993)	Aritathurai – Arulanandan (1978)	Chang, Simons and Richarson (1965)
Novak and Nalluri (1984)	Brooks (1963)	Ackers – White (1973)
May (1993)	Engelund – Fredsøe (1976) modified by Deigaard (1993)	Velikanov (1982)

There are also difficulties in agreement about the predominant mode of transport in sewer sediments since it probably will be a kind of “near-bead” suspension close to a bed-load type. The bed-load mode of transport may be the more broadly found in the literature, applied for the analysis of the transport of inorganic sediment deposits from sewer (De Sutter *et al.*, 2003). On the other hand, bed-load formulations developed for alluvial streams (or modified versions), are present in most of the software for modelling water quality in sewer systems.

The following bed-load sediment transport equation were chosen to briefly be explained at the herein document, because are commonly offered for the sediment transport assessment in urban drainage commercial models that considered water quality issues.

2.4.4.1 Meyer-Peter and Müller (1948), Wong-Parker modification (2006)

The formulation developed by Meyer and Peter, and later modified by Müller (1948) is known as the MPM method.

The formulation allows the calculation of a dimensionless solid flow (q_s*) applicable to granular and non-cohesive particles (Delleur, 2001; Chaudry, 2008). The range of particles for which the formulation was verified is between 0.4 to 30 mm. This formulation also allows to introduce sediment mixtures constituted by several particle sizes and specific gravities, for which a prior determination of an effective diameter for the particle mixture is proposed (equation 2-25).

The MPM relationship is shown in equation 2-24, which gives as result the dimensionless sediment bed flow (q_b*).

$$q_b{}^* = 8.(\theta - \theta_{0cr})^{3/2}$$

$$= 8.\left[{(\tau_0 - \tau_{0cr})}\big/{g.(\rho_s - \rho_w).d_e} \right]^{3/2} \qquad for\ \theta_{0cr} = 0.047 \qquad 2\text{-}24$$

$$d_e = \sum_i (d_i.\Delta p_i).\left[\sum_i \Delta p_i\right]^{-1} \qquad 2\text{-}25$$

Later, Wong and Parker (2006) have introduced a correction in the equation 2-24,which provide better approximations verified in river streams. The updated equation is shown here below.

$$q_b{}^* = 3.97.(\theta - \theta_{0cr})^{3/2} \qquad for\ \theta_{0cr} = 0.0495 \qquad 2\text{-}26$$

2.4.4.2 van Rijn (1984)

Leo van Rijn (van Rijn, 1984, 1993) present a method for the assessment of the sediment transport bed-load as a multiplication between two dimensionless factors related with the flow conditions and the particle characteristics. Its validity was verified for particle sizes ranging between 0.2 to 2.0 mm, and displaying a non-cohesive behaviour.

The sediment bed flow (q_b*) in a dimensionless form can be calculated using the following equations:

$$\begin{aligned} q_b{}^* &= 0.053\,.T^{2.1}.D^{*-0.3}, && if\ T < 0.3 \\ q_b{}^* &= 0.10\,.T^{1.5}.D^{*-0.3} && if\ T > 0.3 \end{aligned} \qquad 2\text{-}27$$

And a transport rate for bed-load sediment by meter width (q_b) in kg/s/m can be obtained from the application of the next equation:

$$q_b = q_b{}^*.[(s-1).g]^{0.5}.d_{50}{}^{1.5} \qquad 2\text{-}28$$

For the calculation of the variables involved, here below are shown the needed equations:

- *dimensionless grain size* (D*) shown in equation 2-19
- *transport dimensionless parameter* (T) using the equation 2-30

$$T = \frac{(u^{*\prime})^2 - (u_{cr}{}^{*})^2}{(u_{cr}{}^{*})^2} \tag{2-29}$$

- *critical mobility parameter of Shields* (θ_{cr}) through the equation 2-18
- *critical bed-shear velocity* (u^{*}_{cr}), equation 2-30

$$u_{cr}{}^{*} = [\theta_{0cr}.(s-1).g.d_{50}]^{0.5} \tag{2-30}$$

- *effective shear stress velocity* ($u^{*\prime}$), through the equation 2-31, where *C'* is the *Chezy coefficient* linked to the particles (equation 2-32), and R_{hb} is the hydraulic radio of the deposited bed of sediments, v is the average mean flow velocity in m/s

$$u^{*\prime} = \frac{g^{0.5}.v}{C'} \tag{2-31}$$

$$C' = 18.log\left(\frac{12.R_{hb}}{3.d_{90}}\right) \tag{2-32}$$

2.4.4.3 Ackers and White (1991)

The formulation reviewed by Ackers (1991, 1996) is based on a previous methodology published also by Ackers and White (1973). The transport prediction focus on the bed-load and suspended-load considered separately. This sediment transport methodology derived from non-cohesive and single-size sediments. It was calibrated using experimental data sets from laboratory flumes.

The last review from 1996, for use in sewers with varied cross-section shapes and based on supplementary laboratory data, has not changed considerably from the initial version developed for fluvial sediment and rectangular channel (Schellart, 2007). The Ackers and White relationship performs poorly (and might even be considered inappropriated) when is applied to predict the mobilization and transport of granular sediment mixtures commonly found in sewer pipe inverts. (De Sutter *et al.*, 2003)

Ackers and White formulation is based on tree dimensionless parameters termed: particle size (D_{gr}), sediment mobility (F_{gr}) and sediment transport rate (G_{gr}), given in the following equations.

$$D_{gr} = \left(\frac{g\ (s-1)}{v^2}\right)^{\frac{1}{3}} d_s \tag{2-33}$$

$$F_{gr} = \frac{u^{*\ n}}{\sqrt{g\ (s-1).d_s}} \left(\frac{Vv}{\sqrt{32}\ .log_{10}(10\ D_m/d_s)}\right)^{1-n} \tag{2-34}$$

$$G_{gr} = \left(\frac{C_V\ D_m}{d_s}\right)\left(\frac{u^{*}}{V}\right)^n = C\left(\frac{F_{gr}}{A_{gr}} - 1\right)^m \tag{2-35}$$

where D_m is the hydraulic mean depth, A_{gr} is the value of F_{gr} at the threshold of motion, v the mean flow velocity, and C_v the volumetric sediment concentration. For the representative particle size is recommended to take the value of d_{50} for uniform size sediments and d_{35} for graded sediments. The coefficients A_{gr}, C, n, and m are empirically assessed related with the D_{gr} value.

2.4.4.4 May (1993)

May proposed that sediment concentration mobilized from the bed can be calculated in two stages. One considering the roughness of the bed of sediments used to find, in a second stage, the overall hydraulic resistance of the pipe.

The effective mobility parameter (F_s) proposed for sediment particles is given in equation 2-30, as function of a transition factor θ' which in turn depends on the particle Reynolds number assessed by applying equation 2-31.

The composite roughness used to obtain the particle Reynolds number is given by the equation 2-32, where P_w and P_b are the wetted perimeter for pipe walls and sediment bed respectively. λ_b is the roughness sediment bed and λ_w the roughness of the pipe walls.

$$F_s = F_{gr}\sqrt{\theta} \qquad 2\text{-}36$$

$$Re_c^* = \left(\frac{\lambda_c}{8}\right)^{0.5}\left(\frac{V\,d_{50}}{v}\right) \qquad 2\text{-}37$$

$$\lambda_c = \frac{P_w\,\lambda_w + P_b\,\lambda_b}{P_w + P_b} \qquad 2\text{-}38$$

The resistance to erosion of the bed is dependent on two dimensionless parameters, the sediment mobility (F_{gr}) and the Froude number (F_d) of the flow, where the sediment mobility depends on the grain friction factor termed λ_g function of the particle diameter and the hydraulic radius.

$$F_{gr} = \sqrt{\frac{\lambda_g\,V^2}{8\,g\,(s-1)\,.\,d_s}} \qquad 2\text{-}39$$

$$F_d = \sqrt{\frac{B\,V^2}{g\,A}} \qquad 2\text{-}40$$

B is the surface width of the flow and A the area of the flow cross section.

Then, the mobility parameter for the bed shear stress (F_b) is selected depending on the values adopted by F_{gr} and F_d. Subsequently, the bed friction factor (λ_b) is assessed from equation 2-41.

$$F_{gr} = \sqrt{\frac{\lambda_g\,V^2}{8\,g\,(s-1)\,.\,d_s}} \qquad 2\text{-}41$$

Finally, the volumetric concentration (C_v) is calculated as a function of a transport parameter η, which in turn depends on F_s.

$$C_v = \eta\left(\frac{W_b}{d_s}\right)\left(\frac{{d_s}^2}{A}\right)\left(\frac{\theta\,\lambda_g\,V^2}{8\,g\,(s-1)\,d_s}\right) \qquad 2\text{-}42$$

The verification of the performance when applied to sewer transport performed by De Sutter *et al.* (2003) also give poor results with the method proposed by May.

2.4.5 Transport of cohesive sediment in sewerage

It was mentioned before that the majority of the research in the field of sediment transport was developed for the hydrodynamic conditions in rivers and open channels. The findings achieved gave rise to developing predictive relationships mainly for the understanding of the movement of granular and non-cohesive particles. From their application in sewerage with cohesive particles the results obtained do not give as good fitting as that found in riverine environments, basically because differences in sediment nature and dynamics of the flow in a sewer network. For instance, in traditional transport formulations it is frequently assumed that the density of sediments is about 2650 kg/m^3, meanwhile sewer sediment are much more lighter (Section 2.2.4.2), introducing thereby errors in the sediment transport assessment.

While the physical processes involved in the movement of sediment particles through the sewer system are essentially the same as those which occur in rivers, the transport equations defined for non-cohesive riverine sediments are not necessarily appropriate to use in sewers. The traditional sediment transport formulations give, nevertheless, the definition of the main principles of the movement and allow understand the main mechanism that controls the sediment incipient motion and transport.

Additionally, experiences in the field conclude that the predictive formulations are highly sensitive to the input variables that characterize the sediment properties, particularly the specific gravity and yield strength (Ashley *et al.*, 2003). Intended to perform a more suitable predictive relationships, components that consider the organic content, the low density of the particles and the fine inorganic fraction are necessary to be introduced in the model.

The traditional concept of self-cleaning velocity used in the design of sewers pipes might be inadequate in many cases, if these limit for particles deposition is not related with the characteristics, nature and properties of the sediments itself. Even the concentration of sediments and hydraulic conditions must be considered in setting the boundaries from which the sediments can be mobilized by the water in sewers (Butler *et al.*, 2003).

Regarding the modelling of the sewer sediments transport, it must be considered that deposits build-up intermittently in sewers, and hence any subsequent re-erosion and movement is greatly dependent on the sediment availability.

As it was described in previous section (Section 2.2.6), environmental conditions regarding oxygen availability and residence time (dry-weather period) might significantly affect the erosion behaviour of organic sediment deposits (Tait, Marion, *et al.*, 2003; Banasiak *et al.*, 2005; Schellart *et al.*, 2005; Seco *et al.*, 2014). Tait, Ashley *et al.* (2003) worked with complex sediment mixtures collected in sewer systems and subsequently tested in laboratory under controlled deposition/erosion environmental conditions. The tests were carried out in an annular flume, trying to reproduce the environmental conditions in which in-pipe deposits form. Based on detailed measurements and observation, the study provides insight into the processes taking place during deposition and subsequent periods influencing on the solid transport behaviour, nevertheless no new sediment transport equations were derived from the finding.

It is clear that the complexity of the processes occurring makes difficult to predict the behaviour of cohesive sediment without comprehensive field knowledge.

2.4.5.1 Differences in considerations made in formulations for sediment transport in rivers and the required for their application in sewage

Although the basic mechanisms of sediment transport in sewers are the same as in rivers, the initiation of motion and sediment transport in sewers differs in several significant ways from transport occurring under fluvial conditions (Verbanck *et al.*, 1994; Ashley *et al.*, 1996; Berlamont *et al.*, 1996; Tait, Chebbo, *et al.*, 2003).

We can identify in the following list the main causes that condition the sediment transport in sewers:

- sewer pipes have rigid contours, there are no possibility of contours erosion
- sewer cross sections are well defined, closed and generally circular, significantly different from those of a natural stream or canals
- sometimes combined sewers may operate in surcharging conditions
- significant variations in the hydraulic conditions in combined sewers and unsteady flows. Sewer pipes are exposed to a wide range of flow variation coming from daily wastewater flows fluctuations during dry-weather, to storm runoff flows
- there is a limited availability of material ready to be eroded
- sewer solids are complex mixtures of cohesive (organic) and non-cohesive materials. Presence of materials from several origin and therefore, with characteristic properties cannot be considered homogeneous in composition or in size distribution (with a much broader spectrum than natural stream sediment size distribution)
- main differences in the properties of the transported materials are related to the organic content and a related cohesive character, which both have a significant influence on the initiation of movement of deposited sediments
- big spatial and temporarily fluctuations in the amount of sediment inputs, in both, a detailed scale (micro-scale) or in the whole system (macro-scale)
- the bed-deposits are often stratified due the fluctuations in sediment concentration in wastewater
- cohesion increases bonding forces interacting between particles, the erosion resistance of the bed may vary with time
- the shear stress vary markedly due to the boundary conditions
- under bed-load mode of transport, the proportion of associated energy losses are considerably higher than those experienced in rivers
- biochemical transformations occur. These processes beyond the physicals are involved on the initiation of motion of cohesive sediments, and the influence can vary over time because time dependent processes

2.4.5.2 Threshold of motion for cohesive sediment deposits

Based on the explained below (Section 2.4.1.1, see Figure 2-6) about the forces acting on a particle under a circulating flow, when considering fine cohesive sediments, the cohesive force (F_C) becomes more important (Mehta *et al.*, 1997).

In-sewer sediments are heterogeneous mixtures of particles, and the presence of fine sediments, biological sludge and greases in sewers enhance the occurrence of cohesion and adhesion mechanism. This interacting processes increase bonding forces interacting between particles that will affect the initiation of motion of the deposits.

Additionally, the biochemical transformations may address to consolidation of the deposited sediment during the called residence time along the dry-weather period. The degree of consolidation has also a significant influence on the value of the critical shear stress and subsequent incipient motion of the particles. In organic deposits, it was also found that consolidation process results in deposits with an increase in density with depth (Parchure *et al.*, 1985; Mehta *et al.*, 1989) (see Section 2.4.5.2.2 for further details).

More difficulties arise because the highly variability in time and space of the sediments characteristics, and the influence that the environmental conditions (oxygen availability, length of the consolidation period).

The quantitative valuation of the critical bed shear stress of cohesive sediment particles is difficult and strongly time and site specific. The high level of variability in the conditions makes that probably, direct measurements are the better way to quantify the critical shear stress for cohesive sediment deposits (Lau *et al.*, 2000).

In the past, several studies have examined the critical shear stress in cohesive or partly cohesive sediment deposits from sewers, or by laboratory work using synthetic cohesive material.

Experimental results on erosion of cohesive-sediment deposits from combined sewers (Nalluri *et al.*, 1992; Oms *et al.*, 2008) conclude that after a consolidation period, the shear stress in cohesive deposits is higher than the values found for non-cohesive deposits. Shear stress values were determined using synthetic cohesive sediment, obtaining values in the order of about 2.5 N/m^2 (Nalluri *et al.*, 1992; Butler *et al.*, 2003). In summary, the resistance to erosion of cohesive sediment deposits typically observed in sewerage might be greater in several levels of magnitude to the threshold of motion shear stress calculated for granular-non-cohesive sediment (Butler *et al.*, 2003)

In studying the influence on the antecedent conditions on the critical shear stress using inorganic cohesive sediments, Lau *et al.* (2000) conclude that deposits formed under flowing conditions developed stronger flocs and links between particles, which results in deposits more resistant to erosion, conclusion previously reached by Ristenpart and Uhl (1993) reported at (Banasiak *et al.*, 2005) from fieldwork in combined sewers. They observed significantly higher shear stresses in deposits subjected to prolonged dry-periods under wastewater flows (3.3 N/m^2) than the values obtained at the beginning of the period (around 0.7 N/m^2).

Nevertheless, during laboratory measurements using organic sediments from combined sewers and synthetic sediments, Banasiak *et al.* (2005) found that biological processes occurring during prolonged dry-periods weaken the strength of the deposits with time. It has been suggested that under oxygen-rich conditions, the aerobic microbial activity liquidize the sediment deposit, reducing the resistance to erosion.

2.4.5.2.1 Determination of the bed-shear stress

As a result of a research carried out by Delft Hydraulics mentioned in (van Rijn, 1993), an empirical formulation was developed in order to contemplate cohesion in the calculation of the critical shear stress. This study was developed for inorganic cohesive solids from rivers (silt and clays). The equation (showed in 2-43) considers the influence of the amount of cohesive particles in the sediment deposit by introducing a percentage parameter p_s called percentage of cohesive matter, assessed for $d_{50} < 50$ µm and p_s ranging between 2 to 20%.

$$\tau_{c\_cohesive} = p_s^{0.5} . \tau_c \tag{2-43}$$

Nalluri and Alvarez (1992) have obtained another empiric relation to the assessment of the threshold shear stress (equation 2-44) applicable in circular pipes with a uniform flat sediment deposit.

$$\frac{\tau_b}{(\rho_s - \rho_w).g.d_{50}} = 0.964.C_v{}^{0.457}.\left(\frac{d_{50}}{R_{hb}}\right)^{-0.765}.f_{sb}{}^{0.41} \tag{2-44}$$

where R_{hb} is the hydraulic radius of the deposited sediment, C_v is the volumetric concentration and f_{sb} a friction factor.

From the review made in previous section, it is certain that one of the main differences concerning transport mechanism in sewers against transport in rivers is the influence of the rigid contours in a cross section on the hydraulic.

The distribution of the shear stress is affected by the influence of a deposit at the inlet. There can be a considerable difference between the hydraulic roughness on the sediment bed and that observed on the walls of the pipes. Thus, there is a non-uniform distribution of the bed-shear stress over the wetted perimeter (Berlamont *et al.*, 2003) that must be considered.

In sewers, the pipe wall is commonly considered like a rigid boundary and the contact surface between solid at the invert of the pipe and water is the called “loose” boundary. Sediment transport equations in sewers with deposited beds must consider simultaneously both conditions of rigid boundary and loose boundary.

2.4.5.2.2 Composite roughness and side wall effect on the hydraulics

A number of methods were developed to estimate independently the bed shear stress applied to the bed and to the walls of the pipe.

The method proposed by Einstein (1942) reported by (Skipworth, 1996; Ashley *et al.*, 2004) is known as the “side-wall elimination procedure”. The objective of the method is basically to separate the effect of the roughness over the sediment bed and the “smooth” walls of the pipe. In this way, allow introduce a correction in by eliminating the effect of the walls on the shear stress and hydraulic calculation used for assessing the transport rate per unit width.

The Einstein’s method of the side-wall elimination was used in previous research in sewer sediments (Skipworth, 1996; Rushforth, 2001; Banasiak *et al.*, 2005). It gives good results when applied in sewers pipes with shallow depths of water (Skipworth *et al.*, 1999; Ashley *et al.*, 2004).

The method is briefly explained below to its later application in the calculation of the transport rate in Chapter 6.

The method consists firstly in divide the water cross section into three subsections as is shown in Figure 2-8.

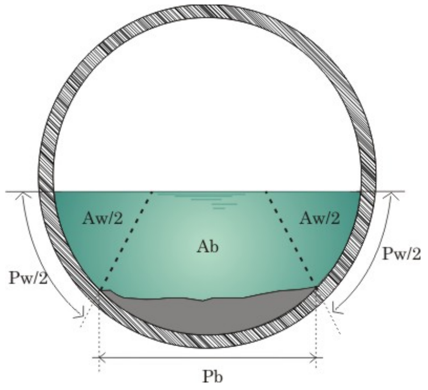


Figure 2-8 Sewer pipe cross sectionand divisions for the application of the Einstein's procedure for side-wall elimination.

The flow in the outside sections (left and right) is influenced by the roughness of the pipe wall. The central subsection is influenced for the sediment roughness. In this way, it is possible to evaluate the geometrical parameters of area (*A*), wetted perimeter (*P*) and hydraulic radius (R_h) by using the following equations, where all the subscripts *b* referred to the bed of sediments, and the subscript *w*, to the pipe walls:

$$A_b = A - A_w \qquad 2\text{-}45$$

$$Rh_w = \frac{A_w}{P_w} \Rightarrow A_w = Rh_w \, . P_w \qquad 2\text{-}46$$

$$Rh_b = \frac{A_b}{P_b} \Rightarrow A_b = Rh_b \, . P_b \qquad 2\text{-}47$$

Substituting equations 2-46 and 2-47 into 2-45

$$Rh_b = \frac{A - Rh_w . P_w}{P_b} \qquad 2\text{-}48$$

Considering the Manning's equation for the wall sections (equation 2-49) and rearranging to obtain Rh_w, it is possible to replace the Rh_w value at equation 2-48.

$$v = \frac{Rh_w^{2/3} . J^{1/2}}{n_w} \dashrightarrow Rh_w = \left(\frac{n_w \, . v}{}\right)^{3/2} \qquad 2\text{-}49$$

$$Rh_b = \frac{1}{P_b} . \left[A - \left(P_w . \left(\frac{n_w \, . v}{}\right)^{3/2}\right)\right] \qquad 2\text{-}50$$

Finally, the Rh_b value obtained in equation 2-50 is the needed to calculate the bed-shear stress (equation 2-51).

$$\tau_b = \rho \, . g \, . R_b \, . S_b \qquad 2\text{-}51$$

where S_b is the slope of the sediment bed surface, which can be considered equal to the slope of energy (J) for uniform flow conditions.

2.4.5.3 Consolidation effects on cohesive deposits

As mentioned previously, in deposits with a cohesive behaviour, consolidation process results in deposits that exhibit an increasing density with depth.

Parchure and Mehta (Parchure *et al.*, 1985; Mehta et al., 1989) developed experimental studies focusssed on the relationship between the bed-shear stress and the sediment deposit depth. Results obtained permit suggest the existence of a stratification regarding strength resistance. Three different zones were established in depth of the deposit. The sediment depth profile with the shear-stress-zones is shown at Figure 2-9.

The upper layer of sediment located just under the water interface exhibits a bed-shear stress that goes from a low value of strength (τ_{s0}) and rapidly increases with depth until a τ_{cs} value. In the second zone there is also an increment of the resistance strength but evidenced much more slowly than in the upper zone. The equilibrium in bed-shear stress is reached once arrived to the third zone, after which, the shear stress is kept almost constant (τ_{cu}) in depth.

The lower resistance to erosion of the bed surface (bed-shear stress τ_{s0}) are probably related with the low density that characterize sediment commonly found in sewers, but also because an intermittent process of deposition and re-erosion caused by the daily fluctuations of the wastewater flows in combined sewers. Thus, when velocity conditions increase over the limit of fluctuations of the wastewater flow, can be rapidly released and sent into suspension.

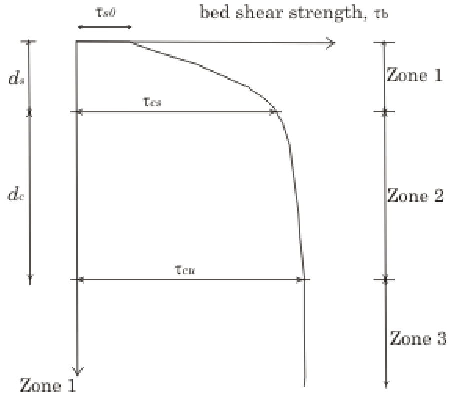


Figure 2-9 Schematic representation of the three zones in a bed-shear stress profile in depth (after (Parchure et al., 1985).

2.4.5.4 Particularities of the erosion and transport mechanisms for cohesive sediments

In the study of the mobilization of solids in sewerage, it is important to note that the way in which erosion starts in cohesive deposits is completely different from what occurs with granular deposits. While for non-cohesive solid deposits there is a gradual entrance of the eroded particles to water to flow, the pattern followed by cohesive deposits begins with the release of isolated particles on the surface of the deposit, followed by a violent collapse throughout the structure.

The sudden release in blocks of sediments is caused by the macro-roughness created by these isolated particles initially eroded, which generate local turbulence and accelerate the erosion process (Nalluri *et al.*, 1992).

Finally, once the deposit begins to move, the behaviour becomes similar to the movement of non-cohesive solids. The particles move in sewer in the same modes descripted for rivers, as a bed-load or suspended load.

Several researchers in the past had identified a highly concentrated transport zone above the bed-deposit in combined sewers (Ashley, Wotherspoon, *et al.*, 1992; Ashley *et al.*, 1994, 1996; Ristenpart *et al.*, 1995). The sediments moving around this zone exhibit characteristic of fluids, and had received diverse names: fluid mud, fluid sediment, organic-near-bed fluid.

This particular mode of transport for sewer particles conveys high suspended concentration of solids in a thin layer close to the interface water-solid deposit. The concentration may vary in depth and the transported sediments exhibit highly organic composition and densities closer to the water density, generally displaying non-uniform size distribution.

From the observations made, it was agreed about the existence in sewers of a particular mode of transport close to the bed giving the name of *near-bed solids (NBS).* The term *near-bed solid* (NBS) is used since these earlier research as a simple and more accurately way of describing the particles moving close to the deposit surface (Arthur *et al.*, 1996)

The near-bed fluid solid transport must be differenced from the bed-load from river transport mainly because the influence of the organic nature of the sediment in the movement (Arthur *et al.*, 1996, 1997).

2.4.6 Existing models for erosion and transport of cohesive sediments

Bearing in mind the described in previous sections, the sediment behaviour will directly influence on the initiation of motion. A sediment transport model suitable for considering the mobilization of prior deposited sediment in-pipes require the comprehensive knowledge about the sediment nature and characteristics, being capable moreover for considering the hydraulic and dynamic in sewerage.

During the last two decades, a wide variety of research was carried out intended to improve the assessment of the sediment transport originated in the release of sediments from in-sewer deposits under time-variable flows.

Most of the models are deterministic (relationships between variables controlling the process modelled). The predictive relations describing the mobilization of cohesive particles in sewers have been based on previous formulations developed for cohesive muds in estuarine. The resultant relationships have, in general, the limitation that were developed from laboratory-scale studies, under controlled conditions of uniform flows that can be quite distant to real hydraulic in sewer pipes. Moreover, many studies were carried out using synthetic sediment, uniform in size and composition, or by using mixtures of inorganics (sand and clays). The evaluation of the behaviour of the sediment deposits and the quantification of the solid transport loads will be, thus, affected by these constraints.

The stochastic nature of the problem itself, adds difficulties in reaching further development of numerical models for the determinations of the rate of sediment transport in a sewer.

Reviewing the regulations, there is a report from the CIRIA (Report No. 141 Ackers *et al.*, 1996) that recommend a formula based on May (1993), explained in Section 2.4.4.4, for the assessment of a bed-load sediment transport in sewers, as the optimum design relationship found from the analysis of the performance of several empirical formulations (Schellart, 2007). No regulation in that respect exists in Spain, where the current typically design of gravity sewer systems regarding transported sediments is carried out under the consideration of a self-cleaning condition to avoid deposition in pipes. In this way, the design is based on a minimum settling velocity fixed value that even does not consider the characteristics of the sediments.

Along the European research on the general transport and erosion principles for sediments from sewers, conclusions were reached showing that both erosion and transport phenomena in sewers are completely dissimilar from those observed in non-cohesive sediment. From these research results several methods and modelling approaches have become available. The main predictive sediment transport developments can be categorized in the following five groups, the first four correspond to deterministic physically-based models: 1) formulations developed from laboratory-scale studies; 2) formulations derived from *in situ* measurements studies; 3) formulations developed for non-cohesive sediment with potential application for cohesive sewer sediments, 4) formulations developed for rivers and later adapted to sewers; and finally 5) conceptual models. A briefly detail of the predictive formulations included in each group is shown below.

Despite of the several current options for sediment load prediction, it is necessary to consider that the development of the majority of transport formulations is based mainly on site-specific data. The wideness of variations on the sediment characteristics and on the hydraulic operation of the sewer systems, leads to a limited applicability of each developed predictive method (Ashley *et al.*, 2003, 2004). There is no widely applicable relationship, each case study need to be considered individually. Furthermore, it must be taken into account the differences in the environmental conditions for deposition, conveyance during time-varying flows, and sediment characteristics at the Mediterranean region in comparison with those in northern regions for which most of the relationships were developed. These differences may lead to errors in the prediction of the sediment transport potential when these models are applied in such different conditions.

The complexity of the overall process, the diversity of the transformation phenomenon in sediment deposits for which there is a limited scientific knowledge and the complex dynamics in the sewer flows make the calibration/validation process essential.

2.4.6.1 Formulations developed from laboratory-scale studies

Erosion and transport of sewer sediments have been modelled in several studies in Europe, mainly in UK and France. Some of the studies were performed using real in-sewer sediments and some others using synthetic sediment with cohesive characteristics that is believed shows a similar behaviour to the displayed by real sediments from sewers. The use of surrogate sediments is justified in order to simulate the of in-sewer deposits behaviour, better controlling the sediment characteristics to perform repeatable experiments.

The sediment deposits are subject to controlled hydraulic condition laboratory tests. The formulations for transport rate prediction are then based on the results of the empirical observations under the various conditions tested.

Laboratory derived equations were obtained in studies carried out in UK by Skipworth, P. (Skipworth, 1996; Skipworth *et al.*, 1999) using homogeneous cohesive synthetic sediment and steady flow, and later by Rushforth, P. (Rushforth, 2001), based on Skipworth's findings but using simple mixtures of artificial non-cohesive and cohesive sediments. Another cohesive sediment transport model was developed in Belgium about the same period by using mixtures of non-cohesive and cohesive materials under unsteady flow conditions (De Sutter, 2000b). The sediment used was made by mixing crushed olivestone (organic sediment), clay (inorganic cohesive) and sand,

The model for assessing the release, erosion and transport proposed by Skipworth (1996) consider the existence of a prior bottom consolidated layer in-pipes. The bed consolidation rate is considered non-linear in depth based on previous findings made by Mehta *et al.* (1997) for estuarine sediments. Skipworth (1996) proposed a four-calibration parameters approach for the assessment of the transport rate based on experimental results with synthetic cohesive sediments. Erosion rates are calculated with an excess shear stress relationship of the type proposed by Parchure *et al.* (1985), where M and n are constants:

$$E = M\left(\frac{\tau_b - \tau_c}{\tau_c}\right)^n \qquad 2\text{-}52$$

By considering a non-linear consolidated bed structure, Skipworth (1996) introduce in the model a way to consider the rheological properties of the cohesive sediments.

Modified version of Skipworth (1996) model was proposed by Rushforth (2001) and later by Kanso *et al.* (2003). Both, as done by Skipworth (1996), also considering a non-linear consolidation in the sediment depth, but for the latter case, without a consolidated bottom layer and a three-calibration parameters approach. As a result of a validation of the Skipworth method by using mixtures of sand and synthetic cohesive sediment, Rushforth (2001) add to the relationship a correction for mixture sediment proportion and adjusting the calibration parameters of the model.

Erosion and transport rates assessed from laboratory tests performed by De Sutter (De Sutter, 2000b) are shown as a function of the percentage of the cohesive binder. The derived equations are based on experimental tests where a sediment bed composed by artificial mixture of cohesive and non-cohesive sediments are subjected to steady flow conditions.

These derived semi-empirical relationships descripted below consider the initiation of motion dependent on an excess shear stress of the type shown at equation 2-52.

Among the main limitations of these formulations is the use of surrogate sediments that might not adequately reproduce the behaviour of real sewer sediment from deposits. Other significant limitation is that most of the cases avoid considering the influence of environmental conditions of the consolidation period as well of the oxygen availability on the resistance to erosion.

Despite the different conditions at which the sediments (real or surrogate) were exposed during tests, all the studies helped in increasing the understanding of sewer solids behaviour subject to erosion under circulating flows.

Later on this dissertation, a field study case of sediment accumulated in sewers with a high organic content and cohesiveness is analysed to evaluate the erosion potential. The consolidation assumption made by Skipworth (1996) and the availability of data from field monitoring campaigns, might allow the application and calibration of this method with adequate fitting degree. Based moreover on the robustness and uncertainty assessment analysis made by Freni *et al.* (2008), the relationship proposed by Skipworth seems the more adequate to predict the sediment erosion in the herein case of study. Therefore, only Skipwoth's relationship is described in more detail below. The application in the case study is shown at Chapter 6.

2.4.6.1.1 Skipworth, P. method (1996)

The methodology proposed by Skipworth (1996) is based on the consideration of several sediment layers forming a bed structure that displays different degrees of resistance against erosion. The method developed is derived from laboratory results obtained from the erosion and transport of sediment previously deposited in-pipe subjected to steady flow conditions. Crushed olivestone flour was used as sediment. The used material constitutes a bed layer with homogeneous size, chemical composition and density (d_{50} = 0.047 mm and density ρ_s = 1450 kg/m^3).

As it was mentioned above, the proposed method is based in an excess shear stress relationship first suggested by Parchure *et al.* (1985) for estuarine deposits. The equation that allows the evaluation of the sediment erosion rate is the shown at equation 2-52. In the equation, E is the erosion rate in g/m^2/s for the applied bed shear stress τ_b in N/m^2, τ_c in N/m^2 the critical shear stress, and M is a transport parameter used as calibration factor equal to the erosion rate when $\tau_b = 2.\tau_c$ and with the same units as E.

Skipworth (1996) considered a structured bed in the in-pipe sediment deposit that shows a weakly upper layer and a stronger underlying layer. It was hypothesised and later confirmed by experimentation that the upper layer exhibits a variation of the erosional strength with depth. Once the lower layer is achieved, the deposit presents a uniform resistant to erosion. The sketch in Figure 2-10 shows the suggested relationship between the erosional resistance and the depth of the sediment deposit. At the upper layer, the erosional strength increases in depth from a surface strength (τ_{cs}) until a value of strength (τ_{cu}) once the thickness of the upper layer (d') is exceeded.

The variation on the resistance to erosion with respect to depth is described with the equations below. For the determination of the critical erosional strength Skipworth (1996) proposed the equations shown below, where the power equation shown firstly in equation 2-53 represents the variation of the critical strength in the upper weak layer.

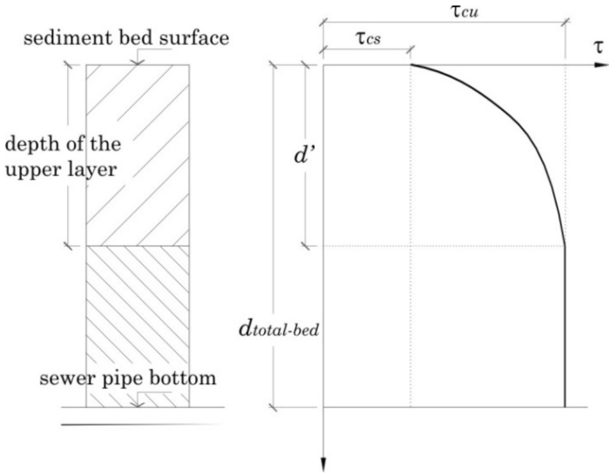


Figure 2-10 Variation of the erosional resistance of the sediment deposit in a depth profile. (after (Parchure et al., 1985).

$$\tau_c = \left[\left(\frac{d}{d'}\right)^{1/b} (\tau_{cu} - \tau_{cs})\right] + \tau_{cs} \quad , 0 \leq d \leq d'$$
$$\tau_c = \tau_{cu} \quad , \quad d > d' \qquad 2\text{-}53$$

In this equation, the independent variable d represents the cumulative depth of erosion, while d' indicates the thickness of the upper layer where the erosional strength takes increasing values in depth as shown in Figure 2-10.

The values of the parameters τ_{cs} ,τ_{cu}, d' and b are related with the structure of the bed deposit and the characteristics of the sediment (sediment particle size and density). Moreover b is a calibration parameter which describes the change in bed strength with depth. The factor M is also a calibration parameter of the model suggested as dependent on the hydraulic conditions (flow regime and slope of the pipe), but also related with the sediment characteristics.

Therefore, due the high dependence on the sediment bed properties, the value of all of these five parameters must be experimentally determined to obtain a more realistic prediction of the sediment transport.

2.4.6.2 Formulations derived from *in situ* measurements studies

This second category comprises the studies of real in-sewer sediments carried out in their environment.

Most of the *in situ* research was carried out in France. Relationships derived from direct *in situ* measurements are mainly based on flushing experiment through the injection of water and subsequent data analysis based on mass balance considerations (Ahyerre, Oms, *et al.*, 2001; Creaco *et al.*, 2009).

Creaco and Bertrand-Krajewski (2009) present a numerical model to predict mobilization by flushing effects on previous accumulated sediment bed, based on the solution of the coupled Saint-Venant and Exner equations by the TVD MacCormack scheme. The model tested the operation of flushing gates in an egg-shaped trunk sewer in Lyon, France.

Arthur, S. (Arthur, 1996; Arthur *et al.*, 1998) carried out a series of field data collection in a sewer system in Dundee, UK. A predictive relationship was proposed based on a multiple regression analysis of dimensionless factors that considered the relevant parameters in the erosion and transport procedure. The predictive relationship used to fitting between measured and simulated values is a seven-calibration parameters approach like the one shown in equation 2-54. The relevant parameters selected and included in the relationship of the method are: ambient hydraulic conditions, inputs to the system, upstream sediment bed characteristics, transported particles characteristics. As it can be seen, the applied shear stress and critical values are included in this relationship as part of the dimensionless factor related with the ambient hydraulic conditions.

$$C_v = a_1 + b_1\left(\frac{I_r\ TSS}{D_r}\right) + c_1\left(\frac{y}{y_{max}}\right) + d_1\left(\frac{\tau_0}{\tau_b}\right) + e_1\left(\frac{\rho_d}{\rho_w}\right) \qquad \textit{2-54}$$

Further knowledge is reached in understanding the sewer sediments behaviour and in-sewer processes from the results and observations made during field data collection. Despite that, one of the main difficulties found from these studies is the lack of repeatability in the conditions and on the characteristics of the analysed sediments, due to the high spatial and time variations observed on the sediment deposited. Consequently, the equations derived from *in situ* measurements are locally and temporal dependent.

2.4.6.3 Formulations developed for non-cohesive sediment with potential application for sewer sediment

Several earlier research have been developed examining the sediment transport for sewer systems considering the movement of non-cohesive granular and uniformly sized sediments, and most of them with no consideration of a limited sediment supply (Nalluri *et al.*, 1994; Arthur, 1996; Berlamont *et al.*, 1996; Skipworth *et al.*, 1999; Rushforth *et al.*, 2003; Ota *et al.*, 2013).

Most of the derived relationships of this group are focused on the particle transport at the limit of deposition (Novak *et al.*, 1984; Nalluri *et al.*, 1994; Arthur, 1996; Ota *et al.*, 2013). In general, the formulae referred to transport rate of the granular, cohesionless sediment, with d_{50} ranging from 0.15 mm to 8.74 mm and specific gravity from 2.53 to 2.65.

A review of literature in this group show relations like the provided by Novak and Nalluri (1975), May (1993) and Nalluri and Ab.Ghani (1993) that give the volumetric concentration (C_v) of the mobilized sediment at the deposition limit. The sediment concentration ($\mathrm{C}_v = \mathrm{f}(\mathrm{d}_{50}, \mathrm{s}, \mathrm{R}_\mathrm{h}, \mathrm{D}_\mathrm{gr}, \mathrm{v}_s, \lambda_\mathrm{s})$) is referred to: the flow velocity, hydraulic radio, a friction factor (λ_s) and the sediment characteristics (mean particle size d_{50}, D_{gr}, and specific gravity). The relationship found by Novak and Nalluri (1975) is shown at equation 2-55.

$$C_v = 4.10\ \lambda_c^{2.04}\left(\frac{d_{50}}{R_h}\right)^{-0.538}\left(\frac{v^2}{8\,g\,(s-1)R_h}\right)^{1.54} \qquad \textit{2-55}$$

Ota *et al.* (2003) in this same trend of research, proposed a predictive equation based on the Meyer-Peter and Müller (1948) formulation for computing the sediment bed load in sewer systems in terms of a transport parameter (θ) referred to the bed load (q_b), and a dimensionless grain size shear stress (ψ'_b). The relationship was based on a series of laboratory experiments in a partly full clear pipe carried out with granular uniformly sized sediment tested at limit of deposition under uniform flows.

$$\phi = 16.5\,(\psi_b' - 0.036)^{1.67}$$

$$\varphi = \frac{q_b}{\left(d_s^3\, g\,(s-1)\right)^{1/2}} \;\; ; \;\; \psi_b = \frac{\tau_b}{(\rho\, g\,(s-1)\, d_s)} \;\; ; \;\; \psi_b = 18\,\psi'^{1.87}_b \qquad 2\text{-}56$$

New approaches of this last group but using adaptive neuro-fuzzy inference system (ANFIS), which is a combination of neural network (ANN) and fuzzy logic (Azamathulla *et al.*, 2012), and gene-expression programming (GEP) (Ab. Ghani *et al.*, 2011) were recently developed as alternative methods for prediction sediment transport. Both cases are based on a self-cleaning criterion to avoid deposition during dry-weather periods. The experiments on which the derived approaches are based were carried out with non-cohesive granular sediments considering clean pipes with various roughness values. Azamathulla *et al.* (2012) obtained a relationship (equation 2-57) for assessing the volumetric concentration (C_v) based on experimental data regression analysis where the parameters involved are the sediment characteristics (d_{50}, ρ_s, D_{gr}), pipe geometry (R_h), settling velocity (v_s) and an overall friction factor (λ_s), basically the same involved in other methodologies.

$$\frac{v_s}{\sqrt{g\left({\rho_s}/{\rho}\right) d}} = 0.22\, D_{gr}^{-0.27}\, C_v^{0.16} \left(\frac{d_{50}}{R_h}\right)^{-0.29} \lambda_s^{-0.51} \qquad 2\text{-}57$$

Despite the considerable effort invested in these studies, a limited successful results were obtained from their application in some sewer systems (Arthur *et al.*, 1996), mainly because site-specific derived relationships and the significant differences in the sediments characteristics from other independent sewer system.

2.4.6.4 Formulations developed for rivers and later adapted to sewers

The transport rate relationships originally developed considering fluvial conditions represent the sediment deposits constituted by homogeneous and, in general, non-cohesive coarse particles (usually larger than 63 µm). There is not even any consideration about the transformation processes that can influence on the consolidation of the deposit or the formation of an upper biological layer, both affecting the start of the mobilization of the particles. From making this oversimplification in the sediment characteristics and processes occurring, inaccurate results might arise.

Typically used formulas are Ackers (1991), Ackers and White (1991), Engelund-Hansen (1967), van Rijn (1984), Yang (1973), May (1993) and Meyer-Peter and Müller (1948). All of them related sediment transport with a critical shear stress. For the further details on the relationships refer to Section 2.4.4. Nevertheless, some of these formulas are included in formulation of some commercial models applied in sewer systems.

Despite the pointed out above, the majority of the current software packages available for quality calculations use transport rate relationships originally developed in fluvial environments.

2.4.6.5 Conceptual models developed for transport in sewers

The purpose of a conceptual model is to provide simplified algorithms by using statistical data analysis that considers the general concepts of relevant physical processes occurring during sediment transport.

Conversely to what happen in deterministic models, the parameters on a conceptual model have no (or partial) physical significance or correlation with the behaviour of the simulated system or process. The determination of the parameters values of this type of models can just be made by calibration against real collected data, which essentially is an indirect fitting between simulation results and measured data.

Through simplistic assumptions, conceptual models give some reasonable predictions about sediment transport when are properly calibrated and the application case has similar conditions to that for which the model was developed.

From a literature review, examples of current conceptual models are the propose by Ruan (1998) (Ruan *et al.*, 1997; Ruan, 1998), Schlütter (Schlütter, 1999a, 1999b). Both based on deterministic hydraulic modelling and parameters calibrated against data measured in urban sewerages.

A more simplified approach was found by Bertrand-Krajewski (1992). The predictive method proposed consist in a simple exponential depletion law that intend to take into account the complexity of the erosion process based on the analysis of data collected in real urban sewer system. The predictive relationship is of the form shown in equation 2-58.

$$E = M\,(1 - e)^{k_{erosion}\,Q\,\Delta t} \tag{2-58}$$

More recently conceptual model development was carried out by Mannina and Viviani (Mannina *et al.*, 2010). The proposed model contains two modules, one for the hydrological and hydraulic calculation, and the second for the consideration of deposition of sediments and pollutants during dry-weather period, and subsequent release and transport during wet-weather flows both, in the surfaces of the catchments and in-sewers. The erosion and transport module is based on previous finding by Skipworth (1996).

The use of these conceptual models is justified by the fact of the lack of data and comprehensive knowledge about sediments characteristics and transformations occurring in sewers. Despite that, calibration process against locally measured data is essential.

2.4.7 Calibration, validation, verification process significance

As it was previously mentioned, the selection of a more adequate formulation for each study case will depend on the level of similarities with the sediment characteristics and sewer dynamics of the case from which the predictive formulation was derived. Additionally, it is also necessary and essential the calibration-validation-verification of the simulated results through the comparison against measured data.

Three steps process is recommended. The process is graphically represented in Figure 2-11. Firstly a calibration step is carried out through the application of one set of input data. Secondly, the model is validated by applying a new independent data set, keeping fixed the values of the constants obtained during calibration. Finally, the validation can be made transposing the calibration constant and running the model in a different catchment (Schlütter, 1999a).

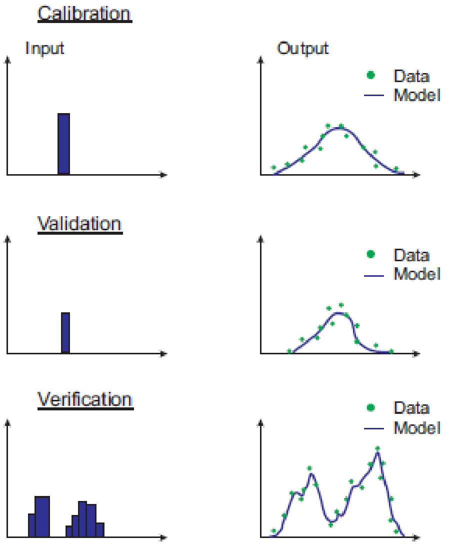


Figure 2-11 Recommended Calibration-Validation-Verification procedure for models. (after (Schlütter, 1999a).

The complexity of the overall process and the stochastic nature of the phenomena occurring during the release and transport of sediment in the course of wet-weather flows in sewers, added to the diversity of the transformation phenomenon in sediment deposits for which there is a limited scientific knowledge, makes the calibration-validation process essential independently the predictive relationship chosen.

Despite the level of detail and complexity in the algorithms to describe the physical and biochemical (if it is the case) processes occurring during release and transport of sewer solids, the model will not give reliable results unless a calibration, validation and verification procedure is followed based on real measured data locally collected.

Additionally, regarding quality data, complex models require data inputs that might be inaccessible for measurement, or that the collection means an expensive and unjustified procedure. Moreover, difficulties increase because the stochastic temporarily and spatially variation of the data that need to be measured in sewer. There are also a potential complexity due the calibration parameters can interact with each other (Ashley *et al.*, 2004).

The selection of the model complexity, and the amount of parameters involved, is limited by the availability and quality of the measured data that will be used as input for calibration (Schlütter, 1999a). The complexity of the model needs to agree on measured data available and on the detail and precision of the desired output.

If model contains too many calibration factors that cannot be measured or verified, the accuracy (and reliability) of the prediction does not be guaranteed (Ashley *et al.*, 2004).

2.5 Sewer flow-quality modelling software packages

Current software packages developed for sewer and urban drainage systems simulate the hydraulic flow routing and water quality performance. Large effort has been made on the accuracy of the hydrology and hydraulic models for detail time varying flow prediction and also for long-term simulations.

Nowadays, available software packages for urban sewer and drainage systems show good performance and high degree of confidence regarding flood routing. Hundreds of applications showed the goodness of the hydrologic and hydraulic modes, matching quite well the calculated values with measured data (flow and water levels).

However concerning quality considering the complexity and diversity of the whole process, the accuracy of the existing models is still limited. The models available provide oversimplifications of the sediment and pollutant transport with a high level of uncertainties (Freni *et al.*, 2008; Schellart *et al.*, 2010; Mannina *et al.*, 2012) and a low end-user confidence.

There is a large amount of commercial and freeware software packages that include modules for sediment and pollutant transport relationships.

Most currently used urban drainage simulation software packages are: *SWMM5* (EPA), *MIKE-Urban* (DHI) and *InfoWorks* (HR Wallingford Software). There exists, nevertheless, a long list on which it can be mentioned the following as examples: *SOBEK* (Delft Hydraulics), *SewerGEMS* (Bentley), *XP-SWMM* (XP Solutions), *PCSWMM* (Guelph University), and *AutoCAD Civil 3D.Stormwater*, the last three use *SWMM* as motor for the hydrology, hydraulic and quality calculations. And there are also some other, originally developed for unsteady free surface flow in rivers, but that can be applied to urban drainage modelling, like the 2D code *Iber* (CEDEX, FLUMEN-UPC, GEAMA-UdC and CIMNE) useful for flood studies along city surface, or the 3D *Flow 3D* (Flow Science) for very specific local studies.

The use of mathematical models for urban drainage systems is well established for research and management of complex sewer systems. However, software costs still limit their use by smaller end-users and designers. Since it first development, *SWMM* (EPA) is a freeware software package. The implementation of *SWMM* under a *Microsoft Windows* interface (version 5 first release in 2004) contributes to increment and facilitate its utilization as a common tool and make it a user-friendly program, which is easily available to students, small municipalities and companies (Cambez *et al.*, 2008).

Within this section it is just desired to provide a global vision about the current software packages capabilities with no intention to analyse which one would provide better assessment of sediment transport rates. The most relevant concept in deciding the software package to be used during a project is related with the quality and availability of logged data, which might determine the type of model to be used, despite maybe there are some others with more advanced technology tools.

2.5.1 Sewer sediment transport in current commercial models

The quality modelling in combined sewer systems is mostly aimed to predict the evolution of sediment loads for time varying flows at the initial phase of storm events, when spill episodes from CSOs structures mainly occur.

All the previous mentioned models, in general, besides the hydrologic and hydraulic calculation, can make the simulation of quality processes occurring on the surfaces of the catchment and in the sewer network. Nevertheless, not all of them consider the effect of the release of sediments from inside the sewer pipes and the effects caused by the cohesive properties and the heterogeneity in composition and size that characterize sediments from sewers. Additionally, almost none of them consider the transformations that occur within the pipes neither its dependence on environmental conditions.

Still nowadays, the software packages simulate sediment transport rates from inside pipes by the use of physically based models developed within riverine environments for uniformly sized non-cohesive material. For instance, Ackers (1991) is one of the predictive relationships linked to sediment transport module of *InfoWorks* (HR Wallingford), and Ackers and White (1973), Engelund and Fredsøe (Fredsøe, 1984) and van Rijn (1984) are between the formulations offered by *MIKE-Urban* (Danish Hydraulic Institute), two of the most widely used commercial software in Europe that current model erosion and transport of sewer sediments (De Sutter *et al.*, 2003; Schellart, 2007).

The inadequacy of the application of these transport relationships in sewer systems with sediment displaying strong differences in nature and behaviour, made that some commercial software start including some considerations about cohesive behaviour. For instance *MIKE-Urban* (DHI) is one of the commercial software which attempts to include cohesively and a range of in-sewer processes (Ashley *et al.*, 2003). Regarding sediment transport considerations, *InfoWorks* developed by Wallingford Software recently allows to specify two sediment fractions that can be modelled independently or dependently. Each fraction can be defined with different porosity, density and settling velocity.

Section 2.5.2 displays a more extended explanation about SWMM5 capabilities and relevant aspects for quality modelling since it is the software package later used at the conceptual methodology described at Chapter 5.

The lack of field data available for calibration and verification, and the uncertainties in the assessment of the parameters increase the difficulties in the use of these software models and reliability of their results. Another concerning disadvantage when dealing with quality models is linked with the complexities in the data logging because the high temporal and spatial variability of the measured quality parameters.

A common aspect between formulations used in these software packages is that most of them have been calibrated using limited data in a small amount of catchments, or in other cases, using data collected from experimental work under controlled conditions, which both generate a high level of uncertainties in the prediction (De Sutter *et al.*, 2003).

The end-user qualification and the knowledge about the modelled catchment and quality processes occurring, and even the modeller knowledge about the model interface and capabilities also influence on the calibration performance and is relevant for getting good simulation results (Schlütter, 1999a).

2.5.2 SWMM 5.0

SWMM (Storm Water Management Model) developed and maintained by the United States Environmental Protection Agency (UP-EPA) is a dynamic modelling module for urban drainage and sewerage systems application. The software package allows the hydrologic and hydraulic simulation based on physical modelling. The aim of the model is to analyse the hydrodynamic behaviour in terms of runoff, and moreover allow the prediction of the evolution of quality parameters both during dry or wet-weather periods built-up and later washed-off from the catchment and mobilized through the system (Rossman, 2009; Gironás *et al.*, 2010).

SWMM is probably one of the most widely used urban drainage software packages since its early development in the 70´s. Freeware software with open source code developed in C++ language, make it easily available for students and small municipalities and consultancies. This is one of the main advantages of *SWMM* in front of high economical license costs of other software with similar capabilities.

Despite its more user-friendly interface (*SWMM 5.0* and recently *5.1*) (EPA Environmental Protection Agency, 2011, 2014), it has some limitations when comparing with its pairs *MIKE-Urban* and *InfoWorks*. Since the current usual source of the network data is a GIS system (Geographic Information System), one of the disadvantages is the limited graphical interface for introducing the elements of the model approach. Nevertheless nowadays exist some projects like *inp.PINS* (*https://sites.google.com/site/inppins/home)* developed by *SWMM* users for integrate *SWMM5* and *GIS* capabilities.

2.5.2.1 Overall quality considerations and sewer sediments mobilization in SWMM5

About quality issues, *SWMM5* comprise modules for solid build-up and wash-off from the surfaces and allow considering the effects of the street cleaning, pollution concentration in dry-weather flow (with hourly, weekly and seasonal patterns), concentration in precipitation, or in other direct inflows as well as from urban soil erosion or ground water infiltration in the network system. It is also possible to considerate decay of pollutants during conveyance in through the system.

The sediment and pollutant transport in the system is based on a mass conservation principle. The particles are supposed to be homogeneously distributed in the water mass, and particles conveyed at the water velocity. This oversimplification in the assuming that all the particles will be mobilized at the same water velocity is unrealistic and adds uncertainties in the prediction. Another limiting factor is that is not possible to modify the density of the sediments or other physical characteristics, and considers single particle size distribution. Moreover, no initial sediments on the pipes are considered.

The quality processes in *SWMM5* may be modelled for a non-limited number of pollutants defined by the user. Regarding pollutants attached to solids, it is possible to contemplate the affinities between suspended solids and other pollutants by direct use of multiply factors (Rossman, 2009).

SWMM5 assume complete pollutant mixing within the pipes in the form of a continuously stirrd tank reactor. Sedimentation in-pipes is not contemplated.

The quality outputs in SWMM 5 are shown as pollutant concentration evolution over time, evaluated in a desired specific location in the system.

Despite *SWMM5* considered the transference of particles through the network system, last updated versions *5.0* and *5.1* do not consider the existence of a sediment deposit inside the conduits that could be released, re-suspended and transported by effect of time varying flows.

Previous version of *SWMM5* considered sophisticated approaches for prediction the concentration loads originated in the in-sewer sediment mobilization. Bed load and suspended loads were considered in a quality module in SWMM 4 with satisfactory results, nevertheless, the calibration process involved too many parameters and was difficult to apply without an adequately set of data (Huber *et al.*, 1992; Bertrand-Krajewski *et al.*, 1993). This module has been pulled out from version *5.0* onwards mainly because changes in the calculations routines.

Despite the conceptual and oversimplifications in the quality module, SWMM5 can lead to reliable result regarding pollutant loads. The reliability of the results is strongly dependents on the availability of locally measured data for the calibration-verification procedure.

2.5.2.2 Build-up and Wash-off from surfaces

SWMM 5 in terms of quality allows the consideration of solids and pollutants accumulated in the surfaces of the catchment during the dry-weather periods and the wash-off process during rain events and subsequent introduction into the conduit system and transport through it. Nevertheless, as it was mentioned above, just can consider the mobilization of pollutants from the surfaces and the inputs from direct inflows or dry-weather wastewater flows without taking into account the influence of the sedimentation in pipes and re-suspension during runoff.

It is necessary to define build-up and wash-off functions that best suit on the real accumulation and runoff wash-off in the catchment. Reductions in the accumulation can be considered due to street cleaning and/or best management practices (BMPs) for each land use assigned to the sub-catchments areas.

The possibility of considering separate land uses for each area of the catchment where a different activity may occur, allows the use of different constants to define the build-up and wash-off processes for the defined pollutants (Rossman, 2009).

SWMM 5.1 (EPA Environmental Protection Agency, 2014) provide with three equations as governing functions for the pollutant build-up process: power, exponential and saturation functions, and the possibility to introduce an external time series for the consideration of the accumulation of pollutants. Regarding wash-off process, there are three available equations: exponential, rating curve and event mean concentration (EMC). For further details about the mentioned relationships refer to (Rossman, 2009).

2.6 Summary

The quality modelling in combined sewer systems is aimed to predict the evolution of sediment loads for time varying flows. There is special interest in the sediments and the pollutants attached loads at the initial phase of storm events, when spill episodes from CSOs mainly occur, in a phenomenon known as “first flush”.

Under time varying flow conditions, first-flush pollution phenomenon (Deletic, 1998) is typically observed in Mediterranean catchments due the singular weather conditions characterized by long dry-weather period followed by storm events. The high variability of the flow regime of the rivers in the region, strongly dependent on the seasonal rainfall, turns in a quite limited dilution capacity of the natural waters in front at urban waters discharges (Prat *et al.*, 2000). In this region it is therefore significant to achieve a good adjustment in the prediction of pollutants loads that can reach natural receiving waters through combined sewer overflows (CSOs) during rainfall. The better prediction of sediment loads might allow to benefit the management of pollutants that arrive to natural streams and generate high oxygen demand in receiving waters.

This literature review shows that the characteristics and behaviour of sewer sediment represented by cohesive sediment heterogeneous mixtures is widely variable over time and space. Moreover, in sewer dynamics, changes in velocity, flow can occur over fairly short periods. In this situation, the mechanisms for which their release and transport through the system occurs during storm conditions is governed by complex processes that are still not completely understood, and must be evaluated for each study case. Both erosion and transport phenomena completely differ from those observed in granular non-cohesive sediment. Sedimentation during dry periods in sewers also displays particularities that are influenced by the cohesive behaviour and interaction between particles.

Considering the aforementioned complexities of the processes occurring in-sewer under different environmental conditions, and the complex nature and behaviour of the sewer sediment itself, this chapter highlighted the findings from several research studies about that the transposition of sediment transport relationships originally developed for fluvial environments is not straightforward and might even be inadequate.

All the sediment transport equations derived from laboratory and *in situ* studies are heavily dependent on the conditions of sediment deposit formation and on the characteristics of these sediments (composition, size distribution, density). The transport rate relationships found from these studies were therefore site-specific and their application in a general context might be inadequate without a detail analysis of the “initial conditions” at which the sediments were subjected.

It was also shown that the consideration of other pollutants mobilization (the called solids attached pollutants) is possible to model by multiplying the sediment concentration by suitable and locally determined potency factor.

This is a fact also that the progress in modelling and the reliability of the results obtained strongly depends on the availability of reliable quality data (Delleur, 2003).

Improvements in the modelling sediment transport become important for the prediction of water quality and the receiving waters protection.

A better understanding of the physical and biochemical properties of the real sediments from combined sewer systems and its behaviour is significant to be considered in water quality models. The more realistic behaviour that could be introduced in a model will allow representing more appropriately the movement of solids in pipes, and predicting accurately the changes in pollutant concentration that can reach a watercourse by urban drainage overflow discharges.

Bibliography of the chapter

Ab. Ghani, A., Md. Azamathulla, H., 2011. Gene-Expression Programming for Sediment Transport in Sewer Pipe Systems. Journal of Pipeline Systems Engineering and Practice **2** (3), 102–106, DOI:10.1061/(ASCE)PS.1949-1204.0000076.

Ackers, J., Butler, D., May, R.W.P., 1996. *Design of sewers to control sediment problems (CIRIA Report No. 141).* CIRIA, Construction Industry Research and Information Association, January 1996., London, UK, ISBN: 978-0-86017-443-1.

Ahyerre, M., Chebbo, G., Saad, M., 2000. Sources and erosion of organic solids in a combined sewer. Urban Water **2** (4), 305–315, DOI:10.1016/S1462-0758(01)00012-7.

Ahyerre, M., Chebbo, G., Saad, M., 2001. Nature and Dynamics of Water Sediment Interface in Combined Sewers. Journal of Environmental Engineering **127** (3), 233–239, DOI:10.1061/(ASCE)0733-9372(2001)127:3(233).

Ahyerre, M., Oms, C., Chebbo, G., 2001. The erosion of organic solids in combined sewers. Water Science & Technology **43** (5), 95–102.

Almedeij, J., Ahmad, E., Alhumoud, J., 2010. Representative Particle Size of Sediment in Storm Sewer Inlets **6** (4), 316–323.

Arthur, S., 1996. *Near-bed solids transport in combined serwers.*

Arthur, S., Ashley, R.M., 1997. Near bed solids transport rate prediction in a combined sewer network. Water Science & Technology **36** (8-9), 129–134.

Arthur, S., Ashley, R.M., 1998. The influence of a near bed solids transport on firts flush in combined sewers. Water Science & Technology **37** (1), 131–138.

Arthur, S., Ashley, R.M., Nalluri, C., 1996. Near bed solids transport in sewer. Water Science & Technology **33** (9), 69–76.

Ashley, R.M., Arthur, S., Coghlan, B.P., McGregor, I., 1994. Fluid Sediment in Combined Sewers. Water Science & Technology **29** (1-2), 113–123.

Ashley, R.M., Bertrand-Krajewski, J.-L., Hvitved-Jacobsen, T., Verbanck, M.A., 2004. *Solids in Sewers. Characteristics, effects and control of sewer solids and associated pollutants. Scientific and Technical Report No.14*, First. ed. IWA (International Water Association) Publishing. Joint Commitee on Urban Drainage, London, ISBN: 1-900222-91-4.

Ashley, R.M., Crabtree, R.W., 1992. Sediment origins, deposition and build-up in combined sewer systems. Water Science & Technology **25** (8), 1–12.

Ashley, R.M., Crabtree, R.W., Fraser, A., Hvitved-Jacobsen, T., 2003. European Research into Sewer Sediments and Associated Pollutants and Processes. Journal of Hydraulic Engineering **129** (4), 267, DOI:10.1061/(ASCE)0733-9429(2003)129:4(267).

Ashley, R.M., Fraser, A., Burrows, R., Blanksby, J., 2000. The management of sediment in combined sewers. Urban Water **2** (4), 263–275, DOI:10.1016/S1462-0758(01)00010-3.

Ashley, R.M., Verbanck, M.A., 1996. Mechanics of sewer sediment erosion and transport. Journal of Hydraulic Research **34** (6), 753–770, DOI:10.1080/00221689609498448.

Ashley, R.M., Wotherspoon, D.J., Goodison, M.J., McGregor, I., Coghlan, B.P., 1992. The Deposition and Erosion of Sediments in Sewers. Water Science & Technology **26** (5-6), 1283–1293.

Azamathulla, H.M., Ab. Ghani, A., Fei, S.Y., 2012. *ANFIS-based approach for predicting sediment transport in clean sewer*, Applied Soft Computing.

Bach, P.M., McCarthy, D.T., Deletic, A., 2010. Redefining the stormwater first flush phenomenon. Water Research **44** (8), 2487–98, DOI:10.1016/j.watres.2010.01.022.

Banasiak, R., Verhoeven, R., De Sutter, R., Tait, S.J., 2005. The erosion behaviour of biologically active sewer sediment deposits : Observations from a laboratory study. Water Research **39** (20), 5221–5231, DOI:10.1016/j.watres.2005.10.011.

Berlamont, J.E., Torfs, H., 1996. Modelling (partly) cohesive sediment transport in sewer systems. Water Science & Technology **33** (9), 171–178, DOI:10.1016/0273-1223(96)00384-8.

Berlamont, J.E., Trouw, K., Luyckx, G., 2003. Shear Stress Distribution in Partially Filled Pipes. Journal of Hydraulic Engineering **129** (9), 697–705, DOI:10.1061/(ASCE)0733-9429(2003)129.9(697).

Bertrand-Krajewski, J.-L., 1992. A Model for Solid Production and Transport for Small Urban Catchments: Preliminary Results. Water Science & Technology **25** (8), 29–35.

Bertrand-Krajewski, J.-L., 2006. *Modelling of Sewer Solids Production and Transport. Cours de DEA "Hydrologie Urbaine"*, Transport. INSA de Lyon, Lyon.

Bertrand-Krajewski, J.-L., Briat, P., Scrivener, O., 1993. Sewer sediment production and transport modelling: A literature review. Journal of Hydraulic Research **31** (4), 435–460, DOI:10.1080/00221689309498869.

Bertrand-Krajewski, J.-L., Chebbo, G., Saget, A., 1998. Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. Water Research **32** (8), 2341–2356, DOI:10.1016/S0043-1354(97)00420-X.

Bertrand-Krajewski, J.-L., Madiec, H., Moine, O., 1996. Two experimental sediment traps: Operations and solids characteristics. Water Science & Technology **33** (9), 155–162.

Butler, D., May, R., Ackers, J., 2003. Self-Cleansing Sewer Design Based on Sediment Transport Principles. Journal of Hydraulic Engineering **129** (4), 276–282, DOI:10.1061/(ASCE)0733-9429(2003)129:4(276).

Cambez, M.J., Pinho, J., David, L.M., 2008. Using SWMM 5 in the continuous modelling of stormwater hydraulics and quality. In: 11th International Conference on Urban Drainage. Edinburgh, Scotland, UK.

Chaudry, M.H., 2008. *Open-Channel Flow*, Springer. ed. ISBN: 978-0-387-30174-7.

Chebbo, G., 1992. *Solides des rejets pluviaux urbains : caractérisation et traitabilité.* PhD Thesis.Ecole Nationale des Pontes et Chaussées. Paris. France.

Chebbo, G., Bachoc, A., Laplace, D., Le Guennec, B., 1995. The transfer of solids in combined sewer networks. Water Science & Technology **31** (7), 95–105.

Clegg, S., Forster, C.F., Crabtree, R.W., 1992. Sewer sediment characteristics and their variation with time. Environmental Technology **13** (6), 561–569, DOI:10.1080/09593339209385184.

Crabtree, R.W., 1989. Sediments in Sewers. Water and Environment Journal **3** (6), 569–578, DOI:10.1111/j.1747-6593.1989.tb01437.x.

Crabtree, R.W., Ashley, R.M., Gent, R., 1995. Mousetrap: Modelling of real sewer sediment characteristics and attached pollutants. Water Science & Technology **31** (7), 43–50.

Creaco, E., Bertrand-Krajewski, J.-L., 2009. Numerical simulation of flushing effect on sewer sediments and comparison of four sediment transport formulas. Journal of Hydraulic Research **47** (2), 195–202, DOI:10.3826/jhr.2009.3363.

Deletic, A., 1998. The first flush load of urban surface runoff. Water Research **32** (8), 2462–2470, DOI:10.1016/S0043-1354(97)00470-3.

Delleur, J.W., 2001. Sediment Movment in Drainage Systems. In: Mays, L.W. (Ed.), Stormwater Collection Systems Design Handbook. McGraw-Hill, ISBN: 0-07-135471-9.

Delleur, J.W., 2003. The Evolution of Urban Hydrology: Past, Present, and Future. Journal of Hydraulic Engineering **129** (8), 563–573, DOI:10.1061/(ASCE)0733-9429(2003)129:8(563).

Dirksen, J., Baars, E.J., Langeveld, J.G., 2013. The impact of fat, oil, and grease deposits on the performance of sanitary sewers. In: 13th International Conference on Urban DrainageSewer Procesess and Network. Sheffield. UK. September 2013.

Dirksen, J., Baars, E.J., Langeveld, J.G., Clemens, F., 2011. Settlement as a driver for sewer rehabilitation. In: 12th International Conference on Urban Drainage. Porto Alegre, Brasil.

EPA Environmental Protection Agency, ., 2011. SWMM 5.0 (version 5.0.022).

EPA Environmental Protection Agency, ., 2014. SWMM 5.1 (version 5.1.006).

Fan, C.-Y., 2004. *Sewer Sediment and Control. A management practices reference guide (EPA/600/R-04/059).* Cincinnati.

Fan, C.-Y., Field, R., Lai, F., 2003. Sewer-Sediment Control: Overview of an Environmental Protection Agency Wet-Weather Flow Research Program. Journal of Hydraulic Engineering **129** (4), 253–259, DOI:10.1061/(ASCE)0733-9429(2003)129:4(253).

Fang, H., Shang, Q., Chen, M., He, G., 2014. Changes in the critical erosion velocity for sediment colonized by biofilm. Sedimentology **61** (3), 648–659, DOI:10.1111/sed.12065.

Fraser, A., Sakrabani, R., Ashley, R.M., Johnstone, F., 2002. Managing sewer solids for the reduction of foul flush effects - Forfar WTP. Water Science & Technology **45** (3), 265–272.

Freni, G., Mannina, G., Viviani, G., 2008. Uncertainty assessment of sewer sediment erosion modelling. Urban Water Journal **5** (1), 21–31, DOI:10.1080/15730620701737033.

Gasperi, J., Gromaire-Mertz, M.C., Kafi-Benyahia, M., Moilleron, R., Chebbo, G., 2010. Contributions of wastewater, runoff and sewer deposit erosion to wet weather pollutant loads in combined sewer systems. Water Research **44** (20), 5875–5886, DOI:10.1016/j.watres.2010.07.008.

Gasperi, J., Kafi–Benyahia, M., Lorgeoux, C., Moilleron, R., Gromaire-Mertz, M.C., Chebbo, G., 2008. Wastewater quality and pollutant loads in combined sewers during dry weather periods. Urban Water Journal **5** (4), 305–314, DOI:10.1080/03087290802201415.

Gasperi, J., Zgheib, S., Cladière, M., Rocher, V., Moilleron, R., Chebbo, G., 2012. Priority pollutants in urban stormwater: part 2 - case of combined sewers. Water research **46** (20), 6693–703, DOI:10.1016/j.watres.2011.09.041.

Geiger, W.F., 1987. Flushing e ects in combined sewer systems. In: Proceedings of the 4th International Conference Urban Drainage. Lausanne, Switzerland.

Gironás, J., Roesner, L.A., Rossman, L.A., Davis, J., 2010. A new applications manual for the Storm Water Management Model (SWMM). Environmental Modelling & Software **25** (6), 813–814, DOI:10.1016/j.envsoft.2009.11.009.

Grabowski, R.C., Droppo, I.G., Wharton, G., 2011. Erodibility of cohesive sediment: The importance of sediment properties. Earth-Science Reviews **105** (3-4), 101–120, DOI:10.1016/j.earscirev.2011.01.008.

Gromaire-Mertz, M.C., Garnaud, S., Gonzalez, A., Chebbo, G., 1999. Characterisation of urban runoff pollution in Paris. Water Science & Technology **39** (2), 1–8, DOI:10.1016/S0273-1223(99)00002-5.

Gromaire-Mertz, M.C., Garnaud, S., Saad, M., Chebbo, G., 2001. Contribution of different sources to the pollution of wet weather flows in combined sewers. Water Research **35** (2), 521–33.

Hitved-Jacobsenv, T., Vollertsen, J., Haaning Nielsen, A., 2013. *Sewer Processes - CRC Press Book*, Second edi. ed. Taylor and Francis Group, ISBN: 978-1-4398-8177-4.

Hoeft, S., Wellmann, S., Tränckner, J., Krebs, P., 2011. Experiments on evolution of particle size in raw wastewater. In: 12th International Conference on Urban Drainage.

Hrissanthou, V., Hartmann, S., 1998. Measurements of critical shear stress in sewers. Water Research **32** (7), 2035–2040, DOI:10.1016/S0043-1354(97)00447-8.

Huber, W.C., Dickinson, R.E., 1992. *EPA/600/3-88/001a. Storm Water Management Model, Version4: User's Manual*, Environmental Protection. EPA. United States Environmental Protection Agency.

Hvitved-Jacobsen, T., Vollertsen, J., Nielsen, A.H., 2013. *Sewer Processes: Microbial and Chemical Process Engineering of Sewer Networks*, Second. ed. CRC Press, ISBN: 9781439881774.

Jensen, H.S., Nielsen, A.H., Hvitved-Jacobsen, T., Vollertsen, J., 2008. Hydrogen sulfide initiated corrosion in concrete sewers - a conceptual apporach for prediction. In: 11th International Conference on Urban Drainage. Edinburgh, Scotland, UK.

Kang, J.-H., Kayhanian, M., Stenstrom, M.K., 2006. Implications of a kinematic wave model for first flush treatment design. Water Research **40** (20), 3820–30, DOI:10.1016/j.watres.2006.09.007.

Kanso, A., Gromaire-Mertz, M.C., Gaume, E., Tassin, B., Chebbo, G., 2003. Bayesian approach for the calibration of models: application to an urban stormwater pollution model. Water Science & Technology **47** (4), 77–84.

Karlavičienė, V., Švedienė, S., Marčiulionienė, D.E., Randerson, P., Rimeika, M., Hogland, W., 2009. The impact of storm water runoff on a small urban stream. Journal of Soils and Sediments **9** (1), 6–12, DOI:10.1007/s11368-008-0038-9.

Keener, K.M., Ducoste, J.J., Holt, L.M., 2008. Properties Influencing Fat, Oil, and Grease Deposit Formation. Water Environment Research **80** (12), 2241–2246, DOI:10.2175/193864708X267441.

Kleijwegt, R.A., 1992. *On sediment transport in circular sewers with non-cohesive deposits.*

Lange, R.-L., Wichern, M., 2013. Sedimentation dynamics in combined sewer systems. Water Science & Technology **68** (4), 756–62, DOI:10.2166/wst.2013.278.

Laplace, D., Oms, C., Ahyerre, M., Chebbo, G., Lemasson, J., Felouzis, L., 2003. Removal of the organic surface layer in combined sewer sediment using a flushing gate. Water Science & Technology **47** (4), 19–26.

Lau, Y.L., Droppo, I.G., 2000. Influence of antecedent conditions on critical shear stress of bed sediments. Water Research **34** (2), 663–667, DOI:10.1016/S0043-1354(99)00164-5.

Lee, J.H., Bang, K.W., Ketchum, L.H., Choe, J.S., Yu, M.J., 2002. First flush analysis of urban storm runoff. Science of The Total Environment **293** (1-3), 163–175, DOI:10.1016/S0048-9697(02)00006-2.

Lucas-Aiguier, E., Chebbo, G., Bertrand-Krajewski, J.-L., Gagné, B., Hedges, P., 1998. Analysis of the methods for determining the settling characteristics of sewage and stormwater solids. Water Science & Technology **37** (1), 53–60.

Mannina, G., Schellart, A.N.A., Tait, S.J., Viviani, G., 2012. Uncertainty in sewer sediment deposit modelling: Detailed vs simplified modelling approaches. Physics and Chemistry of the Earth, Parts A/B/C **42-44** (1), 11–20, DOI:10.1016/j.pce.2011.04.003.

Mannina, G., Viviani, G., 2010. An urban drainage stormwater quality model: Model development and uncertainty quantification. Journal of Hydrology **381** (3-4), 248–265, DOI:10.1016/j.jhydrol.2009.11.047.

McIlhatton, T.D., Ashley, R.M., Tait, S.J., 2005. Improved formulations for rapid erosion of diverse solids in combined sewers. Water Science & Technology **52** (5), 143–150.

Mehta, A.J., Hayter, E.J., Parker, W.R., Krone, R.B., Teeter, A.M., 1989. Cohesive Sediment Transport. I: Process Description. Journal of Hydraulic Engineering **115** (8), 1076–1093, DOI:http://dx.doi.org/10.1061/(ASCE)0733-9429(1989)115:8(1076).

Mehta, A.J., Kirby, R., Stuck, J.D., Jiang, J., Parchure, T.M., 1997. *Erodibility of organic-rich sediments: A Florida perspective*. Rep. UFL/COEL/MP-97/01. Coast. Oceanogr. Engrg. Dept.; Univ. Florida.

Nalluri, C., Alvarez, E.M., 1992. The influence of cohesion on sediment behaviour. Water Science & Technology **25** (8), 151–164.

Nalluri, C., Ghani, A.A., El-Zaemey, A.K.S., 1994. Sediment transport over deposited beds in sewers. Water Science & Technology **29** (1-2), 125–133.

Novak, P., Nalluri, C., 1984. Incipient motion of sediment particles over fixed beds. Journal of Hydraulic Research **22** (3), 181–197, DOI:10.1080/00221688409499405.

Obermann, M., Rosenwinkel, K.-H., Tournoud, M.-G., 2009. Investigation of first flushes in a medium-sized mediterranean catchment. Journal of Hydrology **373** (3-4), 405–415, DOI:10.1016/j.jhydrol.2009.04.038.

Oms, C., Gromaire-Mertz, M.C., Saad, M., Milisic, V., Chebbo, G., 2008. Bed shear stress evaluation in combined sewers. Urban Water Journal **5** (3), 219–229, DOI:10.1080/15730620801924010.

Ota, J.J., Nalluri, C., 2003. Urban Storm Sewer Design: Approach in Consideration of Sediments. Journal of Hydraulic Engineering **129** (4), 291–297, DOI:10.1061/(ASCE)0733-9429(2003)129:4(291).

Ota, J.J., Perrusquía, G.S., 2013. Particle velocity and sediment transport at the limit of deposition in sewers. Water Science & Technology **67** (5), 959–67, DOI:10.2166/wst.2013.646.

Parchure, T.M., Mehta, A.J., 1985. Erosion of soft cohesive sediment deposit. Journal of Hydraulic Engineering **111** (10), 1308–1326, DOI:http://dx.doi.org/10.1061/(ASCE)0733-9429(1985)111:10(1308).

Piro, P., Carbone, M., Garofalo, G., Sansalone, J., 2009. Size Distribution of Wet Weather and Dry Weather Particulate Matter Entrained in Combined Flows from an Urbanizing Sewershed. Water, Air, and Soil Pollution **206** (1-4), 83–94, DOI:10.1007/s11270-009-0088-7.

Pisano, W.C., Aronson, G.L., Queiroz, C.S., Blanc, F.C., O' Shaughnessy, J.C., 1979. *EPA_600-2-79-133_Pisano_Dry-weather deposition and flushing for combined sewer overflow pollution control.* U.S. EPA, Cincinnati.

Pisano, W.C., Queiroz, C.S., 1977. *Procedures for estimating dry-weather pollutant desposition in sewerage systems (EPA/600/2-77/120).* Cincinnati, OH.

Pisano, W.C., Queiroz, C.S., Aronson, G.L., Blanc, F.C., O' Shaughnessy, J.C., 1981. Procedures for Estimating Dry Weather Pollutant Deposition in Sewer Systems. Journal Water Pollution Control Federation **53** (11), 1627–1636.

Prat, N., Munné, A., 2000. Water use and quality and stream flow in a Mediterranean stream. Water Research **34** (15), 3876–3881, DOI:10.1016/S0043-1354(00)00119-6.

Puertas, J., Suárez López, J., Anta Álvarez, J., 2008. *Gestión de las aguas pluviales. Implicaciones en el diseño de los sistemas de saneamiento y drenaje urbano*. CEDEX, Centro de Publicaciones Secretaría General Técnica Ministerio de Fomento., Madrid, ISBN: 978-84-7790-475-5.

Raunkjær, K., Hvitved-Jacobsen, T., Nielsen, P.H., 1994. Measurement of pools of protein, carbohydrate and lipid in domestic wastewater. Water Research **28** (2), 251–262, DOI:10.1016/0043-1354(94)90261-5.

Raunkjær, K., Hvitved-Jacobsen, T., Nielsen, P.H., 1995. Transformation of Organic Matter in a Gravity Sewer. Water Environment Research **67** (2), 181–188.

Van Rijn, L.C., 1984. Sediment Transport, Part I: Bed Load Transport. Journal of Hydraulic Engineering **110** (10), 1431–1456, DOI:10.1061/(ASCE)0733-9429(1984)110:10(1431).

Van Rijn, L.C., 1993. *Principles of sediment transport in rivers, estuaries and coastal seas*. Aqua Publications, Amsterdam, ISBN: 90-800356-2-9.

Ristenpart, E., 1995. Sediment properties and their changes in a sewer. Water Science & Technology **31** (7), 77–83.

Ristenpart, E., Ashley, R.M., Uhl, M., 1995. Organic near-bed fluid and particulate transport in combined sewers. Water Science & Technology **31** (7), 61–68, DOI:10.1016/0273-1223(95)00323-F.

Rossman, L.A., 2009. *EPA/600/R-05/040. Storm Water Management Model. User's Manual. Version 5.0*, Water Management. EPA. United States Environmental Protection Agency, Cincinnati.

Ruan, M., 1998. A conceptual CSO emission model: SEWSIM. Water Science & Technology **37** (1), 259–267, DOI:10.1016/S0273-1223(97)00777-4.

Ruan, M., Wiggers, J., 1997. Modelling sewer emission using simulink. Water Science & Technology **36** (5), 125–131.

Rudelle, E., Vollertsen, J., Hvitved-Jacobsen, T., Nielsen, A.H., 2011. Anaerobic Transformations of Organic Matter in Collection Systems. Water Environment Research **83** (6), 532–540, DOI:10.2175/106143010X12681059116699.

Rushforth, P.J., 2001. *The erosion and tranpsort of sewer sediment mixtures*. PhD thesis.Department of Civil and Structural Engineering. University of Sheffield. UK.

Rushforth, P.J., Tait, S.J., Saul, A.J., 2003. Modeling the Erosion of Mixtures of Organic and Granular In-Sewer Sediments. Journal of Hydraulic Engineering **129** (4), 308–315, DOI:10.1061/(ASCE)0733-9429(2003)129:4(308).

Sakrabani, R., Ashley, R.M., Vollertsen, J., 2005. The influence of biodegradability of sewer solids for the management of CSOs. Water Science & Technology **51** (2), 89–97.

Sakrabani, R., Vollertsen, J., Ashley, R.M., Hvitved-Jacobsen, T., 2009. Biodegradability of organic matter associated with sewer sediments during first flush. Science of the Total Environment **407** (8), 2989–2995.

Saul, A.J., Thornton, R.C., 1989. Hydraulic performance and control of pollutants discharged from a combined sewer storage overflow. Water Science & Technology **21** (8-9), 747–756.

Schellart, A.N.A., 2007. *Analysis of uncertainty in the sewer sediment transport predictions used for sewer management purposes*. PhD Thesis.Department of Civil Engineering. University of Sheffield. U.K.

Schellart, A.N.A., Tait, S.J., Ashley, R.M., 2010. Estimation of Uncertainty in Long-Term Sewer Sediment Predictions Using a Response Database. Journal of Hydraulic Engineering **136** (7), 403–411, DOI:10.1061/(ASCE)HY.1943-7900.0000193.

Schellart, A.N.A., Veldkamp, R.G., Klootwijk, M., Clemens, F., Tait, S.J., Ashley, R.M., Howes, C., 2005. Detailed observation and measurement of sewer sediment erosion under aerobic and anaerobic conditions. Water Science & Technology **52** (3), 137–46.

Schlütter, F., 1999a. *Numerical Modelling of sediment transport in Combined Sewer Systems*.

Schlütter, F., 1999b. A conceptual model for sediment transport in combined sewer systems. Water Science & Technology **39** (9), 39–46, DOI:dx.doi.org/10.1016/j.bbr.2011.03.031.

Seco, I., Gómez-Valentín, M., 2013. Calidad de aguas en tiempo de lluvia: estudio de una cuenca urbana en la región Mediterránea y calibración de un modelo hidrológico y de calidad en SWMM 5.0. In: III Jornadas de Ingeniería Del Agua La Protección Contra Los Riesgos Hídricos. Valencia.Spain. 23-24 Oct. 2013.

Seco, I., Gómez-Valentín, M., Schellart, A.N.A., Tait, S.J., 2014. Erosion resistance and behaviour of highly organic in-sewer sediment. Water Science & Technology **69** (3), 672–679, DOI:10.2166/wst.2013.761.

Skipworth, P.J., 1996. *The erosion and transport of cohesive-like sediment beds in sewers*. PhD Thesis.Department of Civil Engineering. University of Sheffield. U.K.

Skipworth, P.J., Tait, S.J., Saul, A.J., 1996. Laboratory investigations into cohesive sediment transport in pipes. Water Science & Technology **33** (9), 187–193.

Skipworth, P.J., Tait, S.J., Saul, A.J., 1999. Erosion of Sediment Beds in Sewers: Model Development. Journal of Environmental Engineering **125** (6), 566–573, DOI:10.1061/(ASCE)0733-9372(1999)125:6(566).

Skipworth, P.J., Tait, S.J., Saul, A.J., 2000. The first foul flush in combined sewers: an investigation of the causes. Urban Water **2** (4), 317–325, DOI:10.1016/S1462-0758(01)00009-7.

De Sutter, R., 2000a. The erosion of cohesive mixed deposits: implications for sewer flow quality modelling. Urban Water **2** (4), 285–294, DOI:10.1016/S1462-0758(01)00007-3.

De Sutter, R., 2000b. *Erosion and transport of cohesive sediment mixtures in unsteady flow*. Phd Thesis. University of Gent. Belgium.

De Sutter, R., Rushforth, P.J., Tait, S.J., Huygens, M., Verhoeven, R., Saul, A.J., 2003. Validation of Existing Bed Load Transport Formulas Using In-Sewer Sediment. Journal of Hydraulic Engineering **129** (4), 325–333, DOI:10.1061/(ASCE)0733-9429(2003)129:4(325).

Tait, S.J., Ashley, R.M., Verhoeven, R., Clemens, F., Aanen, L., 2003. Sewer sediment transport studies using an environmentally controlled annular flume. Water Science & Technology **47** (4), 51–60.

Tait, S.J., Chebbo, G., Skipworth, P.J., Ahyerre, M., Saul, A.J., 2003. Modelling in-Sewer Deposit Erosion to Predict Sewer Flow Quality. Journal of Hydraulic Engineering **129** (4), 316–324, DOI:10.1061/(ASCE)0733-9429(2003)129:4(316).

Tait, S.J., Marion, A., Camuffo, G., 2003. Effect of environmental conditions on the erosional resistance of cohesive sediment deposits in sewer. Water Science & Technology **47** (4), 27–34.

Tippler, C., Wright, I.A., Hanlon, A., 2012. Is Catchment Imperviousness a Keystone Factor Degrading Urban Waterways? A Case Study from a Partly Urbanised Catchment (Georges River, South-Eastern Australia). Water, Air, & Soil Pollution **223** (8), 5331–5344, DOI:10.1007/s11270-012-1283-5.

Verbanck, M.A., 1990. Sewer Sediment and its Relation with the Quality Characteristics of Combined Sewer Flows. Water Science & Technology **22** (10-11), 247–257.

Verbanck, M.A., Ashley, R.M., Bachoc, A., 1994. International workshop on origin, occurrence and behaviour of sediments in sewer systems: Summary of conclusions. Water Research **28** (1), 187–194, DOI:10.1016/0043-1354(94)90133-3.

Verbanck, M.A., Vanderborght, J.P., Wollast, P., 1990. Size distribution of suspended particles in combined sewers during dry and wet-weather. In: IAHR (Ed.), 5th International Conference on Urban Storm Drainage. IAHR, July 23-27, 1990. Osaka. Japan.

Vollertsen, J., Hvitved-Jacobsen, T., 2000. Sewer quality modeling – a dry weather approach. Urban Water **2** (4), 295–303.

Williams, J.B., Clarkson, C., Mant, C., Drinkwater, A., May, E., 2012. Fat, oil and grease deposits in sewers: Characterisation of deposits and formation mechanisms. Water Research **46** (19), 6319–6328.

Wong, M., Parker, G., 2006. Reanalysis and Correction of Bed-Load Relation of Meyer-Peter and Müller Using Their Own Database. Journal of Hydraulic Engineering **132** (11), 1159–1168, DOI:10.1061/(ASCE)0733-9429(2006)132:11(1159).

Chapter 3

Combined sewer flow-quality *in-situ* monitoring

In Chapter 2 it was identified the significance of account with local data registered at the study site for the calibration/verification processes of any hydraulic and quality model. As a consequence, a much better reliability of the results in modelling will be achieved.

Also, from previous Chapter 2, it was recognised that the application of sediment transport formulations is heavily dependent on the sediment characteristics (composition, size distribution and density). A better understanding on the processes occurring in sewers (and its modelling) is subject to the availability of real data.

This chapter focus in the monitoring of the hydraulic and quality parameters in a combined sewer system that is selected for study. The chapter describes the monitoring project's methodology (Section 3.1), which include an overview of the study catchment, the instrumentation and the description of sampling methodology and quality procedures for the pollutants' analysis.

The monitoring programme followed three purposes: firstly, it was proposed to identify the hydraulics and quality aspects in the combined sewer network during storm events (Section 3.2). Secondly the same purpose is followed in a more general way for dry-weather periods between rains (Section 3.3). Finally, the identification of the sediment deposited in-pipes characteristics (Section 3.4).

A brief summary of the monitored parameters and methodology used is presented at the end of this Chapter.

3.1 Introduction

The monitoring of the water quality and pollutants loads, as well as the characterization of the accumulated sediments during dry-periods, becomes necessary and a valuable resource in the studies of the reduction of pollutants that are released from CSOs.

The wastewater pollutant loads and sediment accumulation rates assessment, based solely on the correlation with the loads contributed by an equivalent population in the area are insufficient in detailed studies of pollutant conveyed and discharged through CSOs.

Wide variability, spatially and temporarily, and local dependence is observed in the quality parameters of combined sewerage (pollutant loads and deposited sediments characteristics). Additionally, the fluctuating hydrodynamic of the flow between dry and wet periods in combined sewer networks should be considered in the pollutant loads assessment. Thus, the application of quality predictive methodologies must be subjected to a process of calibration and verification against locally measured data. Therefore, the predictions made by modelling must include monitoring campaigns. Locally measured data is essential in the reliability of the prediction that can be made with models.

Given the high heterogeneity in composition that water and deposited solids might display, the collection of representative samples is a difficult task. In addition, the procedures of collecting samples are themselves problematic. Obtaining representative samples to analyse the sediment and pollutants characteristics is complex. Monitoring programmes that involve quality parameters in sewers should be carefully planned.

Monitoring programmes detailed below along this Chapter have been carried out in an urban catchment. Monitoring was mainly based on automated sampling and flow rates measurements. Rainfall data was registered simultaneously with flow and quality monitoring. The main purpose was to obtain local specific data to model the hydrodynamic and pollutant transport behaviour in a typical urban catchment in the Mediterranean region.

Rainfall, hydraulic and quality collected data are considered during the analysis and design phase of this research project and for the validation of the proposed sediment transport predictive methodology (Chapter 6).

3.1.1 General overview of the field study site

A subsequent future objective of this research project is the investigations of the problems caused by combined sewer overflows into natural water courses. The local characteristics of dry and wet-weather periods as well as the urban patterns have a strong influence on the sedimentation and re-mobilization of sediments and pollutants from the sewer systems. The climate of the Mediterranean region presents a quite irregular distributed rainfall along the year. Dry-weather periods usually longer than a week are followed by storm events. Under time varying flow conditions, *first-flush* polluting phenomenon (Deletic, 1998; Obermann *et al.*, 2009) is typically observed in Mediterranean catchments due to the singular weather conditions.

The high variability of the flow regime of the rivers in the region, strongly dependent on the seasonal rainfall, turns in a quite limited dilution capacity of the natural waters in front of urban waters discharges (Prat *et al.*, 2000). As it was previously mentioned in Chapter 2, the smallest watercourses are particularly more sensitive to the untreated waters from CSOs because the spill volume is usually higher than the circulating flows during the same period of discharges (Karlavičienė *et al.*, 2009), so then the dilution capacity is considerably reduced if not null.

In this region it is therefore significant to achieve a good adjustment in the prediction of pollutants loads that can reach natural receiving waters through combined sewer overflows (CSOs) during rainfall. The better prediction of sediment loads might allow benefit the management of pollutants that arrive to natural streams generating high oxygen demand in receiving waters.

The herein presented field work study focused on the characterization of the sediments conveyed and deposited in the sewer systems under the influence of the semiarid Mediterranean climate and characteristic urbanization configurations observed in highly populated areas in Catalonia, Spain.

The particularities of the climate and urban patterns promote in-pipes sedimentation and accumulation of deposits with high organic content with cohesive behaviour, whose dynamics of release under wet-weather flows is studied as main objective of this dissertation.

The study site is situated in the north-east of Spain, in the city of Granollers located at 35 km northerly from Barcelona in Catalonia, Spain. Granollers, located in the second crown of Barcelona metropolitan area, is the most densely populated city of the Vallès Oriental district. The town is crossed longitudinally by the Congost River (about 8 km length in the urban area), a tributary of the Besòs River. Land uses on both sides of the river are significantly different. On the right river bank, the use is primarily residential, while the left bank has a mainly industrial use. See left side of Figure 3-1 for details of the location.

An overview of the precipitation regime in the area and seasonal variation of the flows in the river were mentioned in Chapter 2, Section 2.2.1.

3.1.2 Location and description of the urban catchment and sewer system

A detailed analysis of the sewer system and on the availability of suitable locations for *in situ* measurements was made in advance. Information of the combined sewer network was provided by the sewer manager company *Drenatges Urbans del Besós* (DUB). Inspections and previous work for the instrumentation selection for monitoring was made in collaborative work with the managers of the sewer system with the support of the environmental protection consortium *Consorci per a la Defensa de la Conca del riu Besòs* (CDCB). The network and local inspections in the area was supplemented with cartography, orthophotos and topographic bases obtained from the

Cartographic Institute of Catalonia (ICC) (www.icc.cat) and urban plans from the City Council of Granollers

A small urban catchment in the central area of the city was selected for the study, covering a surface of approximately 10 hectares (Figure 3-1, right). The selected area has mainly a residential and commercial land use, with a high level of population density (150 inh/ha). A significant presence of food (bars and restaurants) commercial activity is observed in the studied area. The surface displayed a high degree of imperviousness that reaches almost the whole area in some zones, with an average imperviousness of 84%. Hence, the urban pattern is identified as impervious, residential highly dense and with a centralized commercial area. No industrial discharges are present in the area under study.

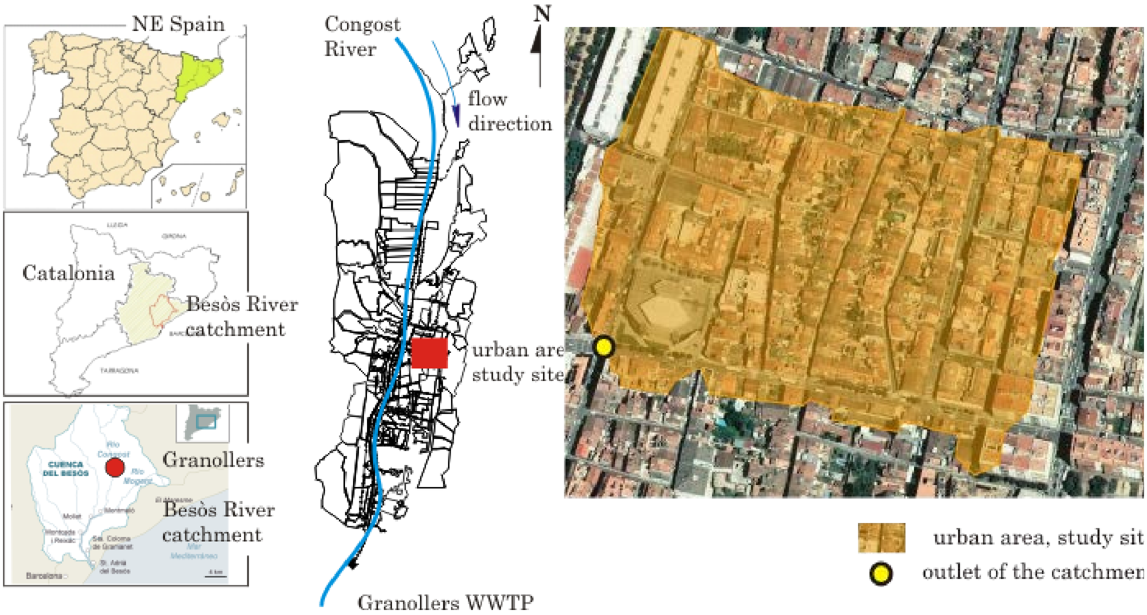


Figure 3-1   Location and extent of the urban catchment, Granollers. Catalonia (Spain).

The whole area is served by a gravity combined sewer system. The sewer network has a tree-type layout, composed in the studied area by all circular cross section concrete pipes with diameters ranging from 300 to 1000 mm. 48 manholes and around 22 km pipes with slopes from 0.005 to 0.022 conform the network in the studied area. General characteristics of the catchment and the combined sewer network are displayed in

Table 3-1. A scheme of the subcatchments and combined sewer network in the studied area is shown in Figure 3-2.

The catchment displays a single outlet situated in the south-west of the catchment (see Figure 3 1, right side and Figure 3-2), is a concrete pipe with an inner 1000 mm diameter (regular circular cross section) and a slope of 0.020.

Figure 3-2 Scheme of the urban catchment and combined sewer network.

Table 3-1: General characteristics for the catchment and combined sewer network of the study site.

urban catchment characteristics		combined sewer network characteristics		
area	10.1 ha	average wastewater flow	24 m^3/h	
land use	residential and commercial	total length of pipes	2.2 km	
surface slope	between 0.005 and 0.022 average 0.013	pipes diameters	between 300 and 1000 mm	
			diameter range	% in length
% imperviousness	between 77 and 93%		300 -400mm	65 %
			500-600 mm	13 %
population density	150 inh/ha		700 800 mm	5 %
			900 – 1000 mm	16 %
		Pipe material	concrete	

Analysed the sewer network in the studied catchment (without inputs from the surrounding sub-catchments), and the topography of the area, it can be considered that all the sewer water collected in the limits of the catchment as well as the drained rainfall runoff will arrive to the outlet point. Enough inlets are located to ensure that no surface flow exits through the streets.

The main sources of the sewerage include the discharges from the residential buildings, cafes and pubs in its area. The whole metropolitan area of Barcelona displays quite low drinking water consumption rates, which is translated in low wastewater flow. According to the data published by the local water management company, the drinking water rates have been decreased in the last years from 129.6

l/inh/day in 2001 to 105.1 l/inh/day in 2012 (http://www.aiguesdebarcelona.cat/evolucion-de-la-demanda-y-del-consumo-diario#). The low wastewater flow influences the reduction of the sediment transport capacity in the network during dry periods, assuming the same production of solids so increasing the sedimentation problems.

Having in mind the high impervious conditions of the studied urban catchment, if it is additionally considered the mentioned low wastewater flows, there is a significant risk of accumulation of organic sediments from domestic sources in the combined sewer pipes during the prolonged dry periods

Moreover, it is suggested that granular and inorganic sediments particles constitute a minor contribution during storm runoff due to the lack of sources for these materials, the limited existence of green or natural areas in the limits of the catchment that can provide coarse material.

3.1.3 Instrumentation for monitoring

For the purpose of this study, the solids and pollutants loads, flow and rain data registers as well as the characterization of sediment deposits were of interest. An overview about the instrumentation to measure these parameters is explained in this section.

The monitoring station is set at the control section in the catchment outlet. The station basically consists of a flowmeter (area-velocity) and an automatic sampler. The instruments main bodies were installed at the street level inside a vandal resistant cabinet. The outside from the network installation has the intention to facilitate the access for data downloading. The sensors (velocity and water-depth sensors, and sampling probe) were installed all underground through an existent storm gutter inlet pipe. The photos and sketch of the installation are shown in Figure 3-3. The position of the sensors in the invert of the pipe for wastewater and stormwater collection is shown in the photos. The change in the location for wet-weather measurements (sensors above the mean wastewater level) had the purpose to avoid continuous blockages of the strainer for sampling,reducing the frequency of the maintenance work.

The water flow was continuously monitored using an automatic portable flowmeter (HACH-Lange, Sigma 950 model) that combined water level and velocity sensors to obtain flow registers. Wastewaters and storm waters flows were thus registered.

The water quality in the combined sewer network from the previously detailed study site was analysed in terms of pollutants concentrations loads based on the samples collected. Meanwhile water flow was continually registered; several single samples were collected linked to the increasing water levels in the pipes during the stormwater runoff events. An increase in excess of the daily fluctuations flow rates triggered the collection of samples. Sampling frequency and trigger conditions are detailed below in Section 3.2.

The samples were collected by an automatic portable sampler (HACH-Lange Sigma SD900 model). The sampler is basically equipped with a peristaltic high speed pump that pumped 1000 ml in about 3 minute interval using 3/8 inches intake tube with a strainer at the end. A distributor arm inside the device is used to store the samples into 24 plastic bottles of 1000 ml capacity at each interval set. Samples were collected from the storage device immediately after the rain event and preserved in the conditions given by the standards methods until analysed.

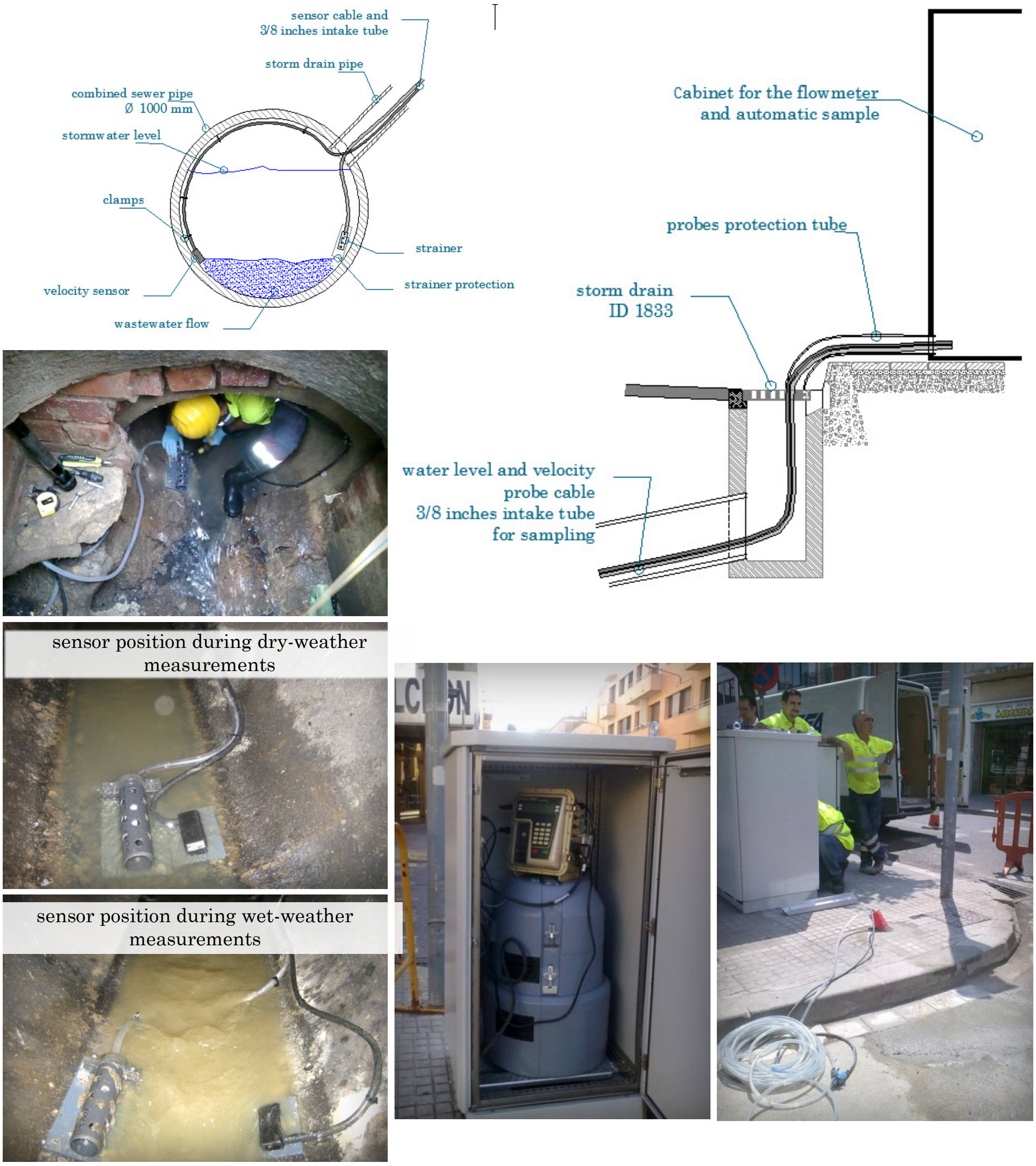


Figure 3-3 Monitoring station for flow measurements and water sampling installation.

The collection of sediments accumulated in pipes was made in different independent campaigns that are later explained in Section 3.4.

The flowmeter was calibrated in a hydraulic laboratory and the combined operation with the sampler was checked previous installation. Maintenance operations and cleansing of the outlet pipe and sensors was periodically planned.

The rainfall records were taken from a recording station that was installed in the vicinity of the flow control point (see Figure 3-4). Difficulties to find a suitable location inside the limits of the catchment for proper installation of this rain gauge made that it was located around 300 meters south-west from the outlet.

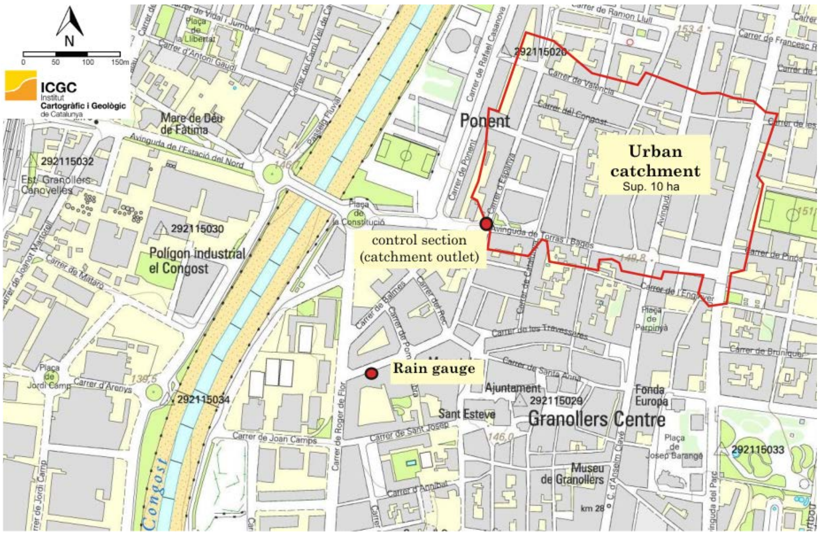


Figure 3-4 Urban catchment limits and location. Location of the raingauge station and control section.

The rainfall station was provided with pluviometer of intensity (HACH Sigma Rain Gauge Tipping Bucket) and GPRS communication system. Several stations in the city that already existed, managed by the environmental protection consortium CDCB, were used for verifications.

All the data collected during the monitoring campaign were subjected to verification in a pre-processing procedure. During this pre-processing of the data those events that presented major disturbances during sampling (blockages of the pumping tube or the probe, failures triggering sampler, power failures, etc.) were discarded.

The representativeness of the samples taken is another key issue since many factors influence on the results. Not just the wide temporal and spatial variation in water quality and sediment composition, but also the way of sampling, handling and preservation of the samples. The location inside the network and orientation of the probes and sensors also may affect the measurements done (Larrarte *et al.*, 2011).

The appropriated sampling technique and preservation is critical in obtaining reliable results that can then be used in the calibration and verification of the quality models.

3.1.4 Sampling, handling and conservation

Wastewater and stormwater sampling was carried out at the catchment outlet. Samples of one litre volume were collected by the automatic sampler in each bottle. After the rain event, in the same place of collection in the catchment, the water samples were transferred to individual 1 litre plastic containers adequately sealed and labelled. During the transfer process, it was taken special care to avoid losing the finest particles. Once the whole sample was moved from the original container, the supernatant water was used to rinse the sampler bottle and drag all the leftover particles.

After collection and moving to the sealed bottles, the samples were immediately transported to the laboratory facilities in the WWTP in Granollers, where they were stored refrigerated until the analysis could be performed. The samples were maintained at 4 ºC minimizing changes in the organic compounds during storage, following the recommendations given for *Standard Methods for the Examination of Water and Wastewater* (2005)

3.1.5 Sediment and pollutant characterization

The pollutant parameters studied are those which were considered the most representatives for the impact on receiving waters, and that were previously monitored in other urban studies in the region. In this sense, all the samples collected during the monitoring campaign were analysed for Suspended Sediments (*SS*), Chemical Oxygen Demand (*COD*) used as organic matter indicator; and Kjeldahl nitrogen (*TKN*) that include organic nitrogen compounds and ammonia. All of them usually used in as water quality indicators.

The analysis of the samples collected during this monitoring campaign were conducted by specialized technicians from the laboratory facilities of the Waste Water Treatment Plant in Granollers, managed by the environmental protection consortium (CDCB). The analyses of these parameters were performed in accordance to the following standards:

- Suspended Sediments (*SS*) following the specification of UNE 872:2006 (BS EN 872:2005, 2005),
- Chemical Oxygen Demand *COD* performed on the water sample without settling, by the method of potassium dichromate UNE 77004 (ISO 6060:1989, 2012)
- Kjeldahl nitrogen (*TKN*) according to UNE 25663 (ISO 5663:1984, 2012)

3.2 Wet-weather monitoring and characterization of water flow and quality

A monitoring programme was carried out along an 18-month period (May 2010 to November 2011). Throughout this period, samples for water quality analysis were collected during rain events with total precipitation over around 10 mm that occur after a dry-weather period longer than a week. These thresholds were established based on previous experience in local catchments of similar characteristics. It was hypothesised that under these conditions there will be sediment and pollutants available to be eroded from the catchment surfaces and from inside the network, as well as the generation of runoff over the surface enough to wash off the mentioned accumulated pollutants. It is then assumed that the accumulation of pollutants both in surfaces and deposited in the pipe inverts, during these periods was sufficient for the detection of increasing pollutant loads at the outlet of the analysed catchment.

After data pre-processing, a total of 7 events were available in the period analysed during the monitoring campaign (discarding events that were considered that might experience from major disruptions). Nevertheless, just 5 of these rain events could be used in quality modelling. For this events total precipitation and rainfall intensity, water depth, velocity and flow data, and quality parameters *SS*, *COD* and *TKN* data were simultaneously available. During the 18 months period, it was observed long periods with few or no rainfall, and then rain events in several consecutive days, making more difficult to collect suitable data and a more elevated number of events.

As it was mentioned before, the sampling start time during rainfall was driven by the flowmeter. Thus, the wet-weather sampling was linked to the increment in the water level/flow inside the pipe. Trigger threshold conditions were established for an increment in the water depth/flow rate related to the regular fluctuations of the wastewater flows (working day average 0.012 m^3/s, peak 0.016 m^3/s). In this way, the activation of the sampling collection was intended to be set at the time when the stormwater runoff starts being conveyed through the outlet of the catchment. Flow and water depth previously registered during dry-periods were used for the trigger adjustment.

The sampling frequency was set at 5 minutes for the first 15 minutes and then more widely spaced temporarily for a total of 2 hours. The intention was being able to better quantify what happens at the beginning of a storm event and analyse the occurrence of first flush pollutant phenomenon. A total of 9 samples were established to be collected for any event in the following elapsed minutes since the trigger: 0, 5, 10, 15, 30, 45, 60, 90, 120 minutes. Due to several operational problems, the collected quality data series was not always complete.

3.2.1 Rain data

The main characteristics of the 7-events for which rain data and the linked flow was recorded at the control section of the catchment are shown in Table 3-2. The first five correspond to events for which samples were collected, subsequently water quality is available.

Table 3-2: Rainfall events registered in the study site. Available data for modelling and calibration.

registered data	Date	total volume [mm]	maximum intensity [mm/h]	duration [hh:mm]	previous dry-weather period length [days] (*)	previous dry-weather period length [days] (**)
rainfall, flow and quality	17/09/2010	19.0	36.2	2:10	9	28
	31/05/2011	26.2	33.5	5:15	15	16
	13/07/2011	5.6	27.5	0:50	8	32
	24/10/2011	6.4	37.0	1:20	25	39
	13/11/2011	11.1	18.2	3:55	6	6
rainfall and flow	09/10/2010	33.5	36.6	10:05	18	21
	12/03/2011	71.6	18.2	18:50	9	22

(*) considering non rain at all occurring in the period

(**) considering period with rain registers <10 mm total precipitation

3.2.2 Flow data

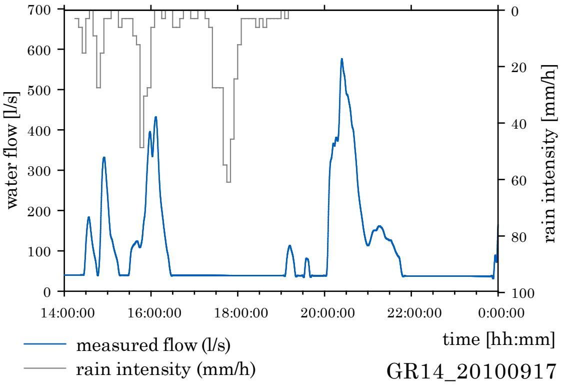
The data obtained by direct measurement with the flowmeter (HACH-Lange, Sigma 950 model) installed in the control section consists in water level and velocity registers. Both collected with a 2 minutes frequency. After the signal filtering and the consideration of the correction for the level position of the sensor, the water discharge has been calculated by applying the formula of Manning (equation 2-11) based on the water level (y), hydraulic gradient (J), and Manning roughness coefficient of the pipe (n_p). The slope of the pipe value was used in replacement of the hydraulic gradient in the formula.

Mean flow velocity (v) registered also with the flowmeter device and the corresponding cross section area (A_w) were used for calibration of the Manning roughness coefficient. Values of n_p ranging from 0.011 to 0.017 (for closed concrete sewer pipes flowing partially filled (Chow, 1994)) were tried in the adjustment (final value $n_p = 0.015$)

$$J = \frac{n_p^2 \,.\, Q}{A_w^2 \,.\, R_h^{4/3}} \qquad 3\text{-}1$$

$$R_h = A_w \,.\, P_w^{-1} \qquad A_w = f(y) \qquad 3\text{-}2$$

Flow data calculated then based on the registers during the mentioned rain events are showed in Figure 3-5. It can be noticed that for all the events, the short time between the onset of the rain water runoff and the peak flow in the exit point of the catchment. This quick hydrological response is possibly caused by the high degree of imperviousness of the surfaces and the small basin area.



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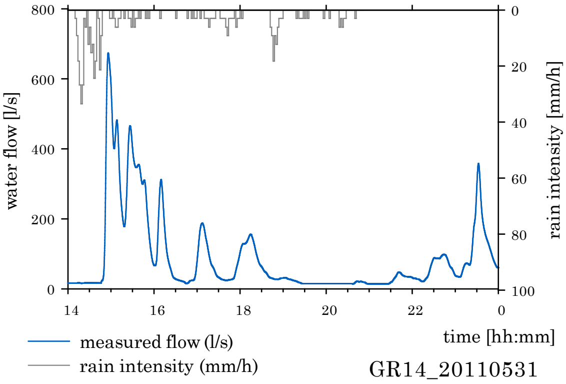

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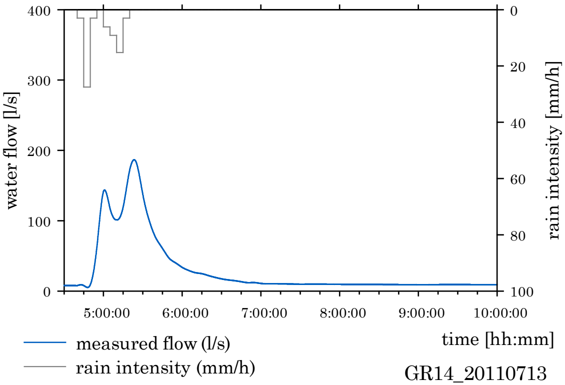

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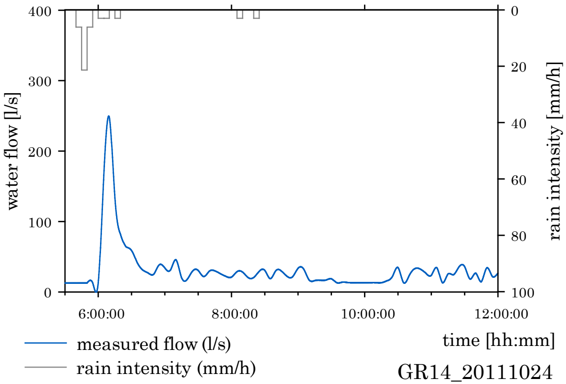

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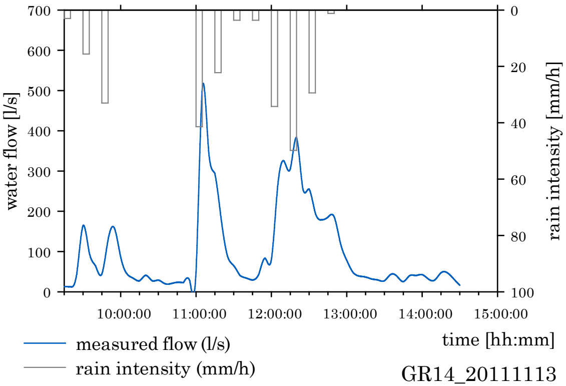

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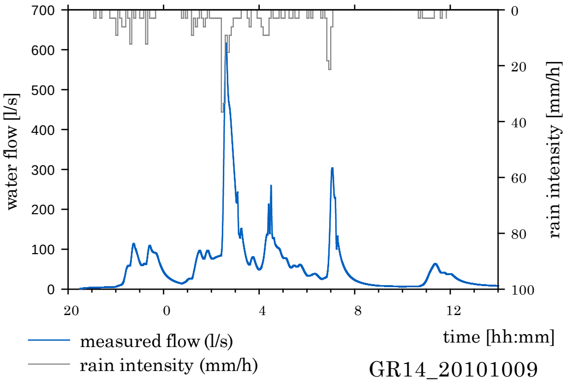

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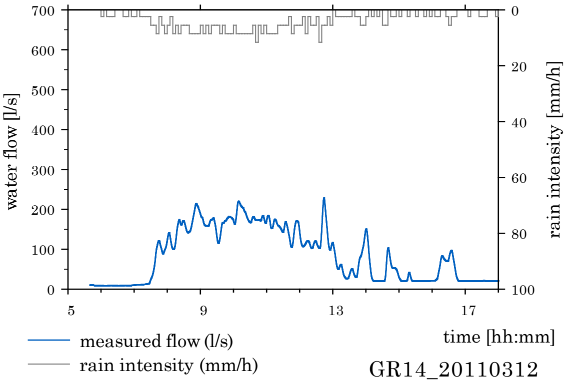

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Figure 3-5 Rain intensity and flow rate data (calculated from water depth and velocity registered after filtering) during monitoring campaign. Measurements at the outlet pipe of the urban catchment.

3.2.3 Water quality characterization

The water samples taken at each time interval during rainfall with the automatic sampler were used to individually analyse for suspended sediment concentration and *COD* and *TKN* concentration loads. The standard used for the analysis was explained above.

Analysed data value for the pollutant mentioned is shown in Figure 3-6 for each rain event. Different rainfall characteristics (intensity and duration) result in different hydraulic conditions and subsequently distinctive pollutants rates linked to these flow rates. It can be noticed that the suspended sediment concentration peak occurred, for all the events, before the hydrograph peak as it was expected.

It is also interesting to notice that a proportional relation between the suspended sediment values and the values measured for the *COD* and *TKN* can be evidenced. The relationships found between sediment and pollutants analysed are shown in Table 3-3. Based on wastewater samples analysed for BOD_5 (see details in Section 3.3.2), a relationship was found with *COD* (BOD_5/COD=1.46), that allows to calculate the showed relationship against *SS*. These relationships are later used in the quality modelling implemented in SWMM5 (Chapter 5).

Table 3-3: Proportional relationship found between suspended sediments and COD and TKN considered attached pollutants.

Pollutant	Relationship against SS
COD	1.23 SS
BOD_5	0.845 SS
TKN	0.013 SS

The measured values of suspended sediments and pollutants and its evolution over time suggest evidence of the occurrence of the first foul flush phenomenon in the catchment.. Pollutant loads are higher at the beginning of the runoff before the flow rate reaches the peak. It also can be seen from the graphs that as the flow rates gradually increase, the pollutant loads were diluted.

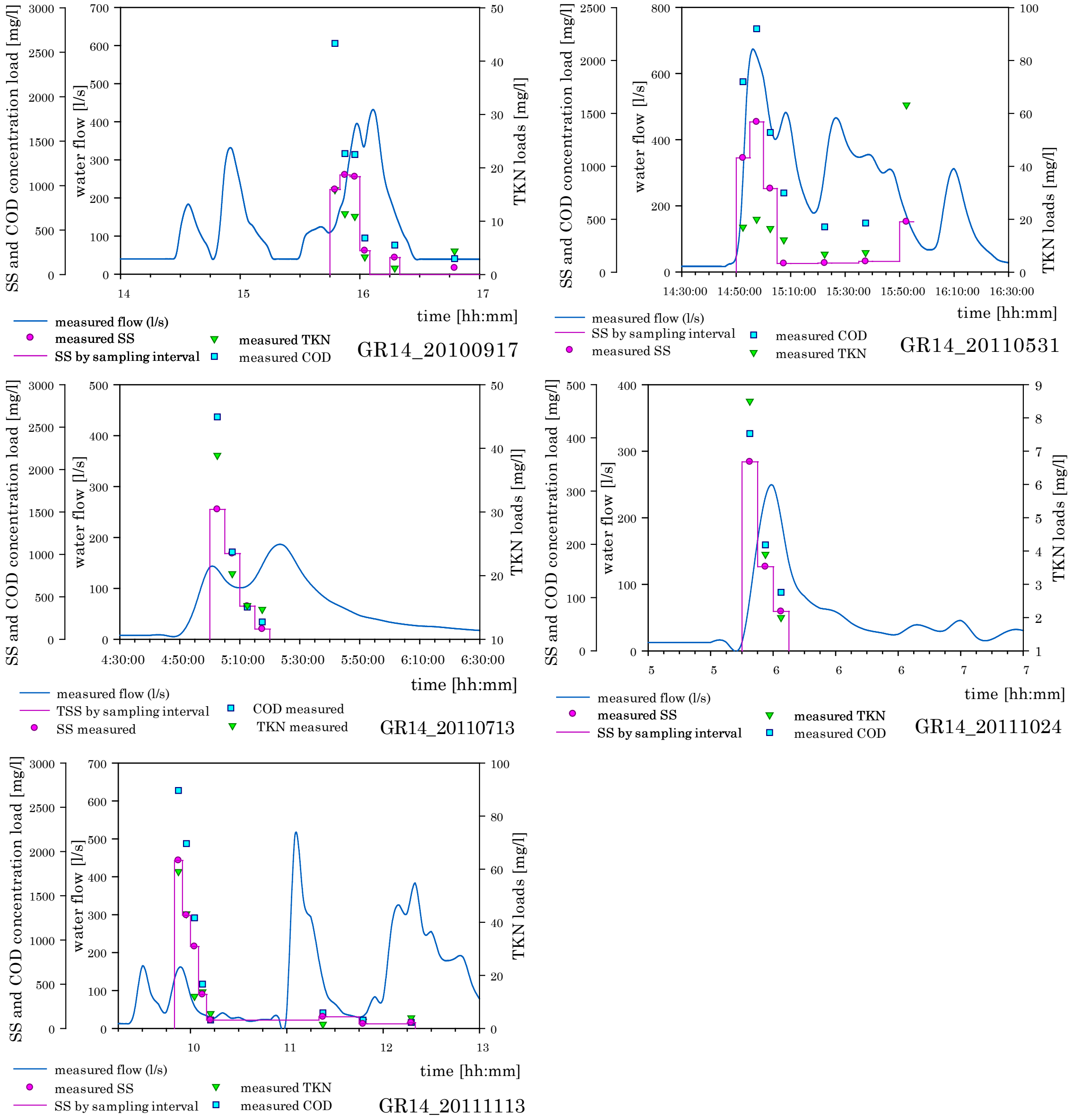


Figure 3-6 Evolution of the sediment concentration loads measured during storm periods. Measurements at the outlet pipe of the urban catchment.

3.2.4 First flush evidence

In an impervious catchment as the one analysed in the study case, as it was expected, the runoff rapidly releases and washes off the pollutants from the surfaces and from inside the network system, and the SS concentration peak precedes the runoff peak. The pollutant first flush phenomenon (discussed in Chapter 2, Section 2.1.2) occurring in the catchment can be clearly seen in Figure 3-7.

From the figure analysis, a significant pollutant first flush phenomenon, defined as 30/80 (Bertrand-Krajewski *et al.*, 1998) (with 30 % of the circulating volume accumulated, the discharged SS mass is at least the 80 %) can be confirmed in the study case for the rain events dated 17/09/2010 and 31/05/2011. Notice that these events have the highest rain intensity. Despite that the 80% was only exceeded for these two events, the cumulative sediment mass curves are above the bisector in all the cases.

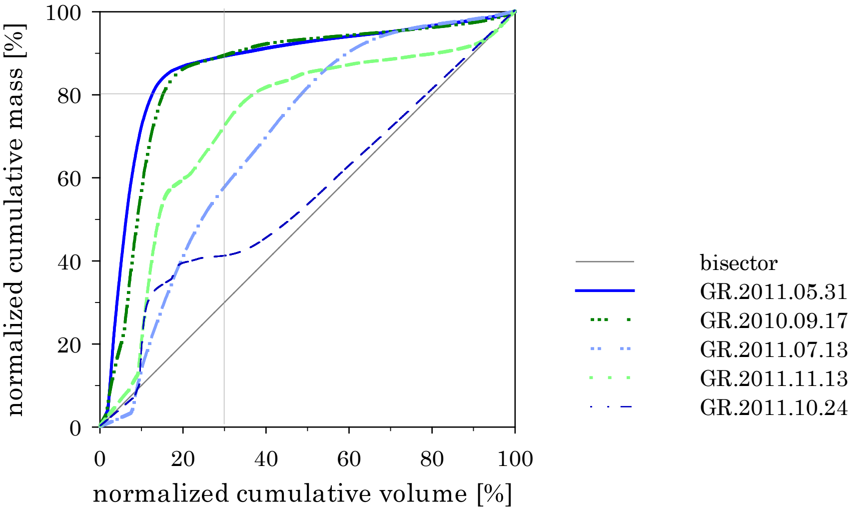


Figure 3-7 Set of curves of suspended sediment mass distribution vs. volume for the events monitored in the study site.

3.3 Dry-weather monitoring and characterization of water flow and quality

Continuous measurements of the wastewater rate were performed at the catchment outlet during the period between July 2010 and September 2010, dry season with few historical rain events. With the available data, daily and weekly patterns could be assessed. The monitoring programme was based on the measurements made by portable flowmeter and automatic sampler whose instrumentation was detailed above in this Chapter.

During this stage the quality characterization of wastewater was also performed. Dry-weather pollutant composition was characterized during three independent campaigns.

3.3.1 Flow data

The 24-hours measurements of water level and mean flow velocity conducted allow for the assessment of the wastewater flow rates. A pattern for wastewater flows could be assessed, which is displayed in Figure 3-8.

Mean flow during dry-weather periods at the outlet of the studied urban catchment was about 0.012 m^3/s (44 m^3/h), and 0.016 m^3/s (56 m^3/h) peak flow average during working days, meanwhile during weekends, flow rate was 0.010 m^3/s mean and 0.015 m^3/s peak.

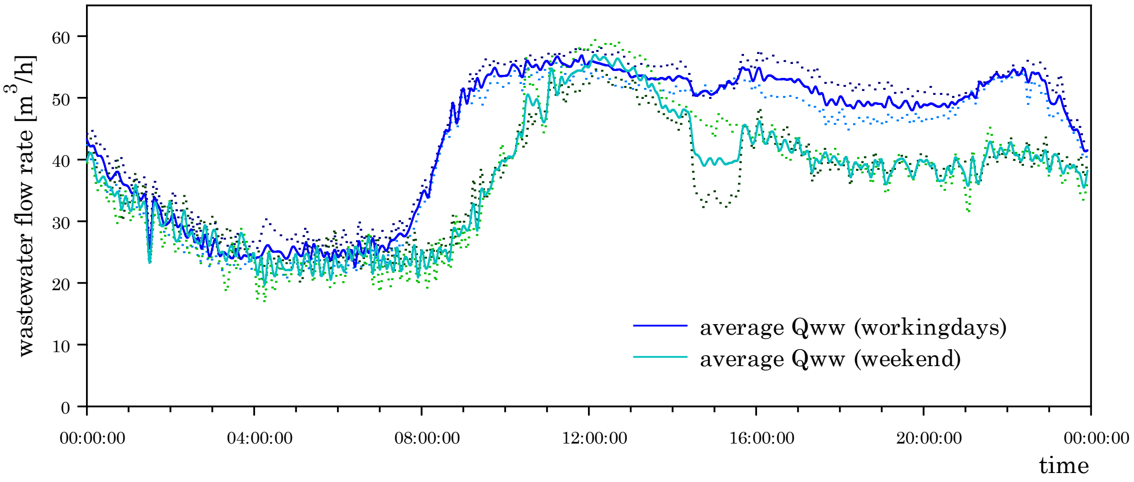


Figure 3-8 Wastewater flow rate meassured at the urban catchment. Comparison between working days and weekend patterns.

3.3.2 Water quality characterization

Previous research work findings in the field of water quality during wet-weather showed that the sediments and pollutants released from the pipe inverts have the most significant influence in term of sources of sediments. The sediments released from the system during first flush could even arrive to the 90% of the total suspended sediment loads measured (Saul *et al.*, 1989). Despite several research work discuss about the existence of the phenomenon, it is widely agreed that the initial stage of the storm runoff in a combined sewer network usually convey higher sediment and pollutant concentration rates than the previous dry-period.

It is also known from previous studies that a direct correlation based only on the equivalent population regardless of the catchment characteristics is insufficient for the characterization of the water quality (Gasperi *et al.*, 2008).

Having all this in mind, the quality analysis performed on the samples collected during dry-weather flows in this project, have the only objective to give a reference of the sediment concentration levels at the onset of the wet-weather period under analysis, for better calibration of the quality model. Moreover, the error in sediment concentration assessment that might be introduced by the approximation of the dry weather SS loads is not significant when compared with the values of the rates of erosion from the pipes.

Therefore, for the characterization of wastewaters in the present study, 6 discrete samples (3 samples/day) were taken in the control section at the outlet of the urban catchment, performed using an automatic sewerage sampler. Samples were collected in July and December 2010, at midday time with 15 minutes delay between samples. The difference in the measured quality parameters between the two periods is not significant.

The collected samples were analysed for SS, COD and TKN. Results of the analysis are shown in the following table (Table 3-4)

Sediment samples during dry-weather periods were also collected at the entrance of the treatment plant as part of a study of the whole catchment (Seco *et al.*, 2013) and analysed for *SS*, *COD*, BOD_5 and *TKN*. Based on previous analysis of these wastewater samples, a relationship in between was found that relates BOD_5 with COD (BOD_5/COD=1.46) which is used in Table 3-4 for BOD_5 calculation.

Table 3-4: Wastewater quality parameters

	SS [mg/l]	COD [mg O_2/l]	DBO_5 (=COD/1.46)	TKN [mg N/l]
Average pollutant concentration in wastewater	182	538	368	36

3.4 Combined sewer sediment deposits collection and characterization

The typical weather in the region is characterised by quite long dry-weather periods usually followed by strong precipitations. The long dry-weather periods combined with the reduced wastewater rates caused by low drinking water consumption causes that the circulating flow has not enough energy to maintain sediment in suspension, and generate suitable conditions for the accumulation of sediments in pipes. Additionally, highly-organic sediments are predominantly observed accumulated in pipes in the combined sewer system of urban areas densely populated with high level of imperviousness, which is commonly found in many cities in the Mediterranean region.

The main sources of sediments in this catchment are the sewerage discharges from the residential buildings and food serving establishments. The sedimentation and accumulation of highly organic solids in sewage pipes is predominant in these catchments, where high impermeability and almost nonexistent green areas, make the chances that granular particles entering into the system are very unlikely.

Large difficulties are found in the sewer sediment collection procedures and in determination of the sediment properties. There are high uncertainties in the representativeness of the collected sample due to the variation of the characteristics of sediments over time and the wide heterogeneous distribution of the sediments accumulated in the network.

Direct measurements of sediment properties inside pipes might be the more precise method for the characterization of deposited sediments however very complicated to perform. The sediment sampling and subsequent laboratory analysis is another possibility but does not involve minor difficulties. Sampling of sediment and analysis of sediments is a complex task and require large effort and involves significant costs.

Special attention and care was taken during the processes of sediment collection, handling, storage, transportation and during the tests performed for this research project. The collected sediments were later use in the laboratory erosion tests, which is explained in Chapter 4.

3.4.1 Sampling, handling and preservation of sediment from in-pipe deposits

In the context explained above, combined sewer sediment were collected from the urban network in the nearby of the studied catchment. The location for sampling is situated in a residential and commercial area, with commerce in its surrounding related mainly with food service (restaurants, pubs and bars). The network in this area has the additional particularity of receiving low inputs of rain water, due to the existence of a parallel drainage pipe that collected stormwater from a small part of the catchment.

The sediments were typically accumulated in a network segment where the conduits have a low slope (0.0021 m/m) and a reduction in diameter downstream the manhole (from 600 to 400mm). The place was selected based on the sewerage operators' experiences, who indicate this location as typical for the sediment accumulation, where it is necessary to perform periodic cleaning. According to the local operators' comments, this pipe typically has a deposit formation over 10 cm in depth.

The sediment collection was conducted during the dry period. To facilitate the work of the personnel who collected the sediment from inside the pipes, the collection was made earlier in the morning when low wastewater flows were expected. Less than 10 cm water-depth in the three campaigns performed was observed during sampling.

The sediment samples were manually collected in a single manhole at the outlet of the 600 mm diameter concrete pipe using a shovel. With the aid of a hoe and the shovel, the total depth of sediment was scraped and removed from the deposit. Despite the alterations in the layers of the deposit and the typical difficulties of the sediment sample collection, for sediment characterization purpose, the gathered samples were considered representative of the whole deposit formed at the invert of the pipe during a dry-weather periods.

Batches for combined sewer sediments were collected in three campaigns: 26/06/2012, 29/11/2012 and 16/09/2013. Despite physical characterization was made for all the collected samples, the first and the last samples were collected mainly to be used in the laboratory work aimed to analyse the effects of environmental conditions on the resistance to erosion (detailed below in Chapter 4). The second batch of sediment was collected particularly for characterization purpose.

The first sample collected was dried during 10 days at low temperature (between 40 ºC and 50 ºC) after which the stabilized weight was observed. The drying process has the intention of evaporate the water content in the sample to make it easier to transport to the laboratory facilities in the UK. Later, a portion of the third batch was also dried at the same environments to obtain a sample under similar conditions, allowing further comparison with sediment maintained under natural conditions. The weight of the sample was made before and after drying process.

Due to the high organic composition of the sediments, biological activity will certainly continue after the samples were collected, so changes in the properties of the sediments might occur during transport and storage. To minimize the possible changes, special conditions of handling, storage and transport were considered.

Thus, after the second and third sampling, the batches of sediments were kept in small sealed plastic containers for the purpose to preserve the original moisture content and avoid reactions with air. In order to retard biological activity and microbiological decomposition in the sediment samples, the third batch of sediments were stored and transported in cool box at 4 ºC ± 1 ºC. The procedure follows in general the advice for the preservation of wastewater samples given in *Standard Methods for the Examination of Water and Wastewater*, (2005) *section 1060 C. Sample Storage and Preservation*. Once in laboratory, the samples were maintained refrigerated at the same conditions, minimizing changes in the organic compounds during storage and transport until testing.

3.4.2 Physical and organic characterization of deposited sediments

A non-homogeneous composition and particle size is observed in the sediment samples, which also exhibit a high presence of fat, oil and greases (FOGs).

The analysis of sediments has been developed to identify main characteristics based on physical properties and on composition (organic matter related with polluting potential).

The density, moisture content and particle size distribution were measured based on methods of soil analysis. *Standard Methods for the Examination of Water and Wastewater*, (2005) was used as reference for the analysis.

A summary of the values obtained in the characterization of the deposited sediments in sewers that have been collected in dates 26/06/2012, 29/11/2012 and 16/09/2013 are shown in Table 3-5. There, the obtained values were displayed comparatively with the values obtained from previous findings in several related research works.

Table 3-5: Characteristics of sewer sediment samples collected in the study site and comparison with sediments from different locations.

sample location or type		characteristic particle size d_{50} [mm]		sediment density [kg/m^3]		organic content (%) (VS/TSS)		gravimentric moisture content (%)	
Granollers (Spain)	batch 1	0.31	± 0.16	1308	± 211	74	± 5		
	batch 2							48	±5
	batch 3			1313	± 95	95.4	± 2	54	±2
	average	*0.31*	*± 0.16*	*1310*	*± 146*	*85*	*±5*	*51*	*±5*
London (UK) (*)		0.8 - 1.0	±1.7	1802		3.6			
Loenen (The Netherlands) (*)		0.3 - 0.4	±3.4	1800		10.5			
crushed olivestones (**)		0.0047		1445		100			

(*) (Schellart *et al.*, 2005)
(**) (Skipworth *et al.*, 1996; Camuffo, 2001; Tait *et al.*, 2003)
(VS/TSS) assumed to be equivalent to the organic fraction

3.4.2.1 Particle size distribution

The sediment samples from in-pipe deposits were measured for size distribution. Characteristic size of the sediment particles (d_{50}) determined from the results of the sieving test (Figure 3-9) was found to be in the order of 0.31 mm with a standard deviation of SD ±0.16. The percentage of particles smaller than 7.5 µm (mesh T200 ASTM-E11) was found in 18% and 63% of the sample in mass was displayed with smaller diameters than 1 mm.

The sediment particles were found to exhibit quite a uniform distribution. Nevertheless it is necessary to deal with these values carefully as the sediment particles were formed by agglomerates of fine sediments and greases that were difficult to disaggregate during sieving in fractions.

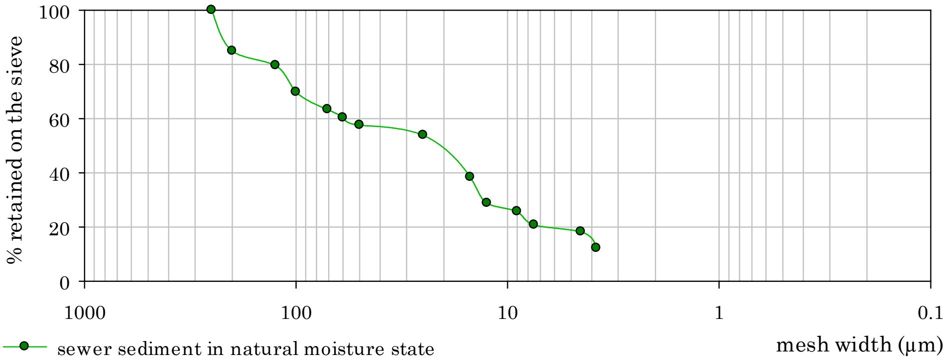


Figure 3-9 Sewer sediment particle size distribution obtained with standard sieve (>1mm sub-sample) and lasser difraction analysis (<1mm sub-fraction).

Due to the high presence of greases in the composition of the sample, the sieve analysis was performed independently for the gross part (>1 mm), following the British Standards (BS 1796-1:1989.*Test sieving*), while the fine part (< 1 mm) was performed by laser diffraction method (ISO 13320:2009 *Particle size analysis.Laser diffraction methods*). This combination of procedures was followed after that the fine sediment sieving test failed (first batch of samples) due to continuous clogging in the sieves mesh because the presence of fat that interfered with the particle separation process.

The followed procedure for analyse the distribution of particles by size involves the general steps below explained:

- The whole batch of sediment sample (about 50 g) was sieved through a 1 mm sieve in order to separate the sample in two fractions. The particles diameters less than 1 mm were collected and reserved for separately further analysis (preserved in a fridge at 4 ºC until analysis).
- The particles retained in the 1 mm mesh were weighted to calculate the percentage of particles retained by mass.
- The gross-sediment sub-sample (containing the particles bigger than 1 mm) was separated according to normal sieving procedure by using a sieve and water (BS 1796-1:1989). Modifications in this procedure were introduced regarding the use of deionized warm water (to help diluting the agglomerates with fat), and that the sieving was manually performed with one sieve mesh at a time.
- Each particle fraction left in the sieves was collected in a beaker by washing with deionized water at room temperature in the invert sense and filtered with a vacuum system. The filtered samples from each fractions were dried in an oven during 24 hours at 40 ºC (to eliminate gravimetric water content avoiding altering the organic matter in the sample), and then weighted to calculate the percentage of particles retained by mass.
- The fine sub-sample was analysed for particle sizes using a laser diffraction analyser (MALVERN device, Mastersizer 2000 version 5.60, with a size resolution for particles from 0.02 to 2,000 µm). The sample was previously diluted in deionized water at room temperature. Standard method was followed (ISO 13320:2009).

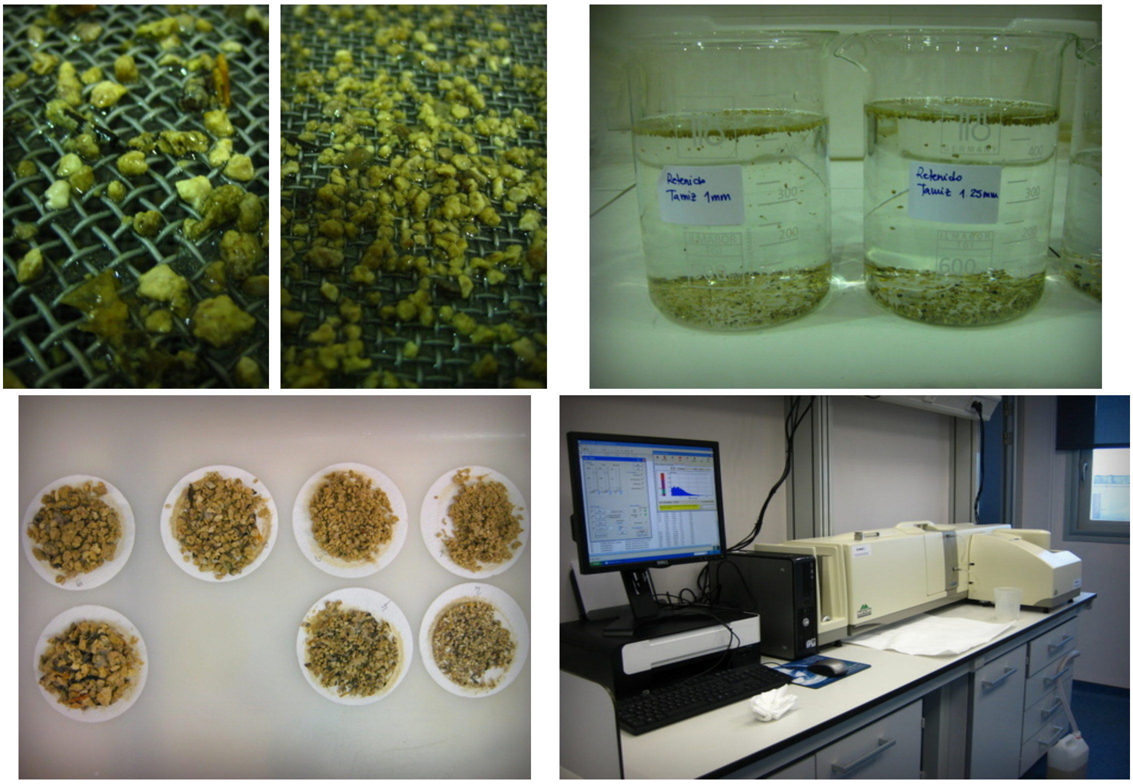


Figure 3-10 Sewer sediment fractions during sieve analysis and laser diffraction analyser.

3.4.2.2 Moisture content and Density of the deposited sediments

Gravimetric water content was measured by oven drying. Standard methodology for the assessment of the water mass is performed drying the sample to constant weight in oven at temperature between 105 ºC. Nevertheless, this temperature does not consider that the sediment might have chemical characteristics that may be affected during the process of drying. As it could be noticed during testing with the sediment collected from sewers, drying at that temperature generates a continued slowly decrease in the mass. It was suggested that these continual decrement in weight was related with the volatilization of some organic compounds.

Taking into account these previous considerations, the mass of dry solids was measured after 5 days of drying the samples in an oven at 50 ºC. The moisture content in dry weight basis was calculated from the difference between the wet and the dry mass of sediments. For the sediment samples tested it was found average moisture content of 51% ± 5 % (Table 3-5).

The sediment density was measured with sub-samples from the first and third batches collected from the sewer system. The mean of three samples obtained in each case showed a particle density of 1308 kg/m^3 ± 211 (from the first batch of sediments) and 1313 kg/m^3 ± 95 (second batch) were found.

A total average sediment density was established as 1310 kg/m^3 ±146.

3.4.2.3 Organic composition

The sediment batch was characterized for organic content, using a standard laboratory method which is the proportion between the volatile solids (*VS*) and the total dry mass of suspended sediments (*TSS*). After drying the samples, the portion of weight lost upon ignition is assumed to be an overall approximation of the amount of organic matter present in the solid fraction. This approach is proposed in the *2540 E* section of the *Standard Methods for the Examination of Water and Wastewater*, (2005) used as reference for the TSS and VS analysis during the laboratory work.

From the analysis of the first and third batch of collected sediments, this VS/TSS relationship was calculated as indicator of the organic matter fraction obtaining an average of 74% ±2 and 93% ±2 respectively.

3.5 Summary

Pollution from combined sewer systems can significantly affect the quality of receiving waters. The release of organic sediments from previously formed in-sewer deposits might give rise to significant reductions in the dissolved oxygen concentration of receiving waters.

The wideness of variations on the hydraulic operation of the system and on the quality parameters (in water and in deposited sediments) make that the application of quality predictive methodologies must be subjected to a process of calibration and verification against locally measured data.

This chapter described the procedures for in-situ monitoring quantity and quality parameters in a combined sewer system under study in the Mediterranean catchment. General patterns of the hydrology and the suspended sediment load during dry weather were obtained. Hydraulic and quality data was also recorded during wet weather. Collected data will be applied in the calibration of the models later presented in this dissertation.

Batches of in-sewer sediment accumulated from a location with persistent sediments were also collected from the combined sewer system of the study case. The sediment samples display non-homogeneous composition and quite uniform and fine size distribution, exhibiting a high organic content and significant presence of fat, oil and greases (FOGs). Methodologies for the assessment of the characteristics of the sediments as well as the analytical results obtained were detailed throughout this chapter.

The distribution of the particles sizes and their density have a significant effect on the application of sediment transport relationships. It will be seen that the organic composition of the sediment is also significant in the prediction of the transport of sediments in sewerage due to its effects on the transformation processes occurring during the dry-weathers previous a rain event.

Bibliography of the chapter

Bertrand-Krajewski, J.-L., Chebbo, G., Saget, A., 1998. Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. Water Research **32** (8), 2341–2356, DOI:10.1016/S0043-1354(97)00420-X.

BS EN 872:2005, 2005. *BS EN 872:2005 - Water quality. Determination of suspended solids. Method by filtration through glass fibre filters*. ISBN: 0 580 45513 0.

Camuffo, G., 2001. *The erosion of organic sediment deposits and implications for sewer systems*. Tesi di Laurea.Universita degli Studi di Padova.Padova. Italy.

Chow, V. Te, 1994. *Open Channel Hydraulics*. McGraw-Hill, ISBN: 07-010776-9.

Deletic, A., 1998. The first flush load of urban surface runoff. Water Research **32** (8), 2462–2470, DOI:10.1016/S0043-1354(97)00470-3.

Gasperi, J., Kafi–Benyahia, M., Lorgeoux, C., Moilleron, R., Gromaire-Mertz, M.C., Chebbo, G., 2008. Wastewater quality and pollutant loads in combined sewers during dry weather periods. Urban Water Journal **5** (4), 305–314, DOI:10.1080/03087290802201415.

ISO 5663:1984, ., 2012. *ISO 5663:1984. Water quality - Determination of Kjeldahl nitrogen - Method after mineralization with selenium.*

ISO 6060:1989, 2012. ISO 6060:1989. Water quality - Determination of the Chemical Oxygen Demand.

Larrarte, F., Pons, M.-N., 2011. Suspended solids concentration in wastewater: Influence of sampling conditions. Urban Water Journal **8** (6), 397–404, DOI:10.1080/1573062X.2011.630094.

Obermann, M., Rosenwinkel, K.-H., Tournoud, M.-G., 2009. Investigation of first flushes in a medium-sized mediterranean catchment. Journal of Hydrology **373** (3-4), 405–415, DOI:10.1016/j.jhydrol.2009.04.038.

Prat, N., Munné, A., 2000. Water use and quality and stream flow in a Mediterranean stream. Water Research **34** (15), 3876–3881, DOI:10.1016/S0043-1354(00)00119-6.

Saul, A.J., Thornton, R.C., 1989. Hydraulic performance and control of pollutants discharged from a combined sewer storage overflow. Water Science & Technology **21** (8-9), 747–756.

Schellart, A.N.A., Veldkamp, R.G., Klootwijk, M., Clemens, F., Tait, S.J., Ashley, R.M., Howes, C., 2005. Detailed observation and measurement of sewer sediment erosion under aerobic and anaerobic conditions. Water Science & Technology **52** (3), 137–46.

Seco, I., Gómez-Valentín, M., 2013. Calidad de aguas en tiempo de lluvia: estudio de una cuenca urbana en la región Mediterránea y calibración de un modelo hidrológico y de calidad en SWMM 5.0. In: III Jornadas de Ingeniería Del Agua La Protección Contra Los Riesgos Hídricos. Valencia.Spain. 23-24 Oct. 2013.

Skipworth, P.J., Tait, S.J., Saul, A.J., 1996. Laboratory investigations into cohesive sediment transport in pipes. Water Science & Technology **33** (9), 187–193.

Standard Methods for the Examination of Water and Wastewater, 21st ed, 2005. . American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA., ISBN: 0875532357.

Tait, S.J., Marion, A., Camuffo, G., 2003. Effect of environmental conditions on the erosional resistance of cohesive sediment deposits in sewer. Water Science & Technology **47** (4), 27–34.

Chapter 4

Incipient motion of cohesive and high organic sediments

Laboratory erosion tests

The good assessment of the critical shear stress on the re-mobilization process of the sediment deposits is of significance. The difficulties in the in-situ determination lead to the establishment of laboratory work capable to characterize and analyse the deposits behaviour regarding strength against erosion.

This chapter describes the laboratory experimentations carried out in order to analyse the erosion resistance and behaviour of high organic sediment collected from combined sewer system mentioned in Chapter 3, Section 3.4.

First, this chapter describes preliminary observations and requirements for carrying out the laboratory studies (Section 0) as well as the procedures for the calibration of the equipment. The test methodology is described in Section 4.2, where the test programme is presented. In Section 0 the results obtained from the series of tests were described and evaluated, which allow analyse the influence of the different conditions on the resistance to erosion of the sediments bed studied. The time length of the consolidation period, the oxygen availability and the influence of the organic composition is examined in this section. Particular analysis is made in Section 0 on the effects of the biodegradability of the organic matter. Finally, in Sections 0 and 0, the conclusions and a summary of the chapter are given.

The sediment transport model developed by using the resulting data from these tests will be presented in Chapter 6.

4.1 Introduction

Sewer sediment shows an agglomerate structure, as it has a variety of sources and contains a mixture of organic and inorganic materials. Organic cohesion together with microbiological activity in sewer sediments can develop strong bonding forces between particles, influencing the structure of the surface of the bed (Mehta *et al.*, 1997; Banasiak *et al.*, 2005). These phenomena can have significant influence on the behaviour of a sewer sediment deposit regarding its resistance to erosion. This "bonding" behaviour adds additional difficulties to the prediction of the rate of erosion and the modelling of sediment transport in sewers, which already involves considerable uncertainty even when this behaviour is not taken into account (Schellart *et al.*, 2010).

In an attempt to quantify the erodibility of high organic sediments and improve predictions of the sewer sediment transport loads, a study on how this composition and the environment at which are subjected affect the initiation of sediment motion is needed.

Based on previous research (Skipworth *et al.*, 1996; Tait *et al.*, 2003a; Banasiak *et al.*, 2005) it is assumed that the degree of consolidation in a cohesive sediment bed is strongly influenced by the time length of the consolidation period and biological activity. It is also considered that consolidation process will result in an increasing bed density and furthermore will cause an increase of erosional strength with depth (Ristenpart, 1995; De Sutter *et al.*, 2003)

This Chapter reports then on a series of laboratory erosion tests performed in two testing programmes, both using real sewer sediment with a high percentage of organic matter (around 80%) found in the urban catchment under study. The aim of this experimental work is to investigate the erosion behaviour of real in-sewer organic-rich sediment, with few studies reported on this topic, and analyse changes in transport potential for different time lengths of antecedent dry-weather period and in-sewer environmental conditions. Hence, the concern was the characterization of the effects on the resistant to erosion of the deposits of sediments subjected to similar conditions like the ones found in the Mediterranean region where the study case is located.

The erosion tests were carried out using an erosionmeter device based on a design by Liem *et al.* (1997) whose operation is explained along this chapter. In these tests a prepared sample of sewer sediment has been exposed to a consolidation period and subsequently subjected to increased shear stress, to simulate increased flows through sewer pipes at the start of a storm event. The erosion tests were performed in a pre-calibrated device under aerobic and anaerobic conditions, and at room temperature (about 23.5 ºC) in a first test programme and at 4 ºC and 20ºC in a controlled temperature laboratory facility in a second programme.

The behaviour of the sediment deposit was monitored in terms of suspended solid concentration used to calculate the erosion rate linked to the applied shear stress.

4.1.1 Preliminary observations on sediment characteristics

The sediments used in the erosion tests were those mentioned in Chapter 3, Section 3.4 collected from a sewer system in Granollers (Catalonia, Spain) in dates 26/06/2012 and 16/09/2013. As it was previously mentioned, the material corresponds to the sediment accumulated in a pipe and manhole situated in a residential and commercial (restaurants, bars) area. They were collected after a relatively long dry weather period of 23 days and 14 days respectively considering the last rain event with total precipitation higher than 10 mm.

The main characteristics of the sediments analysed are shown in Table 3-5. In addition, parameters determined from sediment used in previous studies of erosion tests are also reported.

Table 4-1: Characteristics of sewer sediment samples of different locations.

sample location	d_{50} [mm]	standar deviation SD	sediment density [kg/m^3]	organic content (%)
Granollers (Spain)	0.31	0.16	1310	74
London (UK) (*)	0.8 – 1.0	1.7	1802	3.6
Loenen (The Netherlands) (*)	0.3 0.4	3.4	1800	10.5
crushed olivestones (**)	0.0047		1445	100

(*) (Schellart *et al.*, 2005)

(**) (Skipworth *et al.*, 1996;Tait *et al.*, 2003b)

4.1.2 Laboratory equipment

4.1.2.1 Erosionmenter device

The erosion measurement device used was developed by Liem *et al.* (1997), based on the design proposed by Schünemann and Kühl (1993) named EROMES, with a slight modification introduced by Liem to allow for the use of prepared samples instead of in-situ collected samples.

The main purpose of the device is the assessment of the critical threshold of motion at the solid-fluid interface by applying an angular velocity to the water column resulting in a radial velocity pattern over the sediment deposit, and collecting the resulting eroded material.

The erosion meter utilised in this work (in both testing programmes) consists of a cylindrical Perspex tube (100 mm inner diameter) with a sample container inserted into the bottom of the tube (see details in Figure 4-1). The sample container holds the sediment sample. The sample placed has an exposed surface area of 8170 mm^2. A 50 mm diameter propeller is placed 30 mm above the sediment surface and is used to apply a reasonably uniform shear stress.

There are six vertically spaced sample outlets to remove suspended sediment samples during the tests. Five baffle plates fixed perpendicular to the inner wall of the tube prevent circulating flow (in a vortex pattern) when the propeller is running. Hence, the collection of evenly concentrated sample can be assumed.

A stirrer motor (RW-16 Ika Laboratechnik, speed range: 40-1200 rpm) was used to operate the propeller.

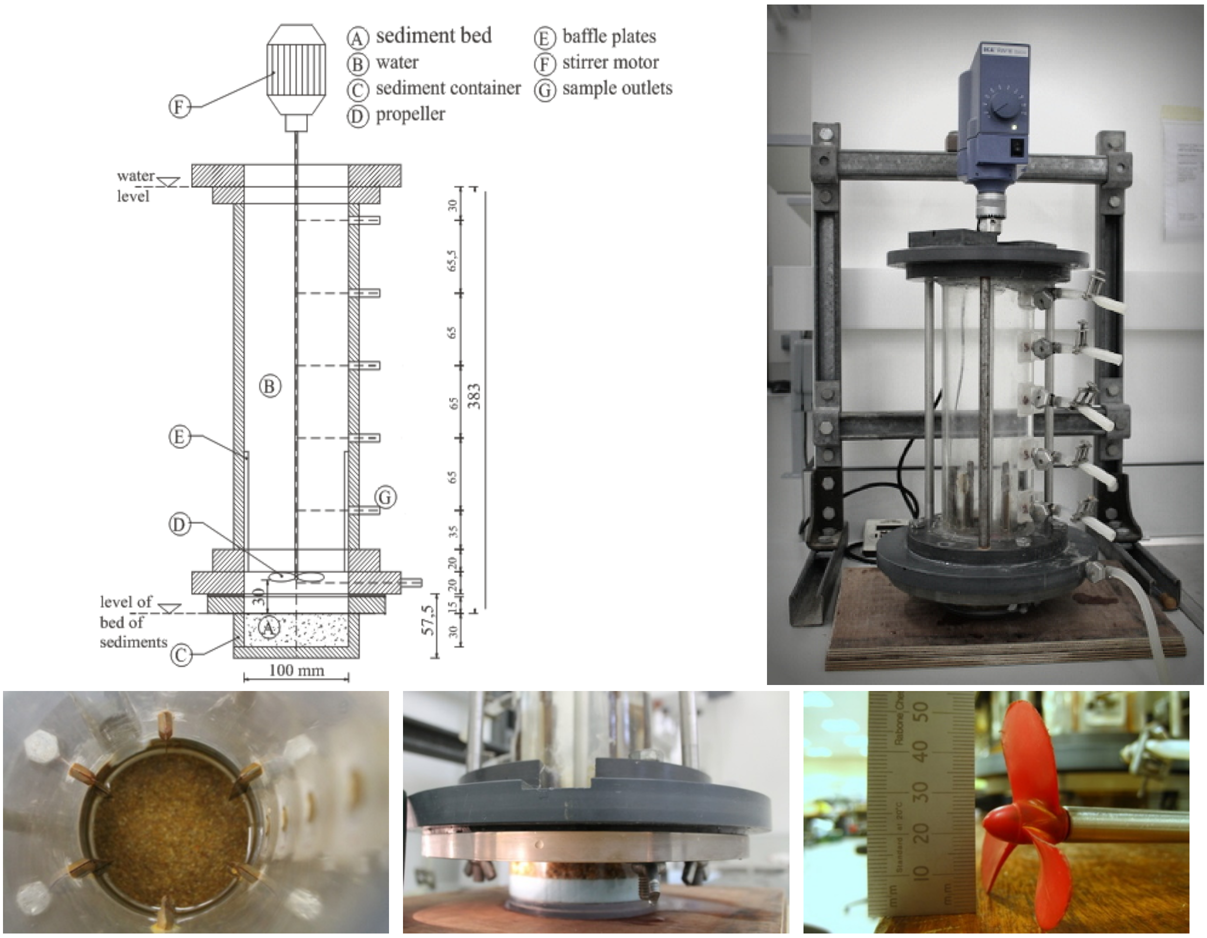


Figure 4-1 Erosion meter device.

4.1.2.2 Other laboratory equipment and instruments

Additional instruments were used in the performing of the test:

- Scales: Two types of weighting instruments were utilised. An average weighing scale (accuracy of 0.01g) and an analytical balance (accuracy, 0.0001g).
- Tachometer: Lurton digital tachometer, model DT-224B, speed range 5 to 99.99 rpm, resolution 0.1 rpm (accuracy ± 0.05% + 1 digit)
- Dissolved Oxygen (DO) and temperature probe: portable dissolved oxygen meter Hach, sens*ion*6, range 0-20 mg/l (0-200% saturation), resolution 0.1%, accuracy ± 1%. Temperature range 0-50 ºC, resolution 0.1 ºC
- Oven (105 ºC) and furnace (550 ºC) for the sample drying, fridge and incubator (for storage of the samples), and a filtering system.

4.1.3 Calibration of the instruments

All laboratory equipment (scales, DO probe, and tachometer) was calibrated in advance by properly trained and qualified personnel from the laboratories were the tests were performed.

4.1.4 Calibration of the erosion meter device

During the test of erosion of the sediment bed deposit, the speed of the propeller used to apply a shear stress over the bed is measured using a tachometer which gives the reading in revolutions per minute (rpm). Hence, calibration of the erosionmeter instrument is essential to find the relationship between revolutions per minute (rpm) of the propeller and the shear stress on the surface of the sediment sample.

Several uniformly sized samples of silicate sand in the range detail in Table 4-2 were used to create single size beds. Sand density of 2650 kg/m^3 was assumed for all the fractions. The calibration procedure for individual sand fractions consist in estimating the critical shear stress, by using the modified Shields criteria (van Rijn, 1984; Camuffo, 2001; Sakrabani *et al.*, 2005), that produce a small amount of particle mobilization

Critical shear stress is described by Wilcock (1988) as the shear stress that produces a small transport rate. However, there are different methods to define the amount of particles in movement to observe the threshold of motion. For the current research the amount of particles in movement was defined as the 5% of the superficial bed moving continuously under a constant water velocity applied during one minute period, which is mentioned by Camuffo (2001) in previous research with crushed olivestone material.

During the calibration procedure, the angular velocity of the propeller is increased gradually until the instant when the start of a continuous movement of the sand particles is observed. The value of shear stress at the threshold of motion for each sand fraction is calculated using the modified Shields criterion (van Rijn, 1984) (equations 2-20 and Figure 2.8 in Chapter 2) and this can be related to the applied angular velocity at that instant. Following the calibration tests, a curve is obtained that relates the angular velocity of the propeller in rpm with the applied bed shear stress.

Table 4-2: Sand sample size used in the erosionmeter calibration procedure.

Sieve Size Sand			Sieve Size Sand		
d_{max} [mm]	d_{min} [mm]	d_{50} [mm]	d_{max} [mm]	d_{min} [mm]	d_{50} [mm]
2.36	2	2.18	0.71	0.6	0.655
2	1.7	1.85	0.6	0.5	0.55
1.7	1.4	1.55	0.5	0.355	0.4275
1.4	1.18	1.29	0.355	0.212	0.2835
1.18	1	1.09	0.212	0.15	0.181
1	0.71	0.855	0.15	0.075	0.1125
			0.075		0.075

Calibration curve as result of the calibration procedure is showed in Figure 4-2. Shear stresses in the range from 0.15 to 1.5 N/m² can be applied during tests. Higher variations in the critical shear stress values are observed under small grain size variations.

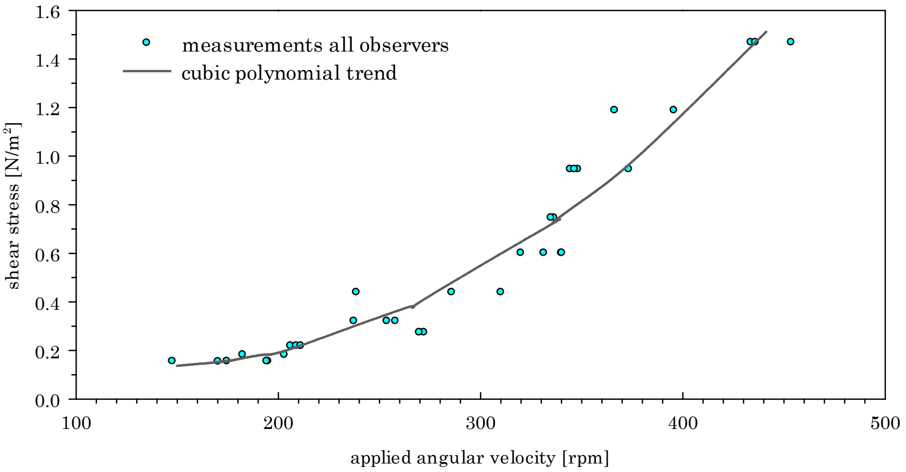


Figure 4-2 Calibration curve, showing mean and SD of shear stress for each particle size

Regarding calibration measurements for different graduated sand sizes, the error in the assessment of the shear stress values can be defined with the value of the standard deviation (SD) in shear stress value obtained at each sand size (average SD=0.07 N/m²)

To account for the influence of the observer in judging the threshold of movement, a calibration procedure was repeated by 5 different observers using the same device at the same conditions (water temperature 20 °C), and using the same samples of graduated sand. To observe the threshold of motion, all observers had being informed of the description of the mobilization condition by Camuffo (2001) beforehand.

The errors in the assessment of the critical shear stress values during calibration procedure are later considered in the assessment of the applied shear stress included above in Section 4.3.3.

4.1.5 Transport and storage conditions before testing the collected sediments

Sediments accumulated in combined sewer pipes in the studied system in Granollers, Spain were collected for the erosion tests study. Details of the collection and characteristics of the sediments can be checked in the Section 3.4 from Chapter 3.

Two types of conservation conditions were tried. Firstly, in May 2012, the collected samples were dried in an oven at 40-50 °C for around 10 days, which had the intention to reach an adequate / minimum moisture level that avoids biological reactions during transporting. These dry-samples were then sent by courier to the laboratory facilities in Bradford, UK where they were tested.

Secondly, conservation of the sediment samples in a natural “fresh” state was tried. After collection, the sediments were stored and transported in cool box at 4 ºC ± 1 ºC before being sent by courier to the laboratory facilities in Sheffield, UK (September 2013), where they were maintained at 4.7 ºC temperature upon arrival until testing. The procedure follows the advice for the preservation of wastewater samples given in *Standard Methods for the Examination of Water and Wastewater*, (2005) *section 1060 C. Sample Storage and Preservation* in order to retard biological activity and microbiological decomposition in the sediment samples. In order to preserve the original moisture content and avoid reactions with air, the sediments were kept in small sealed plastic containers. Once in laboratory, the samples were maintained refrigerated at the same conditions, minimizing in this way changes in the organic compounds during storage and transport until testing.

4.2 Erosion test procedure

The tests carried out during the laboratory research stage (two programmes) followed the scheme described below in the following sections.

4.2.1 Description of the methodology

4.2.1.1 Sample preparation and consolidation period

Regarding the difficulties in collected undisturbed sediment samples from the invert of the sewers pipes, the preparation of samples before testing has the intention to simulate, as close as possible, the natural state of the sediments that were deposited in the real pipes.

Large solids and debris such as leaves, sticks, cigarette butts, cotton swabs and disposable toilet wipes was removed from the sample since they may interfere in the test procedure by causing blockages in the sampling tubes or problems with the propeller operation.

A simple splitting method and quarter technique was implemented prior to laboratory analysis. The objective is to obtain the homogenization in distribution of the particles in the sample for analysis. For the samples stored in a dry condition, due that during drying process the sediments agglomerate, the preparation of the samples for testing include also the prior kindly crushing of the large agglomerates and sieving with a mesh 2.6mm width.

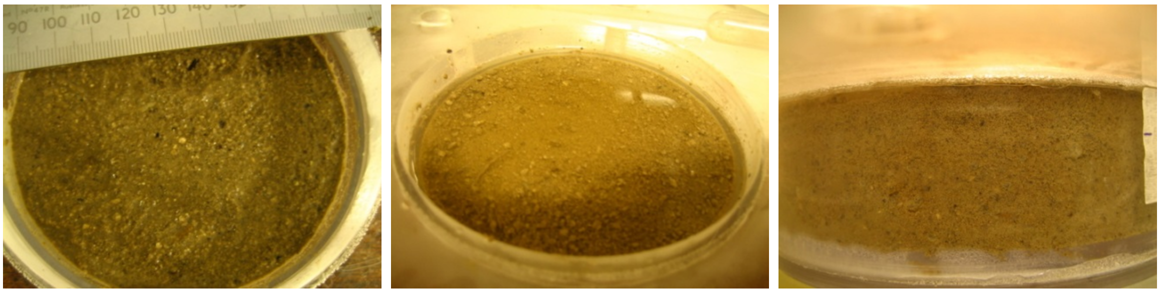
Care was taken during the splitting and sample preparation and in the transfer into other containers in the laboratory to avoid losing the finest particles.

Samples set with dry-stored sediment were prepared mixing a portion of 110g of the pre-processed sediment with 100 ml of warm water to rehydrate the sediment and return the original moisture content. Then the sample is thoroughly mixed and homogenized avoiding the sorting via different particle densities, shapes, sizes. Warm water is needed due to the presence of fat and greases that make difficult the mixing process with cold water. The final appearance is like a paste. The sampler container from the erosionmeter device was filled with these prepared samples. The total height needs to reach 20 to 21mm from the inside bottom, although the surface of sediment should finally reaches 30mm from the propeller (also means 30mm high from the bottom of the container). This initial sediment height has been previously determined by preliminary observation, and was fixed at this value due to the occurrence of an expansion followed by a slight consolidation.

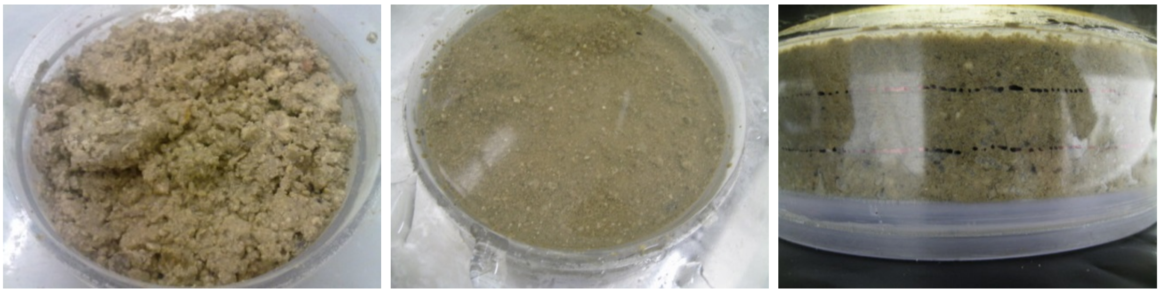
Samples stored in fresh conditions, were directly used after homogenization. In this case, the amount of sediment necessary to fill the container was of 296 ± 16 g. The sample is placed into the container creating a layer of sediment of 30 mm high afterwards tap water is used to fill the recipient until the top. Water to fill in the container is added using a pipette avoiding disturb the surface of the deposit.

Photos of the final appearance of the prepared samples are shown in Figure 4-3.

Finally, a period of pre-consolidation is established based on previous testing, to ensure a sediment bed with adequate strength. This pre-consolidation period is carried out leaving the samples resting in the fridge (at around 4ºC) for 72 hours.



a) Sample prepared with dry-stored sediment.



b) Sample prepared with fresh-stored sediment.

Figure 4-3 Appereance of the prepared samples for erosion testing.

After the pre-consolidation period, the sample is allowed to restore the room temperature. The container is placed then at the bottom of the erosion meter and carefully filled in with tap water at room temperature, avoiding disturbing the bed sediment surface.

4.2.1.2 Performed tests

Immediately later to the preparation of the instrument for the test, a phase of simulation of the dry-weather period in the combined sewer system is established. For doing this, a low bed shear stress (0.15 N/m^2) similar to that found during wastewater flows in the system, was applied over the bed by the operation of the propeller. This phase intend to simulate the conditions in sewers during periods of sediment deposition between rain events. Additionally, the low velocity of the propeller ensures a continuous mixing and creates a uniform environment regarding water temperature and dissolved oxygen (DO) levels. After the simulation of a period of consolidation of this deposited bed, the angular velocity of the propeller is increased gradually simulating increasing water flows in the pipes.

The propeller is placed centred above the sediment bed at 30 mm vertical distance. This position of the propeller and the baffles plates in the internal wall of the erosionmeter will prevent the formation of vortex, also allowing a uniform distribution of the re-suspended sediments when operates.

Increasing shear stress is applied in a stepwise way through the rotation of the propeller. Each step is maintained approximately constant during an interval of 45 minutes. This period for the application of the shear stress steps was assumed to be suitable to achieve a steady suspended solids concentration in the water column, based on the findings by Tait *et al.* (2003b) and verified by Schellart *et al.* (2005).

Based on pre-existent laboratory experience, six standard shear stress steps were applied, aside from the value used during consolidation.

Figure 4-4 show an scheme of the different phases of applied angular velocities-shear stresses.

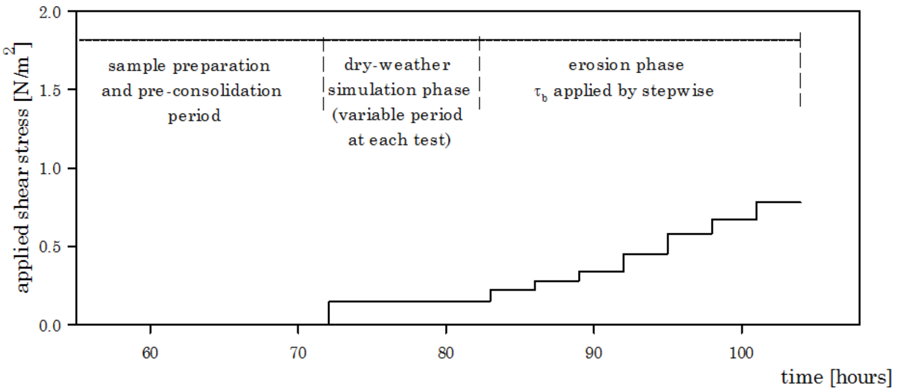


Figure 4-4 Schematic representation of the different phases of applied shear stresses over the sediment bed during the performed erosion tests.

The speed of the propeller was measured using a digital tachometer (Lurton, model DT-224B), which gives the reading in rpm, which is translated in an equivalent applied shear stress through the calibration curve showed at Figure 4-2.

The mean water temperature during all experiments was 23.5 ºC in the first programme and 20º ºC in the second, a value similar to the maximum dry-weather wastewater temperature during spring and summer seasons measured in the sewer system where the sediments were collected.

The level of dissolved oxygen and temperature, as well as the angular velocity of the propeller is recorded in each interval of applied shear stress.

To create an aerobic environment a small air pump was used. During aerobic tests it was attempted to maintain a uniform dissolved oxygen saturation level (8.51 mg O_2/l at 24ºC), so as to promote aerobic microorganism activity. An aquarium air pump is used to incorporate air to the water column. The air stone of the pump was placed in a way to not disturb the sediment surface with the air supply. Full mixed conditions and uniform dissolved oxygen concentration in the entire water volume was assumed due to the flow generated by the propeller.

During each interval of applied shear stress, samples were withdrawn from the six vertically distributed orifices after 3, 10, 30 and 40 minutes, counting from the setting of each new rpm of the propeller. The volume of water removed during the sampling was always restored at the end of the removal step, to maintain a constant volume of water in the erosion meter. The water used for restoring was at room temperature to avoid changes in temperature in the reactor.

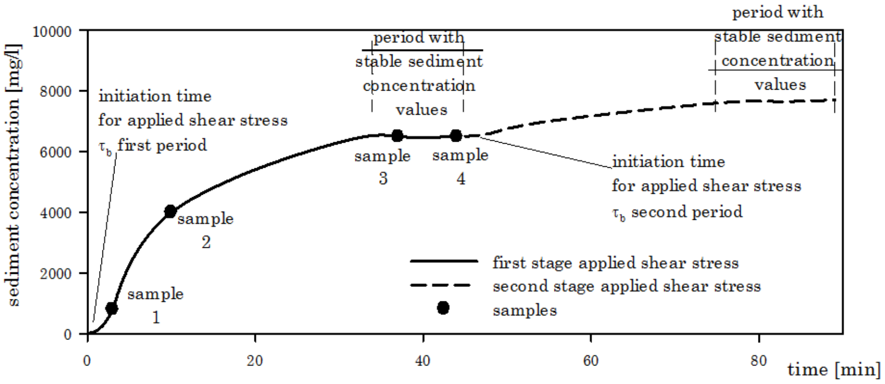


Figure 4-5 Schematic representation of sampling time interval against sediment concentration.

An integrated sample was then prepared with the six samples gathered, assumed to be representative of the whole water column sediment concentration in the erosion meter at the sampling time. Each integrated sample was analysed for Total Suspended Sediments (TSS), Fixed Solids (FS) and Volatile Solids (VS) following the *Standard Methods for the Examination of Water and Wastewater (2005)* tests procedures.

After each erosion test was performed, the remaining sediment deposit was collected and analysed for organic content and particle size distribution.

4.2.1.3 Relationship between erosion rate and bed shear strength

The erosion of sediments from the bed during the experiments was monitored in terms of the suspended sediment concentration and related with the erosion rate *q* as follows (equations 4-1and 4-2):

$$q_i = (C_{SS,i} - C_{SS,i-1})\frac{V}{(A_{s-e}.(t_i - t_{i-1}))} \qquad 4\text{-}1$$

$$q = \sum_{i=0}^{n} q_i \qquad 4\text{-}2$$

where q is the average erosion rate in a shear stress step, q_i is the erosion rate in the instant i expressed in (g/m^2/s), ($C_{SS,i}$ – $C_{SS,i-1}$) the difference in suspended sediment concentration (in g/m^3) between the sampling instant i and the previous $i-1$, V the water volume of the column over the sediment sample and A_{s-e} (in m^2), the surface area of the bed subjected to erosion.

Knowing the value of the erosion rate (q) linked to the applied shear stress (τ_b) it is possible to obtain a function for erosion rate by fitting a curve through the obtained points. The value of the critical shear stress (τ_c) for sediment threshold of motion can be found with this curve.

4.2.2 Test programme

4.2.2.1 First test programme

Tests performed between June and August, 2012 during a research stay at the University of Bradford were carried out with samples stored in dry conditions.

Three different periods of: 16, 64 and 140 hours were used to simulate dry-weather periods. During these periods the sediment bed was subjected to a constant shear stress of 0.15 N/m^2, comparable with the dry-weather flow levels. The sewer sediment samples were also exposed to different oxygen levels during consolidation (see details in Table 4-3), and subsequently exposed to incremental levels of bed shear strength.

Table 4-3: Test condition used in the consolidation periods in the erosion experiments. Firts test programme.

Identificantion of the test	T1	T2	T3	T4	T5
Dry-weather period (hours)	16	64	140	16	64
Environmental conditions	Anaerobic			Aerobic	

A 140-hours test with oxygen supply during the consolidation period was also planned. However, changes in the conditions of the sediments caused that the erosion phase could not be completed. After about 3 hours of stating the dry-period simulation with oxygen, bubbles of sludge appear at the top of the reactor and grow continuously in mass. After about 48 hours elapsed, changes in the colour of the whole mass of sediment (in suspension and in the bed) were noticed, becoming a whitish ochre colour. It was suggested that aerobic bacteria present in the mass of sediment produce transformations in the sediment. The erosion phase of this test was not performed due to not having comparable conditions with the shorter period tests.

4.2.2.2 Second test programme

A second test series was formulated taking into account observations made during the first programme of erosion tests. The experimental and analytical procedures remained the same as those used in the first testing programme. Despite that, some modifications were introduced in the implementation of the tests, based on the earlier results obtained.

All the tests were carried out with 30 mm deep bed of sediment with oxygen supply or not during the consolidation phase as in the first programme. As it was mentioned below in Section 4.2.1.1 (Sample preparation), the main difference between both programmes were that for this second series, sediments in natural “fresh” state were used. Another difference was regarding length of the simulation of dry-periods. Based on the findings of the earlier tests, intermediate dry periods between 16 and 64 hours was suggested. Then, the planned dry-periods were: 16, 27, 40 and 64.

A summary of the tests and conditions for this second programme is detailed in Table 4-4.

Following the primary tests it was concluded that the temperature at which the sediments were exposed during the dry-weather period might influence on the resistance to erosion. Therefore, a better control of the temperature and the analysis of the influence of the biological reactions were formulated. In that regards, this new erosion test programme was carried out in a temperature controlled laboratory facility at the University of Sheffield, UK. The test temperature was set at 20 °C.

Table 4-4: Test condition used in the consolidation periods in the erosion experiments Second test programme.

Identificantion of the test	T6	T7	T8	T9(a, b)	T10	T11(a, b)	T12
Dry-weather period (hours)	16	27	40	64	40	64	16
Environmental conditions	Aerobic				Anaerobic		Aerobic
State of sediment conservation	Natural "fresh"						dry

Repetition test were carried out for 64 hours dry-period at aerobic and anaerobic environment (*T9a* and *b*, *T11a* and *b*).

The establishment of a longer dry-weather period of 288 hours without oxygen supply was also planned. Nevertheless, biological transformation processes during the experiment cause the interruption of the test. Since about 165 hours (from the start of the dry-period) it was observed quick drop in the sediment bed depth and available sediment in suspension due possible to the organic matter consumption occurring under this environment. Changes in odour were also notice after about 48 hours elapsed from the start of the consolidation phase. The odour problems are caused by the hydrogen sulphide formation, associated with anaerobic conditions. Thus, the transformation processes occurring means biological reactions probably caused because anaerobic or active facultative bacteria. Based on this observations and also on the previous (first programme) when long-dry period of storage test under oxygen supply also failed because reactions in the mass of sediments, was suggested that transformation might influence on the resistance of the deposited sediments.

A full discussion of all the results of the first and second tests are shown later in this chapter.

4.3 Laboratory results and discussion

Based on the performed erosion test carried out, the rate of erosion and the strength of the sediment bed against erosion (considered in terms of sediment concentration of the re-suspended sediments) have been investigated by increasing flows.

Here below the results obtained from these tests are presented and a discussion about the influence of the different environment condition on the resistance to erosion is presented.

Despite similar conditions in performing the tests during both mentioned programmes, no direct comparable results were obtained between them. The main reason is due that different batch of sediments were used. The high variability in the sediment accumulation process in pipes meant differences in the composition of any collected sample. A comparison of the sediment collected for being used in these two erosion test are shown in Table 4-5. Different conservation conditions (dry and fresh sediments) might also affect the resistance against erosion.

Table 4-5 Characteristics of the sediments collected from urban catchment in Granollers. Spain used in the erosion tests.

Sediment batch	sediment density [kg/m^3]	organic content [%]	Original moisture content [%]	Conservation
Collection data: 26/06/2012	1308 (± 211)	74 ±5 (VS/TSS)	74 %	Dry (at 50 ºC during 10 days)
Collection data: 16/09/2013	1313 (± 95)	95 ±2 (VS/TSS)	95.4 %	Mantained in natural state of humidity (at 4ºC)

Comparing the sediment composition, first batch of sediment has 74% organic (26% inorganic), second batch, more organic (95.4%). Nevertheless, both samples denote a high organic content. Second sample display moreover a more uniform composition and density. Despite a slightly lesser value of sediment density is observed from the first batch, the larger standard deviation (211 kg/m^3) and the greater presence of inorganic sediments indicates in general less dense material.

Even though the results are not directly comparable, Figure 4-6 shown the shear stress-erosion rate curves obtained by using dry sediments from the first (2012) and second (2013) batch, both tests performed with 16 hours of consolidation period. The higher resistance of the second sediment batch is suggested to be related with the highest organic matter content. The proportion of increment of resistance in depth of erosion is maintained for both tests. More tests are required in order to analyse a trend in terms of the influence of organic content on the bed strength.

As a consequence, results obtained from both laboratory programmes were analysed separately.

Results from previous laboratory work (Tait *et al.*, 2003b; Schellart *et al.*, 2005) using a similar device were also considered in the discussion too, in order to compare the behaviour of real sewer sediment with low organic content and artificial sediment with a very high organic content.

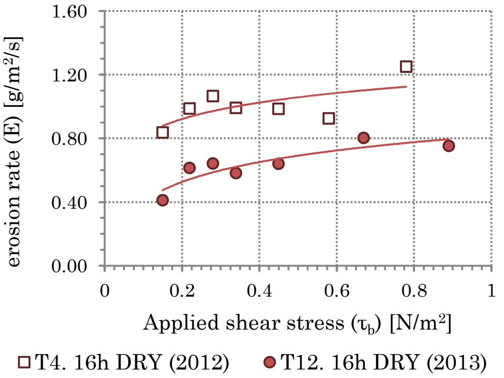


Figure 4-6 Comparison between erosion results obtained from tests with sediment stored at the same conditions (different batches) and same dry-period length.

4.3.1 First test programme results

Figure 4-7 shows the evolution over time of the measured values: suspended sediment concentration (*TSS*), volatile solids (*VS*) and applied shear stress (τ_b) for the erosion test identified as *T1* (16 hours dry weather period, without oxygen supply), displayed here as an example. The increasing values in the concentration of the suspended sediment in the water column are consequence of the increasing shear stress applied at each step.

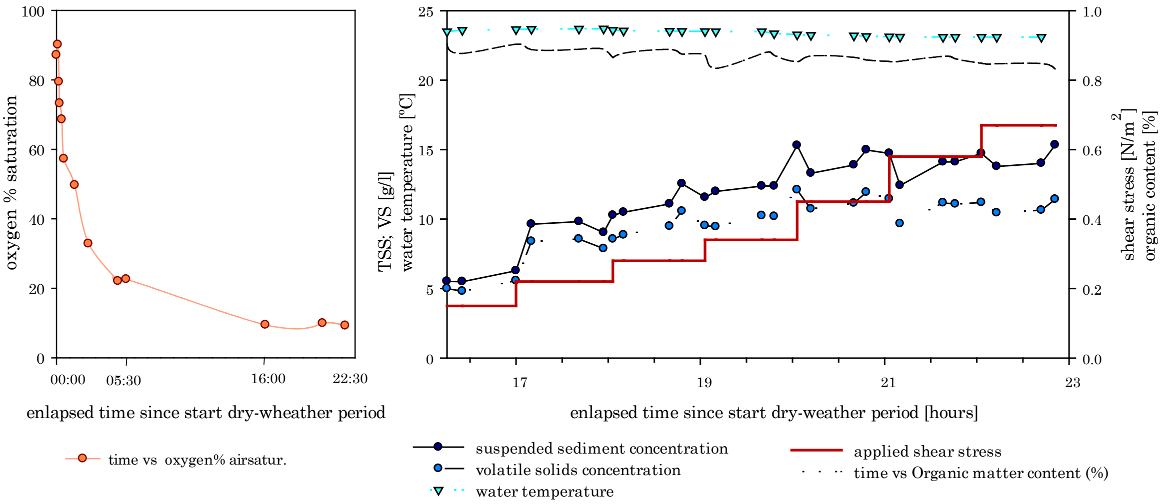


Figure 4-7 Measurements of sediment concentration and applied shear stress during erosion test T1, 16 hours dry-weather period without oxygen supply.

The evolution over time of the total suspended sediments and volatile sediments was analysed during the events. It can be observed that the organic content (as a relation between TSS/VS) is slightly but continuously decreasing as the applied shear stress increases. This might suggest that more organic particles (with lower density) are eroded under lower shear stresses, and more inorganic particles (denser) require higher shear stress to be mobilized.

The test was performed at ambient room temperature. The water temperature inside the reactor was measured. It can be observed that a quite stable value is maintained during the whole test (average 23 ±1 °C). The dissolved oxygen was completely consumed within about the first 6 hours from the beginning of the simulated dry-weather period. This period of oxygen consumption was confirmed during the rest of the tests performed without oxygen supply. The small percentage of dissolved oxygen in water since practically the beginning of the test means that anoxic biological reactions will be predominant.

In contrast, Figure 4-8 shows the behaviour during a test (*T4*) carried out with oxygen supply. Test *T1* and *T4* were both performed with the same length of dry-weather period but different environmental conditions were tested by providing or not oxygen. In general, during the tests performed under aerobic conditions, it can be observed the growth of a biofilm over the deposit mass, possibly due to the aerobic microbial activity.

From the parameters evolution in the *T4* test, it can be observed a possible influence of this biofilm in the erosional resistance of the deposit mass. It is suggested that the biological activity might generate bonding between particles, which is thought to be translated in an increment of resistance against erosion of the sediment deposit. This increment in resistance can be observed in Figure 4-8 through the quite flat curve of *TSS* (average 7.8 g/l, *SD*=0.9*)*.

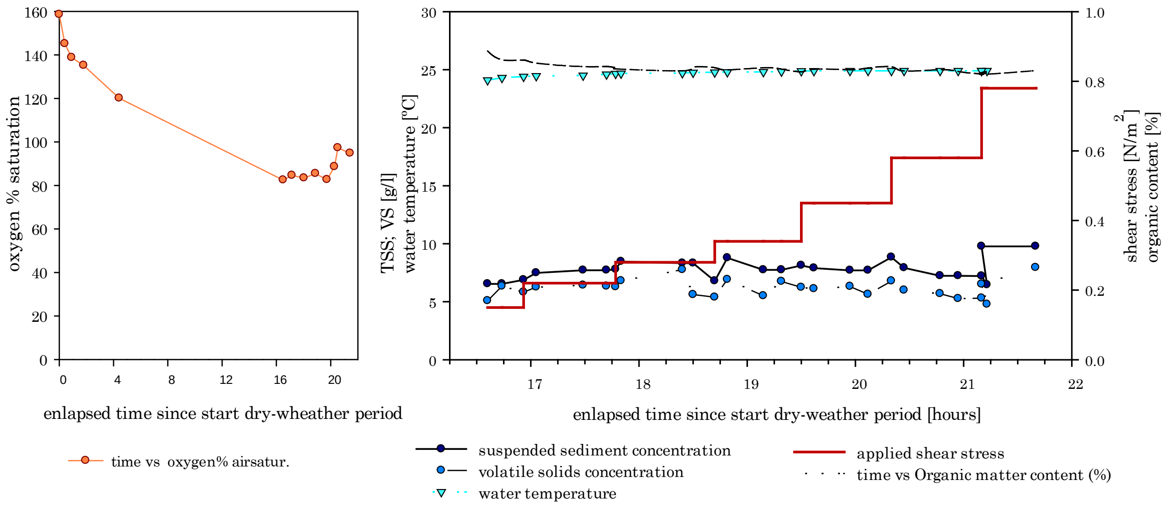


Figure 4-8 Measurements of sediment concentration and applied shear stress during erosion test T4, 16 hours dry-weather period under aerobic conditions.

The *TSS* values were maintained during all the erosion phase around a constant value until the seventh step (τ_b=0.78 N/m^2), when an increment in the suspended sediment concentration was noticed (27% from the average in the previous erosion stages). This variation in *TSS* might mean having reached the threshold of motion of the bed deposit.

In this way, from the analysis from Figure 4-7 and Figure 4-8 it can be initially suggested that the availability of oxygen in water has influence on the organic sediment deposit strength.

4.3.1.1 Erosion rate assessment

The deposited sediment started being eroded as soon as any of the beds in the different tests were exposed to the low shear stress representing the dry weather flow conditions. The absolute threshold of motion was therefore difficult to observe for all experiments carried out.

The value of erosion rate can be determined using equation 4-2 for each of the steps of applied shear stress. The average erosion rate can then be plotted against shear stress (Figure 4-9) to analyse the sediment deposit behaviour during the tests carried out under anaerobic and aerobic conditions and for different dry-weather simulated periods.

In Figure 4-9 it can be seen, in general in all tests, that as the shear stress increased the erosion rate curve shows a slight rise.

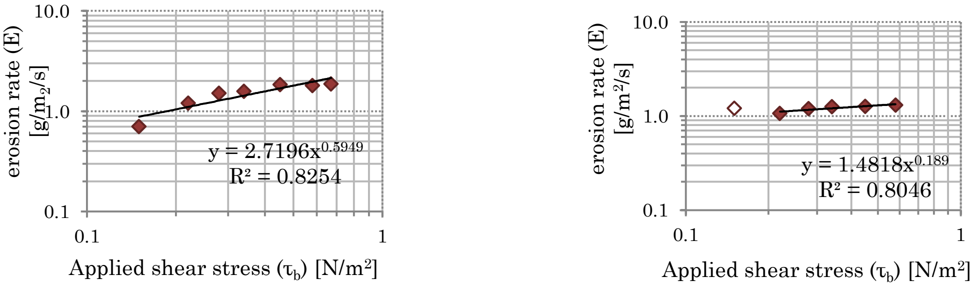
Although flocculation of particles may happen due the characteristics of the sediment, and thus increase the chances of flocs sedimentation, the deposition of particles is not considered significant during the erosion phase of the experiment. Due to the observed overall incremental values of erosion rates, it can be assumed that there is not sedimentation of particles during erosion, and if occurs, is not significant. Particularly, only during test *T4* the erosion rate increased at first and then decreased later. The slight decrease on the erosion rate towards the end of this test may be due to the existence of a locally stronger consolidated layer within the original deposit.

When comparing between tests with increasing periods of consolidation without added oxygen (*T1* to *T3*), there is a clear drop in the overall values of erosion rate, related to the values of the applied shear stress, as the length of the dry period increases. This suggests that as the consolidation period lengthens the deposit strengthens.

Comparing cases *T1* with *T4,* and *T2* with *T5*, which means same dry-weather period length and different oxygen availability, a decrease in the overall values of the erosion rate was noticed with the increase in oxygen. This is thought to be associated with aerobic biological activity, which appears to have generated a stronger deposit regarding the resistance to erosion.

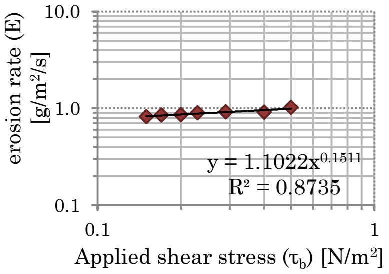
First samples in tests identified as *T2* and *T5* in Figure 4-9 have a relatively high erosion rate, which may be related with a weak layer formed in the upper bed, this may be composed mainly by the settling of lower density particles consisting in flocs of sludge and a high percentage of fats that have not then had the time to be able to transform and generate sufficient cohesive bonding to strengthen, as is the case in *T3* for instance.

It is difficult to find a general trend in erosion rate against shear stress for every condition. It is clear however that the presence or absence of oxygen and the length of the consolidation period significantly influence the behaviour and resistance of the deposit against erosion.

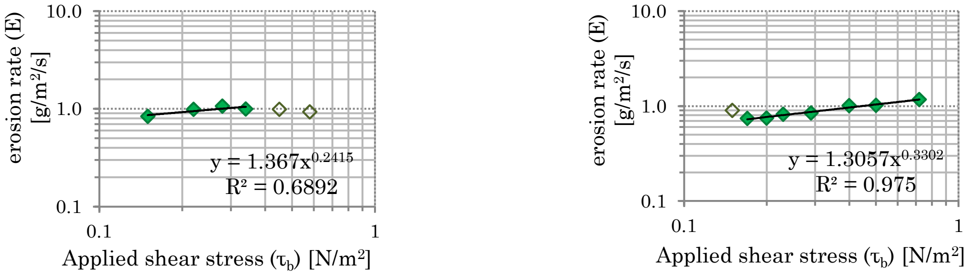


T1 Anaerobic. Dry-weather: 16hs

T2 Anaerobic. Dry-weather: 64hs



T3 Anaerobic. Dry-weather: 140hs



T4 Aerobic. Dry-weather: 16hs

T5 Aerobic. Dry-weather: 64hs

Figure 4-9 Erosion rate against applied shear stress during tests under anaerobic (T1-T3) and aerobic (T4-T5) conditions. Double log plot and trend curves.

An empirical relationship between the rate of erosion and the applied bed shear stress is adopted by establishing a power trend as the best fitting function. Figure 4-9 shows the empirical erosion equation obtained in each test. Differences in the R^2 values can be explained due to the inherent variability in the sample being tested. These trend curves are plotted comparatively in Figure 4-10. A clear tendency of increasing erosion strength in bed can be seen, as the duration of the dry period was increased.

The slopes of the erosion rate-shear stress curves are much lower than that expected for a purely granular bed (1.2 to 1.5). The slopes values range from 0.59 to 0.15 indicating a deposit that is increasing in strength with depth. The increase of strength with depth of erosion can be supposed to be related with changes in the internal structure of the deposit (Skipworth *et al.*, 1996).

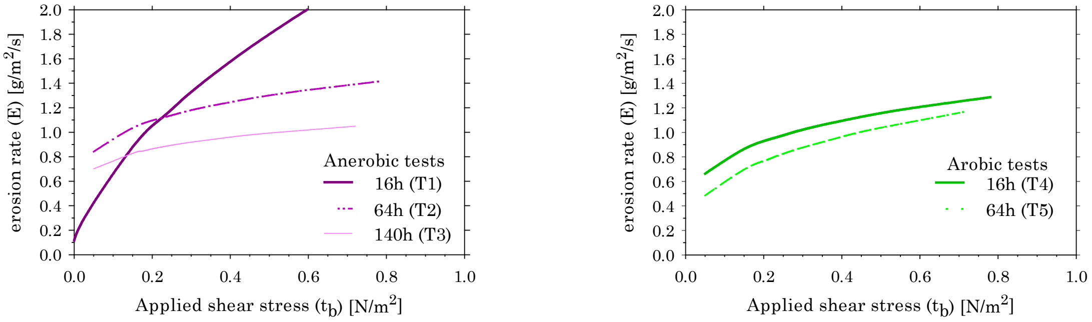


Figure 4-10 Trend curves of erosion rate (power relationship displayed in Figure 4-9) showed comparatively for different length and oxygen supply during the consolidation period.

Same duration of the dry-weather period trend curves but different oxygen availability conditions are compared in Figure 4-11. The effect that the oxygen has on the erosion strength could be analysed from these curves. In tests performed with oxygen supply, the shear stress required for the erosion of the sediments was significantly higher compared with experiments ran without supplying oxygen. This difference is around a 40 % between erosion rate values in tests *T1* and *T4* at 0.6 N/m², and around an 18 % between erosion rate values in tests *T2* and *T5* also comparing trends at 0.6 N/m².

The dotted lines in Figure 4-11 indicate the possible variation that can be considered according to the errors in the assessment of the shear stress during the calibration procedure (shear stress ± 0.07 N/m². See details in Section 4.3.3.2.4). The differences in behaviour are still significant despite the errors that may have been incurred during the tests. The compound error for the shear stress value was calculated following the estimation of the measurement errors and the given accuracy of the equipment, which is explained with more detail in Section 4.3.3.1.

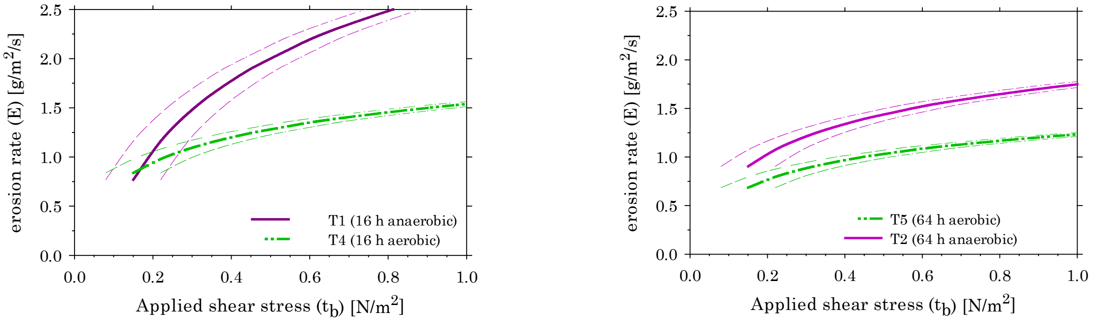


Figure 4-11 Trend curves of erosion rate with erros in the τ_b assessment showed comparatively for test with16-hours length of dry-period and Anaerobic/Aerobic conditions (left) and for 64hours dry-period length and Anaerobic/Aerobic conditions (right).

Another relevant fact was obtained from the analysis of the remaining sediments at the bed after the performed erosion tests. The leftover sediment shows an increasing trend in organic content and a decline in the median size of the particles that form the leftover deposit with the duration of dry weather (Figure 4-12). This behaviour might be explained by the added time available for biological reactions between organic particles during the dry-weather period, resulting in the generation of more bonding internal forces and a stronger sediment deposit. This trend implies that for shorter dry-periods, the finer particles in the mass of sediment were easily eroded. As the dry-period duration increases these finer particles (and more organic) remain at the bed, possibly linked with bonding forces and developing a stronger deposit (also due to biofilm growth), thus the value of the mean particle size (d_{50}) of the solids in the bed is lower.

Oxygen supply during this period leads to a more biological activity and to an increase in the resistance to erosion of the whole bed of sediments.

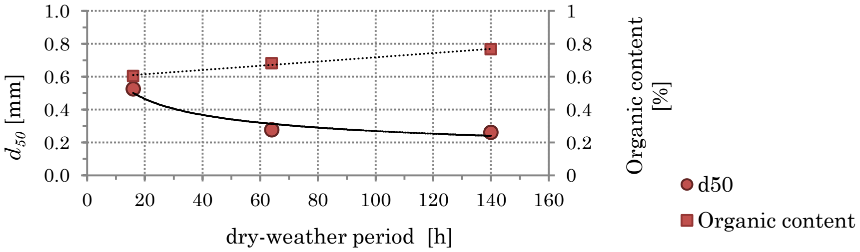


Figure 4-12 Analysis leftover after erosion tests under anaerobic conditions. Variation in particles size and organic content with length of dry-weather period

Not conclusive findings regarding a range of values of the critical shear stress for the deposit were reached from this first set of performed tests.

4.3.2 Second test programme results

In this section, complementary results obtained from laboratory experimentation with a second batch of high organic sewer sediment were reported. As in previous section, the prepared sediment bed subjected to different environmental conditions during a considered consolidation period was tested against erosion. In this case, tests were performed at stable temperature (20 °C) in a laboratory controlled facilities and sediments preserved in natural fresh state are using preferably.

From the results showed in Figure 4-13, the slopes of the erosion rate against shear stress trend curves range from 0.64 to 0.21 for test under aerobic conditions, which denotes rising strength of the deposit bed with depth. That increment is less significant under anaerobic conditions (slope ranging from 0.28 to 0.05).

Under aerobic conditions significantly higher shear stresses (linked to the flow inside pipes) are required to erode similar rate of deposited sediments as the consolidation time increases. For instance, following the increasing dry-weather period tested, in order to erode 0.35 g/m^2/s about 0.27 N/m^2 is needed to be applied under the bed of sediment with 16 hours of consolidation, meanwhile a 58% higher shear stress (about 0.65 N/m^2) will be needed to obtain the same erosion rate in a 64-hours consolidated deposit.

Also analysing the aerobic tests, the convergence of the erosion curves is noticed. This convergence might imply that the value of the critical shear stress at the superficial layer (τ_{cs}) adopts a constant value independently the dry-period simulated, but possible dependent on the sediment characteristics.

In the tested conditions, shear stress values are established in the range of about 0.15 and 0.90 N/m^2.

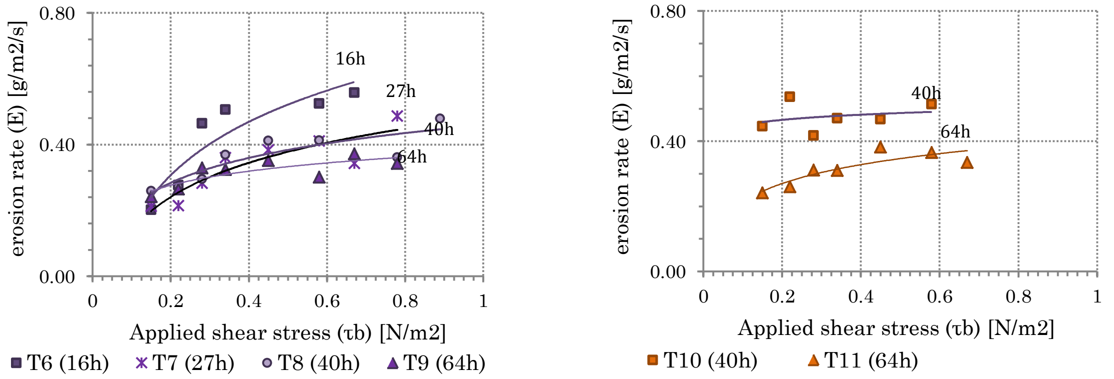


Figure 4-13 Measued values and trend curves of erosion rate (power relationship) showed comparatively for different length during the consolidation period and Anaerobic environment (left side), Aerobic environment (right side). Second erosion test programme.

Not sufficient tests were performed under anaerobic conditions to make a more detailed analysis regarding influence of the consolidation period duration.

The effect of the oxygen is also consistent with previous findings during the first laboratory programme. From curves displayed in Figure 4-14, differences between oxygen availability for the same dry-weather period simulation can be noticed. Strongest beds are formed under aerobic conditions; despite for 64 hours dry-period it was observed just a slight difference in the shear stress necessary for the erosion of the bed. As consolidation time increases, the differences in erosion resistance of the bed become smaller.

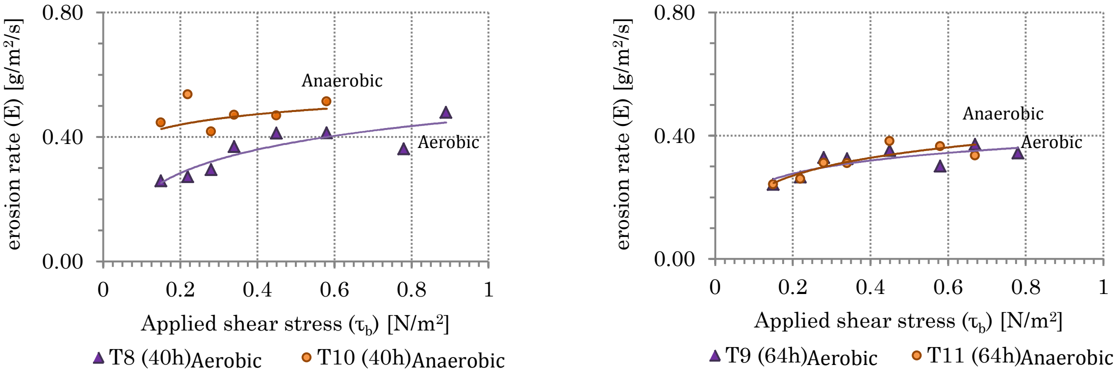


Figure 4-14 Measured values and trend curves of erosion rate showed comparatively for test with40-hours length of dry-period and Anaerobic/Aerobic conditions (left) and for 64hours dry-period length and Anaerobic/Aerobic conditions (right).

The possible variations in the results when the error in the assessment of the shear stress during the calibration procedure is considered (shear stress ± 0.07 N/m^2) are shown in dotted lines in in Figure 4-15.

As it was mentioned before at the beginning of this section, it is not possible to directly compare results from both tests programmes mainly due to the use of sediments from different batch and preserved at different conditions, which might affect the effects on the subsequent erosion tests.

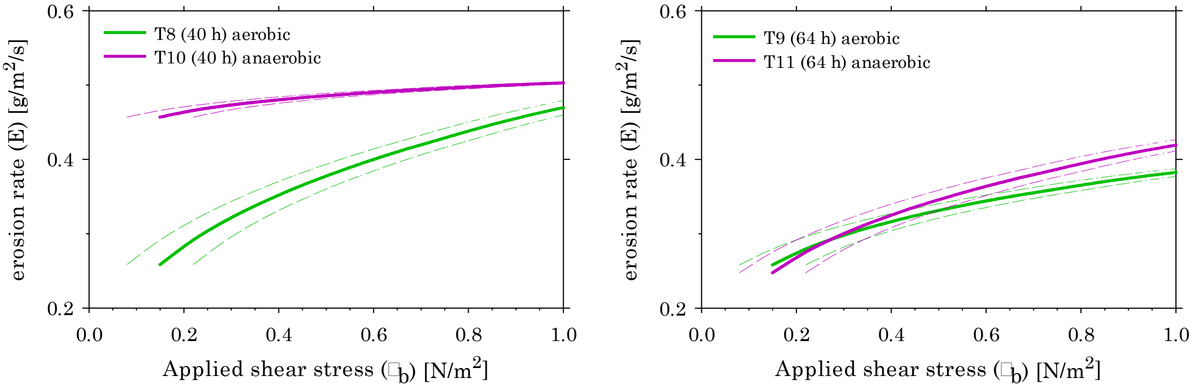


Figure 4-15 Trend curves of erosion rate with erros in the τ_b assessment showed comparatively for test with40-hours length of dry-period and Anaerobic/Aerobic conditions (left) and for 64hours dry-period length and Anaerobic/Aerobic conditions (right).

To account for the possible influence of the different conservation conditions (dry and fresh sediments), an erosion test was carried out using a sediment sample from the second batch, dried at the same conditions as before (first laboratory programme). A comparative graph is shown in Figure 4-16. It can be observed that stronger sediment bed were developed using sediments preserved in natural fresh state in comparison with the erosion results obtained with sediment sample previously dried. From this observation, it is possible to suggest that the drying processes performed inhibit the activity of certain microorganisms (or even produce the degradation of microorganisms) that make possible the development of stronger bonding forces between particles.

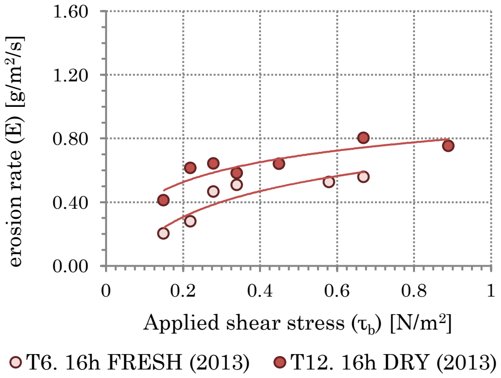


Figure 4-16 Comparison between erosion results obtained from the erosion of sediments stored at different moisture conditions prior tested.

Summarizing, from the analysis of the results obtained from the erosion tests during the second laboratory programme, similar trend is obtained regarding different environmental condition tested. During this new set of tests it is also clear that aerobic environment gives strongest beds regarding resistance to erosion, as well as under increasing length of the consolidation period. It was also verified that increasing strength is reached with depth of the sediment bed.

The results obtained from the new set of laboratory work under aerobic conditions allow for the assessment of the parameters involved in an erosion and transport model, which is explained in Chapter 6.

4.3.3 Observations on measurement accuracy and methodology

4.3.3.1 Observations on sediment concentration assessment

To measure the total suspended sediment (*TSS*) the method described at the *Standard Methods for the Examination of Water and Wastewater* (2005), section 2540.D (*Total Suspended Solids Dried at 103-105 ºC*) was used.

The Standard Method requests for removing sample moisture by oven drying at 103 - 105 ºC until constant weight, which is reached when the weight of the sample does not vary more than 4% of previous weight. Commonly for wastewater samples constant weight can be accomplished in around 8 hours. Drying time depends on the sediment moisture content, but it could be seen that for high-FOG-content sediments the dependence might also be related with the fat content. During laboratory work using high organic sediments with significant FOG content, it was noticed difficulties in achieve a constant weight in the samples. Drying time can reach around 96 hours.

Results taken from the instant weighted measured carried out during the second laboratory programme for TSS analysis until arriving at constant weight in the way asked by the *Standard Method*, were plotted against time. An exponential trend was obtained (Figure 4-17). From the analysis of this drying curve, it was hypothesized that fat and oil degradation can introduce slight variations in the weight of the samples. It can be observed that after around 48 hours of oven drying at temperature required for standard analysis, the rate of weight variation reduces significantly.

Future work is needed in order to analyse the influence of the drying temperature on the degradation of FOGs compounds and the influence of this on the assessment of the total suspended sediments (TSS). In that regards, thermal gravimetric analysis (TGA) was start being performed by researchers of the Pennine Water Group and University of Sheffield using remained sediments used in the second erosion programme mentioned in this Chapter. TGA analysis consists basically in an online weight measurement of the sample while the sample is heated up. Up to date there are no conclusive results that may be mentioned from this analysis.

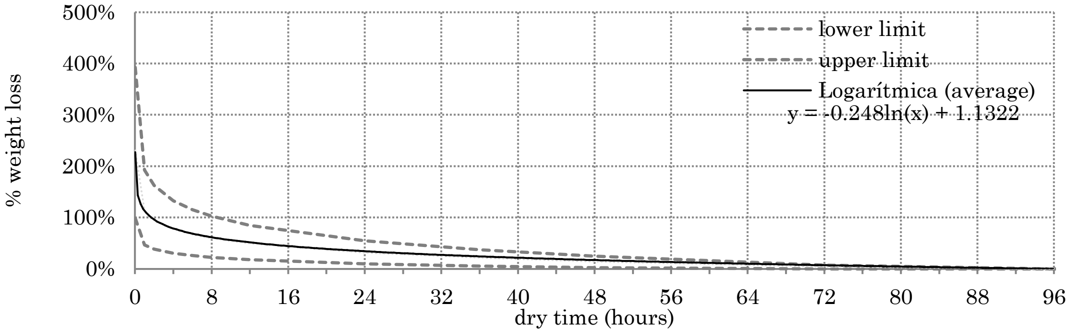


Figure 4-17 Evolution of the sample weight loss during drying at 105ºC for TSS analyisis.

4.3.3.2 Accuracy of the measurements

4.3.3.2.1 Errors in samples volume

Errors in the volume of sampling were reduced by measuring the weight of the samples taken rather than measuring the volume.

A scale with accuracy of 0.01g was used during the sampling, which relates to the error in the volume sampling (Δv_m).

4.3.3.2.2 Errors in TSS analysis

The weighting of samples to perform the TSS analysis following the *Standard Methods* (2005) was done using an analytical balance with a high degree of accuracy, 0.0001g (Δm_s).

Considering the error introduced during the sampling and the error in weighting of the filtered sediment, the total error reached is, in average, 0.5 mg/l for the samples from *T5* test, taken as an example for the calculation. Equations used for the calculations are displayed below.

$$C_{SS} = \frac{m_s}{v_m} \qquad \text{4-3}$$

$$\Delta C_{SS} = \frac{\partial C_{SS}}{\partial m_s}.\Delta m_s + \frac{\partial C_{SS}}{\partial v_m}.\Delta v_m \qquad \Delta C_{SS} = \frac{1}{v_m}.\Delta m_s - \frac{1}{v_m^2}.m_s.\Delta v_m \qquad \text{4-4}$$

4.3.3.2.3 Errors in the calculation of the Erosion Rate

For the assessment of the compound error in the determination of the erosion rate values, it is necessary to consider the errors in the total sediment concentration of the samples, in the measurement of the sample volume, the measurements of the bed surface area and time. By applying equation 4-6, the error reached from the calculation of the erosion rate (q) was lower than 0.0001 g/m^2/s

$$q_i = \left(C_{SS,i} - C_{SS,i-1}\right)\frac{V_w}{A_{s-e}(t_i - t_{i-1})} \qquad \text{4-5}$$

$$\Delta q = \frac{\partial q}{\partial C_{SS}}.\Delta C_{SS} + \frac{\partial q}{\partial V_w}.\Delta V_w + \frac{\partial q}{\partial A_S}.\Delta A_{s-e} + \frac{\partial q}{\partial t}.\Delta t \qquad \text{4-6}$$

4.3.3.2.4 Errors in the calibration process and assessment of the shear stress values

Accuracy in the assessment of the shear stress value is related to the angular velocity, the accuracy of balance for weighting supernatant samples (0.1g), and the accuracy of the balance for weighting filter papers and dry samples (0.0001 g). The error in the assessment of the shear stress values related with the angular velocity of the propeller was determined as 0.07 N/m^2.

The assessed compound errors were graphically displayed in the plot in Figure 4-18. The results for test *T5* were taken as an example. The errors graphs were plotted in both axes of erosion rate (ordinates) and applied shear stress (abscissas) to show the influence of the errors in the final results.

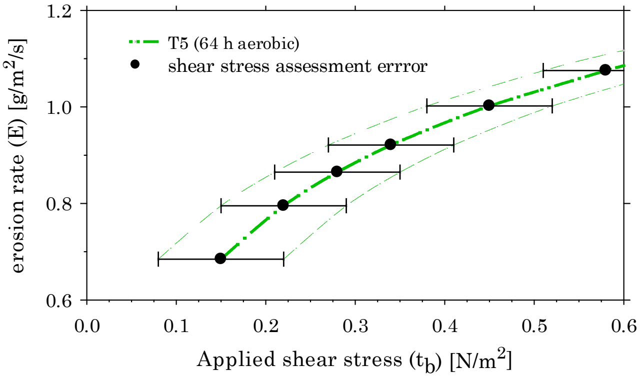


Figure 4-18 Calculated errors in the assesment of shear stress and erosion rate values.

The measurement errors and the errors in the assessment of the erosion rate have not relevant influence in the results shown in the graph. However, the errors introduced by the applied shear stress assessment were much significant.

Previously in Figure 4-11, the assessed errors are showed as upper and lower trend lines. The differences observed in the behaviour of sediment in anaerobic/aerobic conditions and short/long consolidation period remain significant despite the measurement errors.

4.4 Initial studies on the effects of the biodegradability of the organic sediment on the resistance to erosion

Reactions regarding biological transformation processes with sewer sediments have been previously studied (Vollertsen *et al.*, 2000; Banasiak *et al.*, 2005, 2008). These previous researchers conclude that biochemical properties and changes in the deposit composition are of importance and affect the sediment transport behaviour.

Results obtained by Sakrabani *et al.* (2005) from Oxygen Uptake Rate (OUR) experiments using dry and wet weather wastewater samples collected from a combined sewer system showed a higher biodegradability at the beginning of a storm event after which the biodegradability gradually declined. It was suggested that this was influenced by the initial high value of the resuspension of sediment from in-sewer deposits due to the initial rising storm flow rate. Vollertsen *et al.* (2000) suggest that biofilm developed on the surface of the sediment layer under aerobic conditions and that this also has an influence on the levels of biodegradability observed in the initial part of a storm.

Information about the in-sewer processes associated with the measurement of the evolution of deposits is very difficult to obtain because the processes are continually interacting (Raunkjær *et al.*, 1995) and hence increase the difficulties in assessing the temporal change in deposit strength when predicting sewer sediment transport.

4.4.1 Observations on transformation processes

During erosion tests carried out with highly organic sewer sediments containing fats, oils and greases, several transformations of the deposits were observed both under aerobic or anaerobic conditions.

Two different effects were observed occurring during the erosion tests. Firstly, under aerobic conditions, the formation of a upper film over the sediment bed surface (biofilm) that create a kind of elastic layer (that offers resistance to puncture) but in turn stronger regarding resistance to erosion. Secondly, for the longest dry-weather periods planned in both, aerobic and anaerobic conditions, after a certain period of elapsed time since the start of the dry-weather simulated period, the deposited bed become weaker and is easily release into suspension and even disaggregate in more fine particles or diluted.

This last mentioned effect was observed after around 90 hours in aerobic conditions and around 165 hours under anaerobic conditions. Biological transformation processes occurring in the reactor affect the sediment bed in the way that make not possible to perform the erosion test. For the anaerobic case, after this period the initially deposited sediments completely flowed into suspension. Thus, in combination with the visual observation of a high grease and fat content of the sediment, it lead to the hypothesis that anaerobic conditions were causing microbial degradation of large organic molecules like those found in grease/fat, and thereby weakening the sediment deposit.

To test this hypothesis, a further study was carried out in which the Oxygen Uptake Rate (OUR) was measured on sediments from the same batch used in the second erosion rate test programme. These sediments have been kept at 20ºC, under anaerobic conditions, for different durations, and complimentary results were obtained from sediments being kept in an aerobic environment.

The OUR results presented below were used in a first stage in the evaluation of the biodegradability of the organic sediments used in the erosion tests. Further detail on the experiment procedure and sample preparation can be followed at (Seco *et al.*, 2014) added in the annex of this dissertation.

4.4.2 Experimental setup of OUR tests

The apparatus consists of a 500 ml Erlenmeyer flask, with a rubber stopper at the top with an expansion cone on the inside connected to a pipe to allow air outflow during the aeration phase. The dissolved oxygen (DO) in the flask is measured using a Presens oxygen microsensor with a Microx TX3 fiber optic oxygen transmitter (Presens, Germany) and a small aquarium air pump is used for aeration. An experimental setup similar to that described in Jensen *et al.*, (2011) has been used to measure OUR. Photographs and a sketch of the apparatus are shown in Figure 4-19.

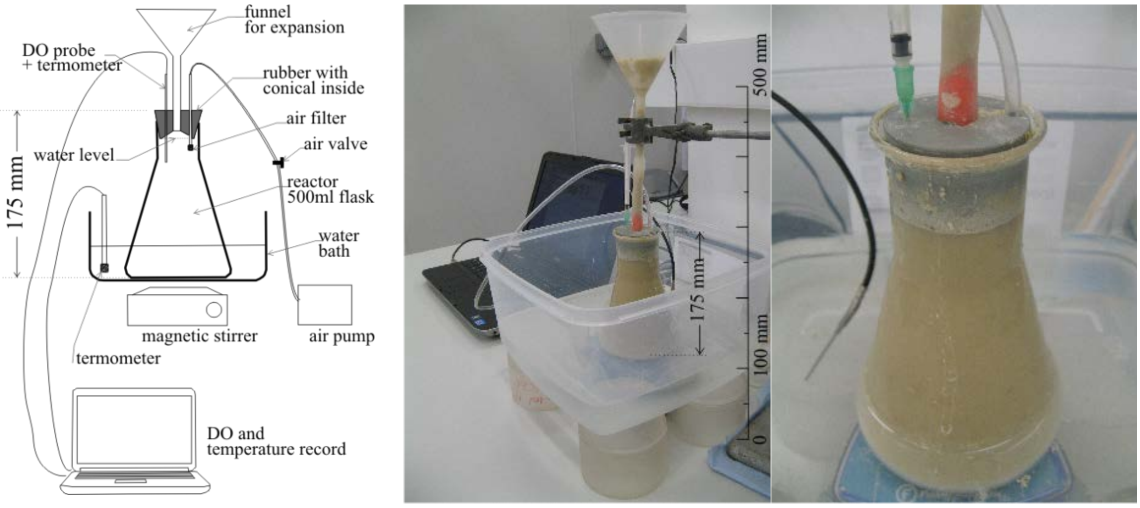


Figure 4-19 OUR test apparatus, consisting of a 500 ml Erlenmeyer flask.

The closed reactor is placed in a water bath on a magnetic stirrer. Continuous mixing allows the sediment sample to be kept in suspension during the test. Due to temperature influence on oxygen consumption rates (Jensen *et al.*, 2011), the water bath was used to buffer temperature possible changes due to the microorganism activity. The average water temperature in the bath was 18.9 ºC (Standard Deviation (SD) = 0.7 ºC) for test 1 and was 15.9°C SD=0.3°C and 16.0°C SD=0.1°C for tests 2 and 3 respectively.

4.4.3 Testing procedures and results

Experimental studies on the influence of the biodegradability of real in-sewer sediments were performed. The tests were carried out at controlled temperature laboratory facilities at 20 °C during deposition period under either anaerobic or aerobic conditions for the purpose of simulating similar conditions to those in the erosion meter prior to erosion tests. The sediment samples were of similar proportion in volume to that used in the earlier erosionmeter tests.

The first performed test (T1) set up was to reproduce anaerobic conditions during a 5-day dry-weather period. For the second test (T2) a control OUR test was completed with no dry weather period. Finally, the same duration as T1 was considered in T3 but under aerobic conditions for 5 days (74% ±5 air saturation level).

Each OUR test cycle begins with air injection into the reactor using the air pump until the oxygen concentration reaches about 80% air saturation. The cycle ends when oxygen concentration drop below 40% air saturation and a new aeration period starts. An example of the aeration-oxygen consumption cycles has been depicted in Figure 4-20.

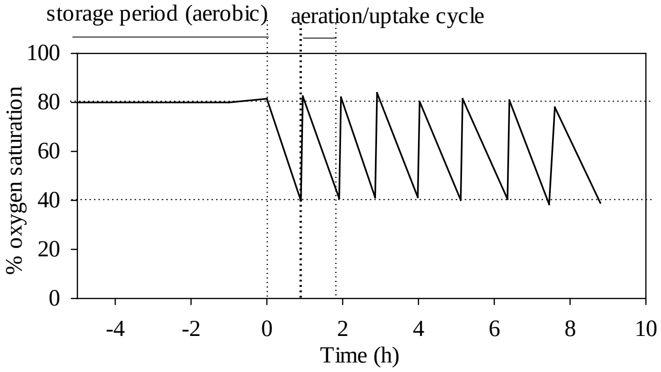


Figure 4-20 Aeration-Oxygen utilization cycles during test T3. The deposition period duration was 5 days. The same aeration/up-take cycle was used in Tests 1 and 2.

The oxygen utilization rates (OURs) in mg/l/h resulting from the test are shown in Figure 4-21. The OUR was calculated from the slopes of the dissolved oxygen concentration in the declining part of each Aeration-Oxygen utilisation cycle.

Results suggest higher oxygen uptake rate for sediment that has been stored under anaerobic conditions (Test 1). From the actual experimental measurements it was observed that the total oxygen consumption during the test was significantly higher for the sediments stored under anaerobic conditions (Test 1. comparing with the sediment stored under aerobic conditions (Test 3).

Although a small number of tests were conducted it can be hypothesised that there is a link between the weakness of the sediment deposits formed under anaerobic conditions and the degradation of the organic matter observed in the erosion tests. Further experiments would need to be performed using sediment with different percentages of organic matter and FOG content to confirm and evaluate the influence of the organic and FOG transformation processes on the resistance to erosion.

These initial results indicate the Dissolved Oxygen conditions during the consolidation of the sediments, as well as the organic content and proportion of FOG are of important in the analysis of the behaviour of sediment deposits.

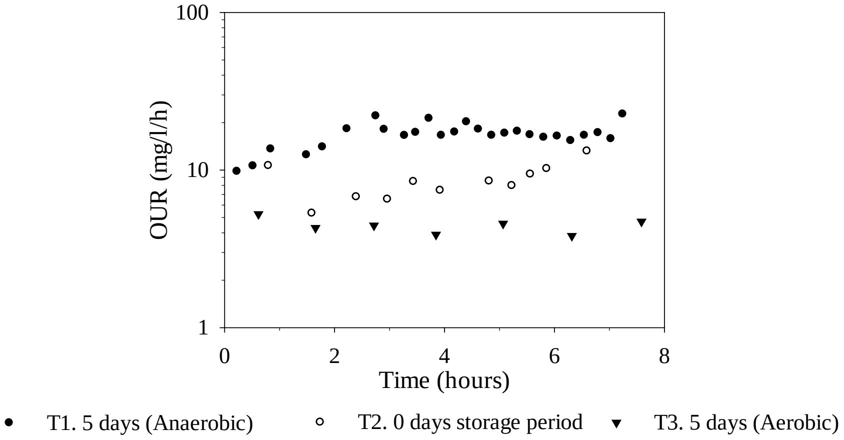


Figure 4-21 Comparison OUR after different sediment storage periods with anaerobic/aerobic conditions during dry-weather simulation period.

4.5 Conclusions

A series of erosion laboratory tests has been performed, by using an erosionmeter device, under aerobic and anaerobic conditions in order to study the erodibility and transport of sediments deposited in the invert of sewer pipes, as well as the influence of the microorganism activity on the resistance to erosion of the sediment.

From the results obtained in both test series it is clearly seen that conditions at which sediment deposits were subjected previously to the erosion phase have a very strong effect on the erodibility of the bed, both regarding length of the antecedent period of consolidation or the aerobic/anaerobic environment. It is suggested that environmental conditions in the consolidation phase may generate changes in the nature (because the biological growth) and in the structure (because the formation of bonds between particles) of the highly-organic sediment bed. These transformations strengthen or weaken the bed deposits regarding resistance to erosion.

The effect that the oxygen has on the erosion strength could be analysed from curves in Figure 4-11 and Figure 4-14. In tests performed with oxygen supply, significantly higher shear stresses are necessary to mobilize the deposited sediments compared with experiments ran without supplying oxygen, and these differences in resistance are less marked as the consolidation time increases. The differences in behaviour under aerobic/anaerobic conditions of the sediment beds in terms of resistance to erosion are still significant despite the errors that may have been incurred during the shear stress measurements, which is graphically shown in Figure 4-11 and Figure 4-15. A trend regarding the combined effect of aerobic/anaerobic and the length of the dry period also is noticed from these figures. It can be seen that as consolidation time increases, the differences in erosion resistance of the bed become smaller.

Erosion rates obtained varying the length of the consolidation periods can be seen in Figure 4-10 and Figure 4-13. In tests carried out with sediment preserved with their natural moisture content and aerobic environment, a shear stress of about 0.27 N/m^2 is needed to be applied under the bed of sediment with 16 hours of consolidation in order to erode 0.35 g/m^2/s, meanwhile about 0.65 N/m^2 (58% higher) was needed for obtain the same erosion rate in a 64-hours consolidated deposit. This suggests that increasing consolidation period leads also to increasing strength of the deposited beds.

Also, from the analysis of the sediment remained in the bed after erosion tests, it might be suggested that the longer the dry-weather period a stronger deposit is developed. The finer and more organic particles were retained in the whole mass of the bed after the erosion test was performed, which means particle linkages are developed and the resulting beds are more resistant to erosion.

Similar erosion patterns have been observed between the results obtained in this work and those found by Tait *et al.* (2003) using synthetic sediment, both with a clear increase in the resistance of the deposited bed with time of consolidation, especially when there was oxygen available. Conclusions about the significant influence of the organic content, oxygen availability and length of the consolidation period (dry-weather) on the subsequent erosion of the deposit are similar also to that observed by Schellart *et al.* (2005).

Although there were similarities with previous findings related to the general behaviour of the sediments, the immediate suspension of sediments at the beginning of the erosion test suggests marked differences in the shear stresses at the threshold of motion. Lesser magnitudes of critical shear stresses can be predicted from the tests conducted in this work with the high-organic sediment found in Granollers (Spain) with regards to those collected from London (UK) and Loenen (Netherlands) with low-organic content, and the synthetic sediment. This behaviour is assumed to be due to the differences in the sediment properties with regards to both, the relatively low density and the high organic composition and high bacterial potential activity.

Similar behaviour was observed comparing with the results from Ahyerre *et al.* (2001) who carried out studies of erosional behaviour in real combined sewer with sediment that also present a high organic content and low density. Ahyerre *et al.* (2001) confirm by direct measurements in combined sewers systems that erosion of this type of deposited sediment happens even at low shear stresses of around 0.5 N/m^2.

Based on laboratory findings using real sewer sediments, it was observed that high organic sediment deposits display lower shear strength against erosion with respect to the boundary shear stresses displayed by inorganic deposits. Despite the strength of the deposit increases in depth, the relative low values observed may be the cause of the strong first flush of suspended sediments observed at the beginning of storm events in these combined sewer systems.

In the tested conditions, shear stress values are established in the range of about 0.15 and 0.90 N/m^2. General trends of behaviour could be assessed from the series of tests performed, but not conclusive findings were reached about the value of τ_c. The values of the boundary shear stress of the deposits is strongly dependent on the sediment characteristics (composition and size distribution) and on the conditions at which sediment deposits were subjected during consolidation period.

The results obtained from the second laboratory programme in aerobic conditions allow for the assessment of the parameters involved in the model of erosion and transport that will be explained below in Chapter 6. Thereby, the assessed values of the parameters are supposed that consider the intrinsic characteristics of the sediments (particle size distribution, density and cohesive properties) and the existence of underlying in-sewer biochemical processes that both influence on the sediment bed properties over time and transformation effects.

This chapter also presented initial experimental observations on the influence of the biodegradability of highly organic sediments in an attempt to link biological transformation processes with their transport potential. Oxygen Uptake Rate (OUR) tests were performed in that regards. Despite only a limited number of OUR tests being carried out, the results obtained suggest organic materials in the sediment having been degraded to a more readily biodegradable form during the anaerobic deposition period and that these readily biodegradable compounds were oxidised readily once oxygen was introduced into the system.

By linking the results obtained from the OUR tests with previous results from the erosion tests, is clear that microbial activity can influences the sediment transport potential when they are exposed to different anaerobic/aerobic conditions during the in-pipe deposition period.

Sediment deposits composed of organic matter and containing a considerable amount of FOGs were less readily biodegradable when kept under aerobic conditions. Reaeration in sewer network may therefore prevent the formation of more readily biodegradable organic matter which destabilises the sediments when metabolised by the microorganisms in the sediments. Aerobic transformation processes may reduce the risk of release of large amounts of easily/rapidly biodegradable pollutants when the threshold of motion of deposited sediments is exceeded, which could cause spikes of very low DO levels in receiving waters. Further work is needed to confirm these hypotheses and so allow for the proper characterization of the transformation processes in highly organic sediment deposits in sewers.

General trends on the behaviour of sediments under different consolidation conditions and how this affects the erodibility of the bed were found through laboratory work with high organic sediments. Nevertheless further laboratory investigation is needed to understand transformation processes in sediment deposits and their effect on erosion and transport. A better understanding of deposit strength changes would lead to better prediction of pollutants discharged into natural watercourses during rainfall and so will allow contributing to the development of “smarter” pollution control strategies.

4.6 Summary

A series of laboratory tests were carried out to help estimate the erosional resistance and hence erosion rate under storm runoff conditions over deposited sediment beds. The laboratory investigation was aimed to examine the erosion behaviour of the highly organic sewer sediments consolidated under different conditions regarding oxygen availability and length of the dry-weather period at room temperature.

An erosion meter device was used in the examination of the erosional behaviour of the sediments. High-organic sediments collected from a combined sewer system were used in the laboratory determinations.

A prepared sample placed in the bottom container of the erosionmeter is exposed firstly to a consolidation period and subsequently subjected to increasing shear stress. The action of the propeller at low velocity (applied shear stress 0.15 N/m2) simulates the flowing conditions during wastewater flows inside pipes for the period of consolidation of the bed. Increasing shear stresses were applied in stepwise way simulating flowing conditions during rainfall. All tests contained a consolidation followed by an erosion phase.

Bed deposits subjected to aerobic conditions encourage the development of a biological layer that can be the responsible for the increasing in strength of the deposited bed. Higher shear stresses are experimented under aerobic conditions compared with experiments ran without supplying oxygen. Despite the significant higher resistance for sediments consolidated during short periods under aerobic environment in front to the same period of consolidation but anaerobic conditions, these increments in resistance become smaller as the consolidation time increases.

From the analysis of the results, it was also suggested that under the same aerobic/anaerobic environment, as the consolidation period lengthens the deposit strengthens.

This chapter also presented initial experimental observations on the influence of the biodegradability of highly organic sediments in an attempt to link biological transformation processes with their transport potential. Oxygen Uptake Rate (OUR) tests were used to determine the biodegradability of organic sediments. The aerobic/anaerobic consolidation environments were varied in order to simulate alternating redox conditions that the sediment would be exposed to during the dry-weather “deposition period” in a combined sewer system.

Bibliography of the chapter

Ahyerre, M., Oms, C., Chebbo, G., 2001. The erosion of organic solids in combined sewers. Water Science & Technology **43** (5), 95–102.

Banasiak, R., Tait, S.J., 2008. The reliability of sediment transport predictions in sewers: influence of hydraulic and morphological uncertainties. Water Science & Technology **57** (9), 1317–1327, DOI:10.2166/wst.2008.297.

Banasiak, R., Verhoeven, R., De Sutter, R., Tait, S.J., 2005. The erosion behaviour of biologically active sewer sediment deposits **39** Observations from a labo (20), 5221–5231, DOI:10.1016/j.watres.2005.10.011.

Camuffo, G., 2001. *The erosion of organic sediment deposits and implications for sewer systems.* Tesi di Laurea.Universita degli Studi di Padova.Padova. Italy.

Jensen, H.S., Lens, P.N.L., Nielsen, J.L., Bester, K., Nielsen, A.H., Hvitved-Jacobsen, T., Vollertsen, J., 2011. Growth kinetics of hydrogen sulfide oxidizing bacteria in corroded concrete from sewers. Journal of hazardous materials **189** (3), 685–91, DOI:10.1016/j.jhazmat.2011.03.005.

Raunkjær, K., Hvitved-Jacobsen, T., Nielsen, P.H., 1995. Transformation of Organic Matter in a Gravity Sewer. Water Environment Research **67** (2), 181–188.

Van Rijn, L.C., 1984. Sediment Transport, Part II: Suspended Load Transport. Journal of Hydraulic Engineering **110** (11), 1613–1641, DOI:10.1061/(ASCE)0733-9429(1984)110:11(1613).

Sakrabani, R., Ashley, R.M., Vollertsen, J., 2005. The influence of biodegradability of sewer solids for the management of CSOs. Water Science & Technology **51** (2), 89–97.

Schellart, A.N.A., Veldkamp, R.G., Klootwijk, M., Clemens, F., Tait, S.J., Ashley, R.M., Howes, C., 2005. Detailed observation and measurement of sewer sediment erosion under aerobic and anaerobic conditions. Water Science & Technology **52** (3), 137–46.

Seco, I., Schellart, A.N.A., Jensen, H.S., Gómez-Valentín, M., Tait, S.J., 2014. Effect of the biodegradability on erosion of highly organic sewer sediment. In: 13th International Conference on Urban Drainage. Sarawak, Malaysia. September 2014.

Skipworth, P.J., Tait, S.J., Saul, A.J., 1996. Laboratory investigations into cohesive sediment transport in pipes. Water Science & Technology **33** (9), 187–193.

Standard Methods for the Examination of Water and Wastewater, 21st ed, 2005. . American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA., ISBN: 0875532357.

Tait, S.J., Marion, A., Camuffo, G., 2003. Effect of environmental conditions on the erosional resistance of cohesive sediment deposits in sewer. Water Science & Technology **47** (4), 27–34.

Vollertsen, J., Hvitved-Jacobsen, T., 2000. Resuspension and oxygen uptake of sediments in combined sewers. Urban Water **2** (1), 21–27.

Wilcock, P.R., 1988. Methods for estimating the critical shear stress of individual fractions in mixed-size sediment. Water Resources Research **24** (7), 1127–1135, DOI:10.1029/WR024i007p01127.

Chapter 5

Development a methodology based on SWMM5 to consider the release of the in-pipe deposited sediments

Software packages available for quality modelling in combined sewer system are aimed in general, to predict the evolution of pollutant loads under time varying flows when CSO episodes may occur. In Chapter 2 it was highlighted that SWMM5 has a quite good performance regarding hydrodynamic modelling. Although, regarding quality modelling issues, SWMM5 does not consider the effect of the release of sediments from inside the sewer pipes, which was identified as the main source of sediments and pollutants at the beginning of a storm event, when CSO discharges occur.

In that context, this chapter describes the design of a conceptual model that can be applied in SWMM5 that might allow to consider the mobilization of pollutants from inside the network system. First, in Section 5.1, the chapter will give an overview on the SWMM5 capabilities and the reasons for its selection. The basis for the design of the proposed methodology and the system requirements for its implementation are presented in Section 5.2. Later, its application in the study site where data (previously presented in Chapter 3) is available for verification is described in Section 5.3, which also shows the results obtained.

The applicability of the proposed conceptual model is then discussed in Section 5.4 where conclusions are given too, followed by a brief summary of all the presented in the chapter.

5.1 General overview on quality modelling with SWMM5

In previous Chapter 2, Section 2.5, it was shown that among the available software packages for urban sewer systems, not all of them involve quality aspect in modelling. Moreover, among those which include quality modules, just a limited number considers the modelling of the accumulation of pollutants during dry-periods inside the pipes of the system and later mobilization when a storm event is simulated.

Two of the most used commercial software packages, *InfoWorks* (HR Wallingford) and *MIKE-Urban* (Danish Hydraulic Institute), include modules that allow to model the erosion and transport of deposited sewer sediments. Although these modules provide oversimplifications in the sediment and pollutant transport modelling, they require a large number of user-prescribed parameters values. The difficulties in a reliable assessment of these parameters (that can even be locally dependant) increase the difficulties in their application, and in the uncertainties of the obtained results.

Knowing these difficulties in the practical application of the models, it is proposed the development of a calculation scheme that using a reduced number of pollutant parameters, let consider the transport of previous deposited sediments and attached pollutants within the network. In this way it was intended to provide a realistic first approximation of the assessment of the sediment and associated pollutant loads and their evolution over time concerning the pollution problem due to discharge through CSOs.

By using the software SWMM5 in the projected development, special regard was considered on the easily access to the tool that allows its applicability. The choice of SWMM5 for the proposed model is then based on the easy access to this tool and its proven calculation capacity in terms of quantity, that make this software package one of the hydrologic / hydraulic models most currently used not only in in Spain, but in the rest of the world, by sewer managers in small municipalities and in consultancies. As it was introduced in Chapter 2, SWMM5 (US-EPA) (Rossman, 2009), is a freeware software package, and is of simple application and proven reliability in the calculation. Thus, these advantages, greatly facilitates its wide use, covering almost all the demands raised by any specialist who wants to work in solving urban hydrology problems at minimal cost.

This section introduces on the SWMM5 quality capabilities and basic tools related to quality modelling that will be used later in Sections 5.2 and 5.3 in the design and in the application of the conceptual prediction pollutant loads module.

5.1.1 Quality model in SWMM5

From previous discussion in Chapter 2, it was seen that SWMM5 allows for the consideration of the build-up and wash-off of sediments and pollutants accumulated in the surfaces of the catchment. However, no consideration is made with regards to pollutants that might be accumulated inside the system and their subsequent mobilization when flow conditions vary.

In the quality module, SWMM5 also allows for considering functions for reduction of build-up (because street cleaning or best management practices)

For the utilization of the quality module, the pollutant must be defined and associated to other pollutants if required. Different uses of the surfaces with regards to establishing of independent patterns of build-up and wash-off must be defined.

Below, the accumulation and wash-off function available in SWMM5 are briefly introduced based on the more detailed explanation that can be followed in the manual of the software (Rossman, 2009). These tools will be used later in the predictive module developed.

5.1.1.1 Accumulation in surfaces (build-up functions)

The amount of sediments and pollutants accumulate on the catchment surface is a function of the number of dry days before a rain event. The defined function for the accumulation is also dependent on the frequency and techniques used for the cleaning of the surfaces, the traffic intensity, and the characteristics of the surfaces (vegetal cover and the urbanization patterns).

The accumulation in SWMM5 is described by exponential functions (that tend asymptotically to a limiting value), potential or saturation relationships, and it can also be proposed (since the version 5.019), with a user-defined function that must be introduced as an external time series. The details of the parameters of each one and the equations are detailed in the software manual, here below a plot of the typical functions is showed in Figure 2-1. Accumulation of pollutants can be also introduced in the model as an initial total mass of sediment distributed uniformly over the surface.

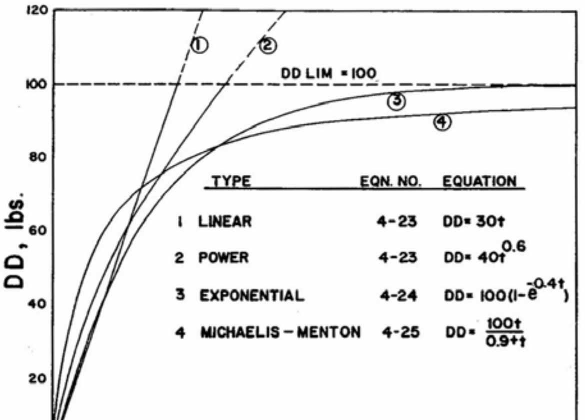


Figure 5-1 Comparison between linear and three nonlinear buildup equations available in SWMM5 (with arbitrary values) (after (Huber et al., 1992))

There is not a better option. Despite it is not possible to establish one function as the better approximation; the exponential function is one of the most widely used in the state-of-the-art. Nevertheless, each study case must be experimentally analysed.

The pollutants build up until to a certain level. The limiting value is related to an equilibrium state or static condition reached when the removal rate approaches the rate of accumulation. That equilibrium threshold is a function of the rate at which pollutants are deposited on the surface of the catchment during dry-weather. Thus, this period needed to reach the equilibrium condition is variable from catchment to catchment, usually found varying from 5 to 20 days (Arthur, 1996; Arthur *et al.*, 1999; Ashley *et al.*, 2004).

5.1.1.2 Release of pollutants from surfaces (wash-off functions)

The washing of pollutants by runoff is itself a complex process. The stochastic nature of the runoff that will mobilise the deposited pollutants linked to factors such as the rainfall characteristics (intensity, duration of the event and total height of precipitation) has a significant influence. In addition, the release and transport of pollutants by runoff is affected by the sediment characteristics as well as the surfaces conditions (prior moisture state, roughness, slope, etc.).

For its consideration, SWMM5 presents a simplified conceptual model. This model considers together the erosion processes of the impact produced by raindrops, and the originated by the surface runoff. Thus, this combination of erosion process is considered through a wash-off coefficient (k_e). For the assessment of the eroded mass of pollutants, a direct relationship between the available mass of accumulated particles and rainfall intensity is assumed: The equation 2-11 shows that relation, in which M_a (given in kg) is the accumulated mass of pollutants over the surface during the time t; $i(t)$ is the intensity of the rainfall (given in mm/h) that is linked with the runoff flow rate (Q) and k_e is the wash-off coefficient (in mm^{-1}).

$$\frac{dM_a}{dt} = -k_e\,.\,i(t).\,M_a(t) \qquad \textit{5-1}$$

The relationships that SWMM5 give as options for the wash-off calculation are derived from this previous equation. The wash-off function options in SWMM5 are: exponential, rating curve, and even mean concentration (EMC).

Through the use EMC for the wash-off representation, a constant pollutant concentration loads is assumed during the simulation. Rating curve method produce pollutant loads that only are functions of the runoff rate, and finally, the exponential function represent the pollutant wash-off as a function depending on both, the runoff rate and the amount of pollutant mass remaining on the catchment surface (Gironás *et al.*, 2009; Krebs *et al.*, 2013).

So then seems that the rating curve or the exponential function might better represent the washing-off process in a catchment surface, although the EMC method is widely used in the practice. The reasons of the use of EMC method are related with its simplest application, and because in many studies there are not enough data to implement a more sophisticated wash-off model, or even no enough field measurements to calibrate the pollutographs resultants.

The Nationwide Urban Runoff Program (NURP) conducted by EPA (Environmental Protection Agency from US) provide of estimations of the EMCs values usually found in urban surfaces, based in long term observations (EPA Environmental Protection

Agency, 1983). The local assessment of EMC values for a pollutant (e.g. TSS), require long time series of measurements that may give reliable mean values.

5.1.1.3 Quality routing

After that the pollutants are washed-off from the sub-catchment surfaces, they enter to the network and are conveyed through the system by the flow routing.

For quality routing, SWMM5 makes the assumption of a complete mixing within each conveyance pipe during simulation, in the manner of a continuously stirred tank reactor (Huber *et al.*, 1992). The concentration is therefore predicted as the weighted sum of the inputs concentrations. This means that all the pollutant concentration (from the eroded mass and water runoff in a catchment) that enter in a pipe is completely mixed with the concentration load that came from upstream, and is directly conveyed to the next downstream pipe.

For quality simulation in SWMM5 it is also possible to consider the pollutants that enter into the system through wastewater flows or other direct input, which are also mixed with upstream pollutant loads. But one important aspect is that SWMM5 does not consider any deposition of pollutants in pipes or re-suspension from in-pipe deposits during routing.

5.2. Proposed methodology for transport of in-pipe sediments

As it was explained before, for the particles transfer in the system, SWMM5 assume that the pollutants propagation inside the pipes is based on that a complete mixing procedure, Therefore, in the generated routing process, there is not a relation with the flow velocity available that can be used to consider the re-erosion of particles that were accumulated in the inlets of the pipes, or even deposition processes.

The proposed methodology is aimed to assess the total sediment load evolution generated under time varying flow conditions related with a rain event. The sediment concentration loads assessed should be able to consider the release and transport of the previous deposited sediments both, in pipes and on the catchment, as well as any other input (wastewater and direct inputs).

The methodology presented below along this section, proposes the assessment of the sediments released from in-pipe deposits and conveyed in the network, through a simplified conceptual approach based on the currently quantity and quality tools available in SWMM5. One of the objectives was to keep the transport model as simple as possible, so that, a reduced number of parameters are required.

Later, the simplified approximation developed is linked with the existing quality module in SWMM5. In this way, the results obtained from the approach proposed for the assessment of the release and transport from the in-pipe deposits are added to the SWMM5 results that provide the assessment for the pollutant loads from surfaces, wastewater and other inputs.

In this way, it is intended to obtain a tool with a reduced set of quality parameters that can provide good initial approximation results concerning the CSOs discharges of sewer sediments and attached pollutants.

As a basis for the calculation, the hydraulic and hydrologic SWMM5 model was used. So then, the decision of working with SWMM5 was based not just in its good relation module reliability/economical cost, but also in the possibility to use the reliable hydrodynamic module as the basis for the quality calculations. Additionally, the use of SWMM5 gives the opportunity, through its open source code, to incorporate new developments in order to expand their capabilities.

5.2.1 Methodology description

Based on the concepts introduced above, a simplified method assuming the existence of a relationship between accumulation and wash-off relationships over the surfaces of the catchment and inside the pipes has been developed.

In order to simulate the mentioned sewer quality processes, the proposed module considered as previously known the mass of sediments that could be accumulated during dry-periods. The model of the catchment and combined sewer network is modelled in SWMM5 and simulated for a storm event. Then, artificial sub-catchments that represent each pipe with sedimentation problems are defined, and the hydrographs at the inlets of these pipes analysed to obtain an equivalent rainfall. The wash-off and erosion of sewer sediments previously deposited in pipes are simulated during the wet weather by applying the equivalent rainfall data in a new SWMM5 simulation made on the artificial sub-catchments. Back again into the original model of the catchment, the predicted sediment pollutographs from the artificial sub-catchments are load in the outlet of each corresponding pipe, and a new simulation with the original rain data is performed. As a result of this last simulation, the final pollutograph that integers all the sources of pollutants is obtained (Seco *et al.*, 2011).

The model assumes that any transformation process occurs in the sediment bed deposited in-pipes during dry-periods. Also, the properties of the sediments are not directly considered. The influence of the sediment characteristics is only considered through the calibration of the obtained sediment loads against measured data.

The sub-sections below show the proposed procedure for the prediction of the transport of the sediments deposited in the combined network by using current SWMM5 tools.

5.2.1.1 Hypothesis and initial considerations

Some conditions as hypothesis for the simplification of the proposed model were established as the bases for the calculation. The following initial considerations were made:

- The mass of sediment accumulated in the pipe inverts during the previous dry-period, as well as its distribution in the network is known.
- Other pollutants like COD (related to BOD5) and TKN are considered attached to the solid particles and therefore, the assessment of the concentration loads were considered as fractions of the sediment concentration loads.
- No transformation process occurs during the dry-weather period.
- No sedimentation occurs during runoff.

5.2.1.2 Assessment of the deposited sediment in-pipes

The total mass accumulated during a dry period, if possible, could be obtained from direct measurement from the analysed sewer system. Nevertheless, the monitoring of the depth of the deposited layer is a complex task and there are at the moment just few researches conducted for this purpose.

The volume/mass per day of sediment effectively deposited under wastewater flow rate during dry-weather periods and distributed in the pipes can be assessed by the application of different available predictive methodologies. Independently of the way from which it is obtained, it is required as initial condition for the application.

In this work, the quantitative evaluation of the mass/volume of sediments accumulated by day was performed by the application of the predictive method developed by William Pisano (EPA 1979, 1981), introduced in Chapter 2, Section 2.3.2. The method was chosen based on its ease of implementation. The method also allows for the analysis of sedimentation patterns in the network.

The application of the method of Pisano is detailed later in Section 5.3.1.3, as a complementary calculation for the application of the methodology in the case of study. First, a prior analysis of the sedimentation trend is performed. The identification of sedimentation patterns allows for the evaluation of the pipes in the network that are more susceptible to the particle deposition. Then, the prediction of the mass of sediments that could be deposited by day and the total depth of the layer of the deposits in the dry-period are assessed.

The pipes that were identified as having sedimentation potential will be from here the sections of the network at where the proposed simplified methodology will be applied.

5.2.1.3 Conceptual relationship between wash-off in catchments and pipes. Artificial sub-catchment definition

The release of previous deposited sediments and transport by runoff inside the pipes is dependent, in addition to the flow rate, on the sediment characteristics and the physical conditions in the conduit (roughness, slope).

It was hypothesised that the wash-off process occurring over the surfaces of a catchment may be analogous to the erosion and transport happening inside the pipes. In the supposition of equivalent hydraulic conditions, is then suggested that the simplified conceptual equations for wash-off available in SWMM5 may produce similar results in terms of pollutographs as those produced by the erosion of existing deposits in the sewer.

Therefore, an analogy between the real pipe (where sedimentation occurs), and a defined artificial catchment (hydraulically equivalent) is proposed.

The following considerations are made to establish the characteristics of the artificial sub-catchment based on the pipe.

- The geometrical parameters length and slope of the surface for the artificial sub-catchment are defined the same as the original pipe.
- For the case of circular cross-section pipes, the area and width for the catchment is obtained geometrically from the half cylinder. The area corresponds to the side wall of the half cylinder, and from them the width can be calculated. The use of the half of the pipe cross-section is based on previous findings that suggest that the higher percentage of sediment transport in suspension in sewerage is made as a fluid mass near the deposited sediment surface where the longitudinal velocities are lower. Then, based on SS concentration profiles, the so-called *near-bed solids* are considered the large portion of sediments and pollutants in sewerage (Arthur *et al.*, 1996, 1998; Verbanck, 2000; Chebbo *et al.*, 2003). Thus for this work, it is hypothesised that the total mass of suspended sediments are conveyed within the lower half of the pipe.
- The material of the pipe (and its roughness) is maintained the same as the material of the surface of the sub-catchment generated.
- Finally, it is also considered complete imperviousness in the whole surface, without depressions that may cause water storage.

A schematic representation of the geometrical parameters of both, pipe and artificial sub-catchment is showed in Figure 5-2.

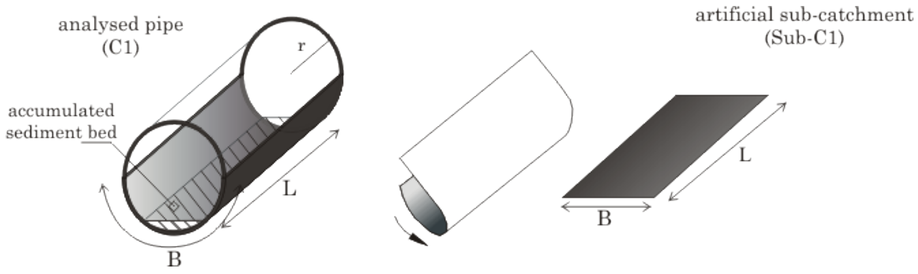


Figure 5-2 Scheme of the analogy between geometrical parameters from the original pipe and the created artificial sub-catchment.

This analogy needs to be considered individually for each pipe with sediment accumulation potential.

5.2.1.4 Simulated rain event

Another significant aspect that should be considered in the analogy is the equivalence between pipe/artificial sub-catchment with regards to the rain-runoff transformation.

Additionally to the dependence on the sediment characteristics, the sediment transport rate is highly dependent on the hydraulic conditions inside the analysed pipe. The remobilization of sediments process is directly related to the flow rates that determine the boundary shear stress values. In this sense, the adequate evaluation of the runoff on the surface of the artificial catchment will rise to better prediction of the sediment loads mobilized.

The rain data to be used in the assessment of the sediment loads from inside pipes (by using the artificial sub-catchment analogy) will be different to the real rain event, and should be calculated. Thus, in the implementation of the analogy it is necessary firstly to define an artificial rainfall that generates over the new artificial sub-catchment the same flow rate as that generated at the upstream end of the real pipe by the effects of the real rainfall in the catchment upstream the considered pipe.

In advance it was verified that the hydrograph obtained in small (< 1 ha) and regular catchments has a quite similar pattern than the rainfall hyetograph. Then, it was suggested that the definition of an equivalent rain event can be based on the hydrograph obtained at the inlet of the analysed pipe, by effect of the real rainfall. In this way, it was found that the rain intensity (i) at each time interval can be calculated from the inverse proportional relationship between the flow inside the pipe (Q_p) and the area ($A_{a\ sub\text{-}c}$) of the artificial sub-catchment (equation 5-2).

$$i\left[\frac{mm}{h}\right] = \frac{Q_p\left[\frac{m^3}{h}\right]}{A_{a\,sub-c}\,[m^2]}\,.1000 \tag{5-2}$$

The followed procedure to obtain the artificial rainfall is schematized in the figure below (Figure 5-3). Using the original data for rainfall and the urban system a first simulation is made by using SWMM5, from which the hydrograph at the inlet of an analysed pipe is obtained. Then, applying the equation 5-2 at each time step and using the data of that hydrograph, a new hyetograph of a rain event that is considered analogous to the original is found. Through the application of this equivalent rainfall to the artificial sub-catchment, the runoff generated on the surface should be similar to the hydrograph firstly observed in the upstream end of the pipe.

Following this procedure, it was observed that the response of the artificial sub-catchment subjected to the artificial rain in terms of flow rate is equivalent to the response obtained in the original pipe from the system. The errors in the transformation were found to be lower than a 1 % in terms of volume, which is acceptable.

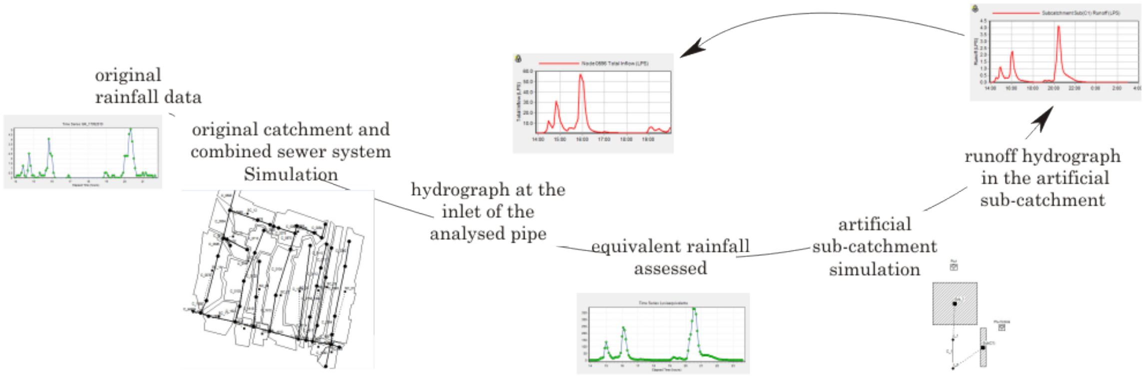


Figure 5-3 Schematic procedure for the obtaining of an equivalent rainfall data to be used in the generation of runoff over the artificial sub-catchment.

The Figure 5-4 shows an example of calculation of the equivalent rainfall from arbitrary values taken for the original rainfall and pipe. The graph in (a) shows the hyetograph and hydrograph obtained in the analysed pipe after the simulation of this original rain data on the catchment and sewer network, meanwhile (b) also shows hyetograph and hydrograph but for the artificial sub-catchment after the simulation with the equivalent rain event. Finally, the last graph (c) shows a comparison between the runoff in the original pipe and over the artificial sub-catchment, and can also be seen the direct relation with the rainfall data.

5.2.1.5 Sediment erosion and transport simulation

The depth of previously deposited sediment during dry-weather (measured or assessed through prediction relationships) may be introduced in SWMM5 in two ways: as one of the properties parameters of the artificial sub-catchment (initial mass accumulated in kg/ha) or as a build-up function dependent on the daily rate of mass accumulation.

For the assessment of the erosion, the assumption of similarity between the two elements, original pipe and artificial sub-catchment, will let use the wash-off equations provided by SWMM5. Basically these equations are a conceptual simplification of the erosion and transport process for which a direct relationship between the available mass of accumulated sediments and precipitation intensity is assumed.

Next, a simulation is run in SWMM5 for the artificial sub-catchment created for the analysed pipe by applying the previously determined equivalent rainfall. The temporal evolution of the sediment loads, termed analogous *sedimentograph*, is obtained as result. This analogous sedimentograph should be contrasted against the real sedimentograph derived from the erosion of previous deposited sediments in the inlet of the pipe.

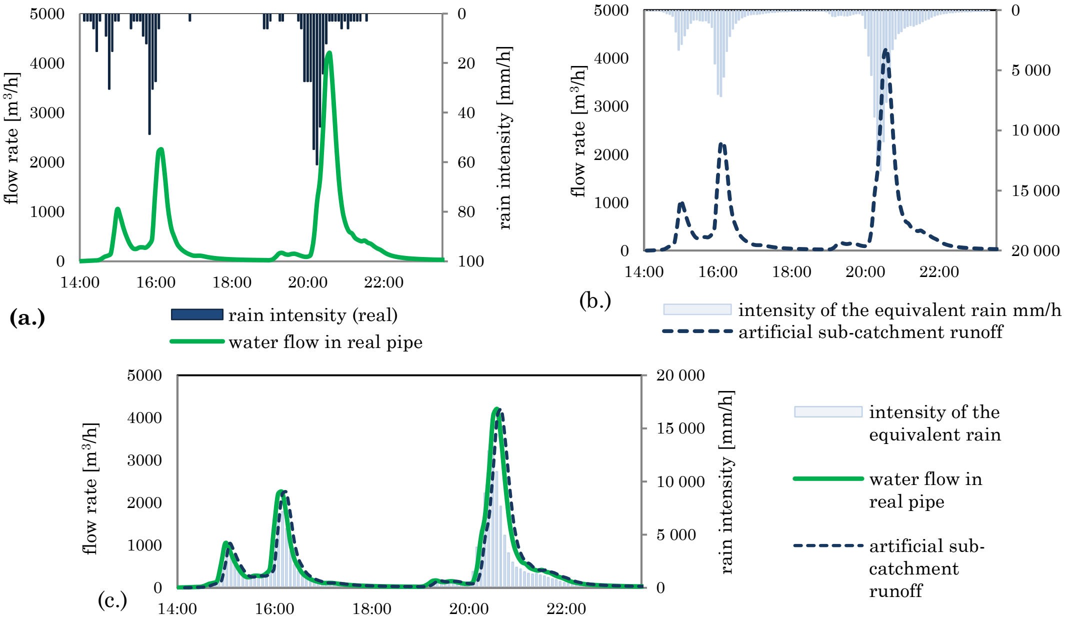


Figure 5-4 Comparison between real rainfall and pipe runoff (a) against equivalent rain and runoff over the artificial sub-catchment (b) (values are taken arbitrary).

The selection of the wash-off function to be used in the artificial sub-catchment should be verified from the best fit against measured data (real sedimentograph) at each studied pipe. In that process, a calibration of the parameters involved in the wash-off equation is needed. Later in this chapter it will be discussed about the calibration process and the reliability of the results obtained (see Sections 0 and 5.4).

The methodology process explained until here must be followed for each pipe where sediments were accumulated during dry-period.

5.2.1.6 Total suspended sediment loads. Coupling of the wash-off models

The total suspended sediment load considered the evolution of the sediment loads that are contributed not just from the in-pipes deposits but also from the catchment surfaces, wastewater and any other source.

Following the methodology, the analogous sedimentographs that were obtained from each pipe are entered at the corresponding outlet manhole of each analysed pipe. In SWMM5, these sediment evolutions can be loaded as direct input (user-defined time series) in the node.

As a result of a new SWMM5 simulation with the real rain data, the total suspended sediment evolution is obtained at the outlet of the catchment or in an outlet point for CSO discharge. Thus, this sedimentograph integrates the contribution of the different sources of sediment, originated by washing of the surfaces, provided by the wastewater and these that were eroded from deposits in the pipes.

A new calibration/verification procedure can subsequently be performed against total suspended sediment evolution measured at the control section of the studied catchment.

5.2.1.7 Pollutants attached to suspended sediments

The estimation of the evolution of the present pollution load discharges is possible through the application of this methodology. To do this, it is considered that the presence of organic matter (measured by COD or BOD_5 indicators) and Nitrogen among others can be represented as a fraction of the transported solids. This must be verified from samples analysis but in many catchments this co-pollutant concept has been verified. Thereby the hypothesis that the processes of accumulation and flushing of contaminants such as BOD_5 follow the same law for solids, and that the relationship between them remains constant, is agreed.

In the SWMM5 model this proportional relationship between pollutants and solids is entered in the definition of each pollutant.

5.3 Application of the methodology in a study case

In this section, a detailed procedure for the implementation of the proposed methodology in a real case of urban catchment is presented. Previous data required for the implementation as well as results obtained are shown below.

The selected modelling area is located in Granollers, Spain, in the town centre district, with a combined sewer system from where quantity and quality data was obtained as part of this research work during a monitoring programme that was presented in Chapter 3. Refer to that chapter for further details of the site and collected data.

As bases for the implementation of the proposed conceptual methodology, it is necessary to have available the hydraulic and hydrologic calibrated model of the studied area from which the flow rates during wet weather will be obtained. Additionally, the previous knowledge of the sediments that were accumulated inside the network and its distribution is also necessary. The procedures for the assessment of both requirements are here introduced.

5.3.1 Previous calculations

5.3.1.1 Hydrodynamic model

The hydrological model of the catchment is defined based on sub-catchment delineation complemented with topography data, site plan distribution. This subdivision in contributing areas is associated to the combined sewer network. The level of detail in the division allows to consider the contribution of wastewater flow at each section of the network and the input of runoff during rainfall.

The Figure 5-5 shows the combined sewer network map with additional layers that display the streets distribution, city plan, and ground elevations, which is the support information in the creation of the model. The Figure 5-6 shows the SWMM5 study area map with the distribution of 16 sub-catchments, 47 pipes (links) and manholes (nodes).

The hydrologic and hydraulic model calibration and verification was performed based on the rainfall and the flow rate data collected in the catchment and detailed in Chapter 3. The monitoring was performed at the outlet pipe cross section (manhole ID 0848) that can be seen in the down-left corner of the area of the catchment.

The properties of the sub-catchments in the model (imperviousness, roughness, and slope) were initially defined based on the previous mentioned available information and *in-situ* observations. Complementarily, land use plans and orthophotos were also used. These parameters and the width of the sub-catchment were adjusted in a calibration process using the locally measured data. Assessed dry-weather flow rates patterns (Chapter 3, Section 3.3) were also incorporated in the model.

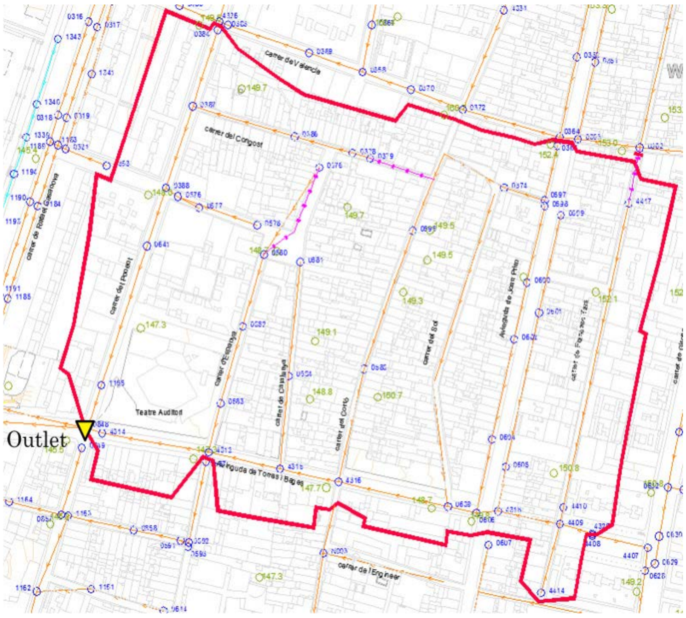


Figure 5-5 Partial image of the studied area obtained from a CAD file with the detailed data of the sewer network, street, site plan and topography information.

Figure 5-6 Layout of the combined sewer network implemented in SWMM5 showing manhole locations and catchment subdivision for the hydrodynamic modelling.

The roughness coefficient for pipes was also considered a calibration parameter.

The model was calibrated with four storm events (17/09/201, 09/10/2010, 12/03/2011 and 24/10/2011) and verified with two additional independent storms (31/05/2011 and 13/11/2011). The Figure 5-7 shows results obtained for some of the events after the hydrodynamic calibration/verification process.

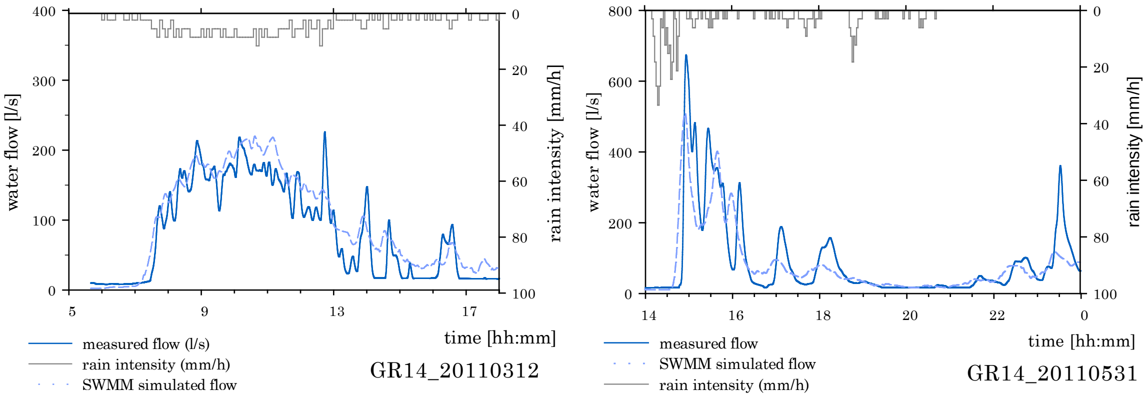


Figure 5-7 Hyetograms and hydrograms measued and simulated after calibration/validation of the hydrodynamic model of the catchmen. Results are shown for the events of the 12/03/2011 (on the right) and of the 31/05/2011 (on the left) as examples.

The results obtained show in general a good level of adjustment regarding the measured flow rate. The errors obtained from the calibration/validation were about < 18% in volume and < 10% in maximum flow rate for all the events.

5.3.1.2 Quality model

The accumulation (build-up) of sediments over the surfaces of the catchment during dry-periods and the subsequent wash-off from by runoff effects can be directly implemented in the model of the catchment in SWMM5.

One type of land uses, residential and commercial use, was established in the sub-catchments regarding the definition of the rates of build-up and wash-off in the surfaces. The formulations for build-up and wash-off and the adopted parameters values are shown in Table 5-1.

Table 5-1: Suspended sediment build-up and wash-off parameters and defined functions in the quality model implemented in SWMM5.Land use: residencial-commercial.

Land use	Pollutant	Build-up		Wash-off	
Residential-commercial	Suspended sediments (SS)	function	Power (POW)	function	Exponential (EXP)
		max accumulation	60	Coefficient	0.20
		Accumulation rate	21	Exponent	0.70
		Power	0.25	Cleaning removal efficiency	20
		normalizer	area	BMP	0

The adopted accumulation rate of sediments in the sub-catchments is 21 kg/ha/d, is in the same range of parameters obtained from calibration in previous research. In that regards in Santander, Spain by Temprano *et al.* (2006) a similar rate of 17 kg/ha/d of solids accumulation in urban catchment was obtained. Non comparable results were found in the bibliography related to wash-off in urban residential catchments.

Results obtained from the quality simulation are shown in Figure 5-8. The quality model since here solely considers the erosion by runoff of previous deposited sediments in the surfaces of the catchment. In addition, wastewater solids contributions are also taken into account. Nevertheless, none consideration is made in this model for possibly solids accumulated in the pipes of the combined sewer network. It can be observed in both episodes showed as examples, that the simulation results do not reach the peak of the sediment concentration measured during a storm event.

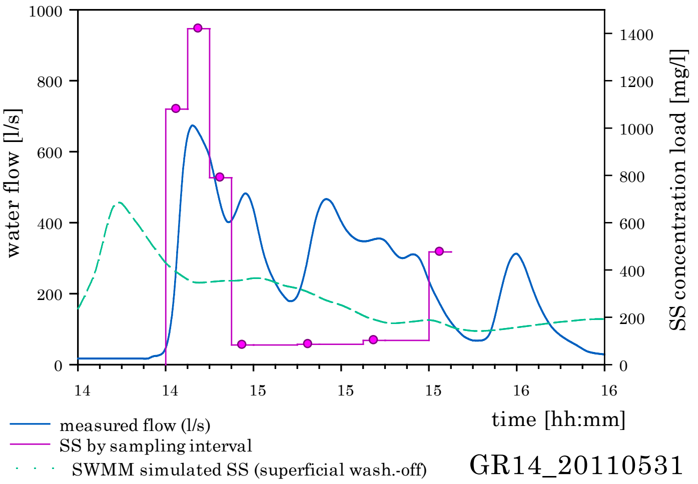


Figure 5-8 Suspended sediment evolution from wash-off from the cathcments surfces simulated with SWMM5. Comparison against measured data. Results are shown for the events of the 31/05/2011 as examples.

In the development of this work the version 5.0.022 of SWMM5 was used. Recently, with the release to version 5.1.005, the results of the application were validated. Non relevant differences in terms of volume, flow rate and the sediment and pollutants loads were obtained (less than 0.01% comparing with results obtained by simulation with previous version).

5.3.1.3 Prediction of the sediment accumulated in-pipes

The application of the predictive methodology proposed by Pisano, W. (1981) (explained in Chapter 2, Section 2.3.2.1) will allow obtaining the initial data required for the application of the sediment transport model. The prediction of the volume/mass of sediment accumulated in sewer pipes is based on a direct correlation between the equivalent population (pollutant loads in wastewater) and the characteristics of the sewer system.

The sedimentation in pipes is a complex and highly variable process in which stochasticity also plays a significant role. High level of uncertainties was observed in prediction of the process of sedimentation in sewerage. Thus prediction of sedimentation based only in few parameters, may be insufficient for a realistic characterization of the deposition process. Nevertheless, in order to obtain a possible initial situation that allows implementing the proposed methodology, the prediction made with the application of the method of Pisano is considered sufficiently approximate.

The distribution of the sediment deposited in the sewer network is not uniform. Thus, previous to the assessment of the mass of sediment deposited in dry-weather, it is firstly necessary to analyse sedimentation patterns. This analysis will allow identify the pipes that have more predisposition to the sedimentation of particles under wastewater flow conditions to focus on them.

By applying the Pisano method, varying the values of the variables involved, the following set of graphs obtained (Figure 5-9) allow for the analysis of a trend of sedimentation. The graphs were obtained by the application of the methodology, maintaining constant the variables related with the population density and dry period (arbitrarily established as 20 days). Highest influence is observed regarding the slope of the pipe. The lines at 5 cm and 10 cm deposit depth are given only for reference.

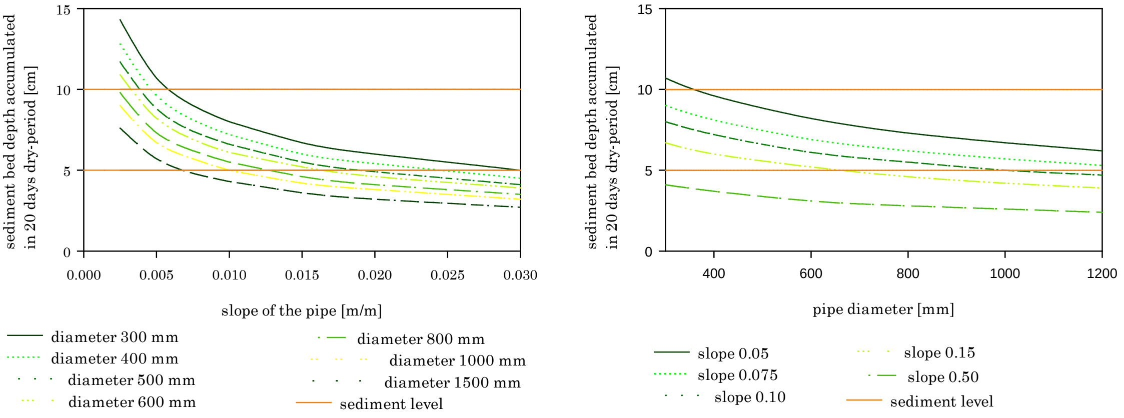


Figure 5-9 Variation of the sediment bed depth regarding slope of the pipe (graph on the left) and diameter of the pipe (on the right), by aplying Pisano method.

As conclusion from Figure 5-9, in general it can be observed higher trend of deposition of particles in pipes with lower diameters and slopes. The trend of sedimentation was considered that can be significant if any of the following conditions is reached:

- Pipe diameter lower than 400 mm and slope below 0.015.
- Pipe diameter between 400 and 800 mm, and slope below 0.075.
- Pipe diameter higher than 800 mm and slope below 0.05.

Although, in the analysis of the network it is necessary to consider additionally sections where there are changes in cross sections or slopes (changes in the water velocity), and the settling velocity of the particles must be considered.

By the application of these conditions in the analysed sewer network, the pipe sections that are highlighted in Figure 5-10 were those that displayed the highest trend of sediment deposition. Therefore, the prediction of erosion and transport of deposited sediment will be focused on these pipes.

The power equation 2-4 (Chapter 2, Section 2.3.2) proposed by Pisano for the prediction of the rate of accumulation was applied in the selected pipes for analysis. The assessed rates of sediment mass accumulated by pipe per dry-day are showed in Table 5-2.

Figure 5-10 Layout of the combined sewer network where pipe segments with the highest probability of deposition of sediment during dry-periods are highlighted.

Table 5-2: Rate of sediment accuulated in-pipes with deposition propensity. Dry-weather period of 16 days (rain event 31/05/2011).

pipe	diameter [mm]	slope [m/m]	served area [ha]	sediment accumulation rate [kg/day]	total sediment depth [m]
1	400	0.015	0.367	68.80	0.010
8	300	0.013	0.092	103.13	0.014
9	300	0.013	0.141	164.69	0.023
12	300	0.012	0.062	86.64	0.012
13	300	0.012	0.111	54.33	0.008
14	300	0.012	0.101	109.13	0.015
11	1000	0.017	0.068	35.96	0.005
28	1000	0.003	0.147	216.05	0.030
29	300	0.010	0.325	105.66	0.015
41	300	0.013	0.267	71.78	0.010
45	300	0.012	0.27	49.56	0.007
46	400	0.008	0.643	168.02	0.023
Dry-weather period [day]		16			
Sediment density [kg/m^3]		1310			

From these calculations, the average rate of sediment accumulated in pipes obtained for the analysed pipes was about 103 kg/day, which mean an average of 14 mm of sediment depth accumulated during a 16 days-period in a 500mm diameter pipe. Sediment with an average density of 1310 kg/m^3 (value obtained from analysis of the collected sediment, see details in Chapter 3, Section 3.4.2) was considered in the sediment depth assessment.

The values of deposition rate assessed were later used in the artificial catchment models for taking into account the build-up inside pipes.

5.3.2 Model building and application of the conceptual methodology

An artificial sub-catchment is then generated for each pipe for which analysis of the released and transport will be performed. The generated catchments properties are correlated with the characteristics of the pipes as referred from the explained procedure.

The equivalent rainfall is assessed based on the hydrographs resulting from the simulation of the original model in SWMM5 at each inlet node. The Figure 5-11 shows the hydrograph simulated and the rainfall generated in some of the analysed pipes.

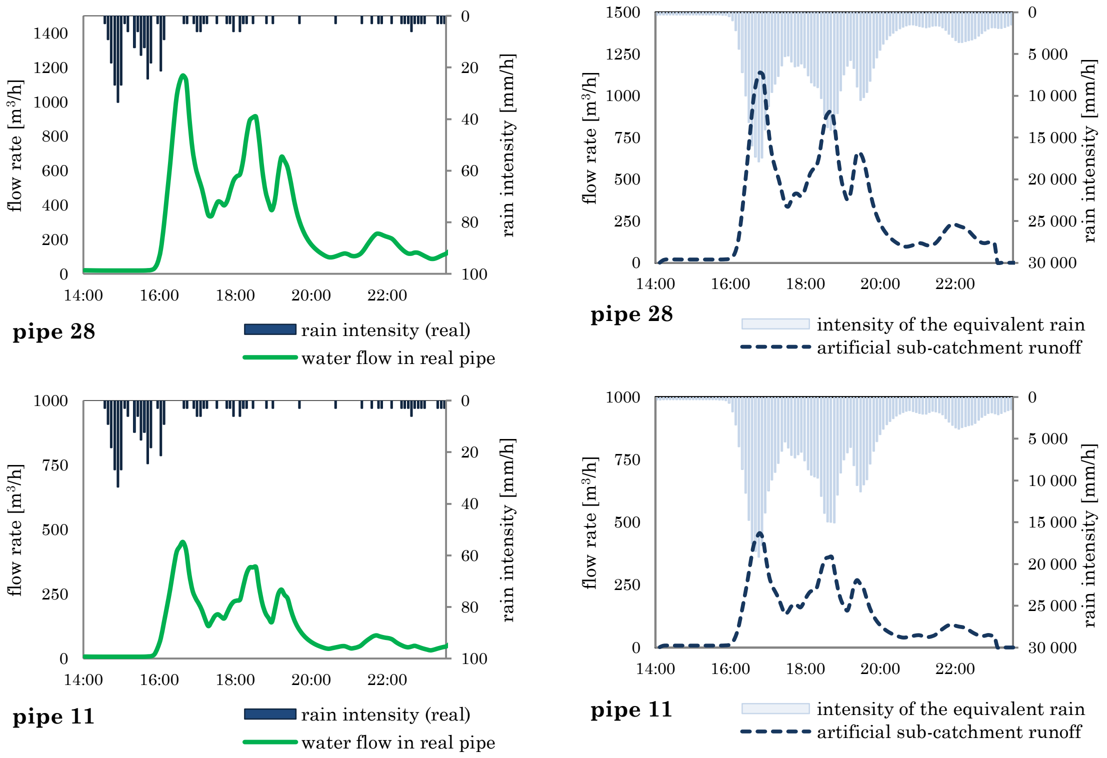


Figure 5-11 Simulated hydrograph at the inlet of some of the pipes and corresponding artificial sub-catchments that are subjected analysis regarding erosion of deposited sediments.

The Suspended Sediments (*SS*) are the sole water quality pollutant considered in the application of the methodology. In SWMM5, other pollutants can be defined depending on the *SS* concentration as it was explained before, by using the coefficients of proportionality. Suspended sediments are defined in the presented case in mg/l. A particular type of “land use” was defined for the artificial sub-catchment to characterize the surface of the catchment in terms of quality regarding the generation and washing-off of the pollutant.

From the previous calculation by Pisano method, the sediment accumulation rate for each analysed pipe was obtained. This rate is loaded in the properties of the artificial sub-catchment in SWMM5 (as "initial build-up"), in units of sediment mass per area, and also a wash-off function defined.

After the setup of the quality parameters, a new simulation is performed with SWMM5 for the artificial sub-catchments (representing the original pipes). The rain data assessed (equivalent rainfalls) are applied individually to each artificial sub-catchment. In this way, the surface of the artificial sub-catchment is subjected to an analogous runoff to that originally occurring in pipes.

The suspended sediment load evolution is obtained in consequence from each created sub-catchment. These concentration loads solely considered the sediment that was mobilized from the deposits accumulated inside the pipes.

5.3.2.1 Calibration and results

The simplified approach must subsequently be calibrated on the basis of measured SS data loads. Consequently, the evolution of sediment mobilized just from the deposited sediments beds is needed. Nevertheless, the individualization of the contribution of each sediment sources that achieve the outlet of the pipe during rainfall runoff is extremely hard to obtain by measurements. Given the difficulties in obtaining individualized measured data, the parameters involved in the model were calibrated against SS loads concentrations obtained by applying other predictive empirical formulations.

Previous work (Seco *et al.*, 2012) reported on the results obtained from the application of the methodology by using a simplified model of the catchment. In that verification, the formulation of van Rijn (1984) (Chapter 2, Section 2.4.4.2) was used for the generation of a sedimentograph that allow for the calibration. Density of sediment (ρ_s) of 2520 kg/m^3 and characteristic particle size d_{50} of 0.71 mm were used in that opportunity regarding the lack of data in the characterization of the material, and also due to the range of applicability of the van Rijn formulation.

Good performance was obtained in that opportunity in the prediction of sediments transport, despite it was highlighted the need to introduce more adequate characteristics of the sediments, and the consideration of the cohesion in the bed of sediments.

As a consequence, it was suggested that for the calibration of the release of sediment in the artificial sub-catchment the comparison against results obtained from formulation particularly developed for cohesive sediments will indirectly take into account the related properties. Thus, the Skipworth (1996) relationship (Chapter 2, Section 2.4.6.1) was used. For its application, the characteristics of the parameters of the sediments obtained from the analysis detailed in Chapter 3 were used (ρ_s = 1310 kg/m^3 and d_{50} = 0.31 mm).

Firstly, a pre-calibration process was performed individually at each pipe selected for the application of the artificial sub-catchment methodology.

For the simulation in SWMM5 of the pollutants loads generated by the runoff within each artificial sub-catchment, there are three options that were mentioned before. The use of the EMC relation might be unsuitable for the application in the release of pollutants from in-pipe deposits since a mean weighted pollutant load is considered constant during the simulation. The other options for consider the wash-off, rating curve and exponential functions, were checked. After examine the performance of the relationships, a "rating curve" was chosen as the function that best fit to the washing-off process from inside the pipes. The generation of sediment runoff is much faster using the exponential curve but do not fit with the simulation results used for the comparison and calibration.

The wash-off coefficients are iteratively adjusted in the calibration process based on the evolution of SS concentration loads calculated by the mentioned relationship at each pipe. A rating curve function (equation 5-3) with coefficient of k_e = 0.00015 and exponent of c = 4.2 was established.

$$M_a(t) = k_e \, . Q^c \tag{5-3}$$

Figure 5-12 shows, for the rain event of 31/05/2011, the results obtained in different pipes taken here as examples. It can be seen that despite achieving a similar maximum concentration, a good fit could not be achieved in terms of mass of sediment and on the time evolution.

The use of an exponential wash-off relation would consider the remained sediment on the surface, despite that, the use of this function in a quite small catchment as the proposed for the pipe representation give an immediate reaction, washing all the mass of sediment available before the first 10 minutes since runoff starts. The "rating curves" relationship do not use the amount of sediment remaining as a limiting factor, and because of that produce a pollutant load evolution that continues over time, as can be seen in the curves in Figure 5-12. The sedimentographs obtained by using the rating curve method look similar to the runoff discharged from the same pipes (Figure 5-11).

Comparing wash-off simulation results from SWMM5 and the Skipworth method results, errors between 0.5 and 4% were found with regards to maximum SS concentration loads. Errors over 150% were found with respect to the total mass of sediments eroded at each pipe. The suspended sediment evolution calculated by applying van Rijn formulation with the newer sediment parameters is showed also in Figure 5-12 as reference. Higher errors in SS concentration (between 18 to 148%) were found from the comparison against values resulting from van Rijn relationship.

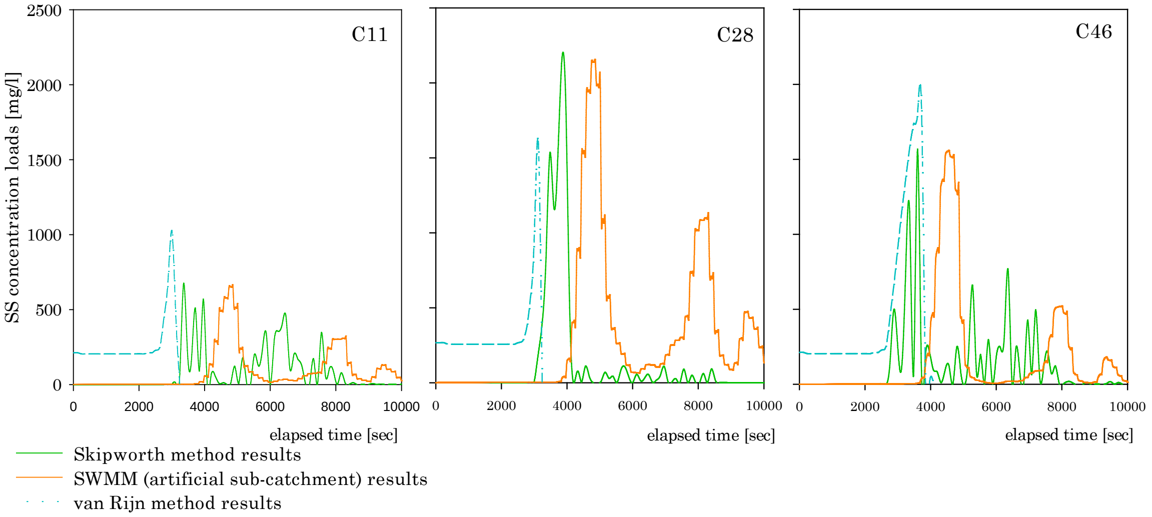


Figure 5-12 Comparison between SS loads calculated by Skipworth and van Rijn relationships and results obtained from SWMM5 following the artificial sub-catchment procedure after a calibration procedure. Pipes 11, 28 and 46 from the urban system are showed as examples.Rain event: 31/05/2011

Another relevant finding was that the evolution of the suspended sediments calculated by SWMM5 in the way proposed, showed a delay of about 20 minutes with respect the simulated by other formulations. The delay, as well as differences in the profile of the SS concentration over time are suggested to be related with a possible consolidation and cohesive behaviour of the sediments deposited. That behaviour is considered in the estimation made by the Skipworth formulation. In the wash-off model in SWMM5, the sediments released from the sub-catchments are a result of a direct relation with the runoff flow (rating curve function). The characteristics of the particle and the threshold shear stress for motion cannot be modified in SWMM5. The use of an exponential function might give better adjustments with regards to the van Rijn simulation results, but again, the behaviour of cohesive particles is not considered.

Despite of this analysis, the performance in individual pipes, with errors below 10% for maximum concentration load by comparing with Skipworth simulation, can be considered sufficiently approximated for the pre-calibration of the erosion/transport at each pipe.

After this first pre-calibration procedure, the obtained sedimentographs are introduced in the model of the whole catchment at the outlet manhole of each analysed pipe. A new integrated simulation in SWMM5 is then performed. In this way, the final SS concentration load obtained at the outlet of the system reflects the combined effect of the wash-off produced from each pipe from the whole catchment and the contribution of SS loads from sources considered in the previously created SWMM5 model (wash-off in surfaces and wastewater), all routed through the conveyance network.

The evolution of the solids obtained at the outlet of the urban catchment can then be verified with the measured sediment concentration during the precipitation events registered.

Results for a measured storm event of the 31/05/2011 are shown in Figure 5-13. The graphs show the comparison between simulated and observed values obtained from the two modelling approaches, SWMM5 without modifications and SWMM5 plus artificial catchments methodology after the pre-calibration of the release from each individual pipe.

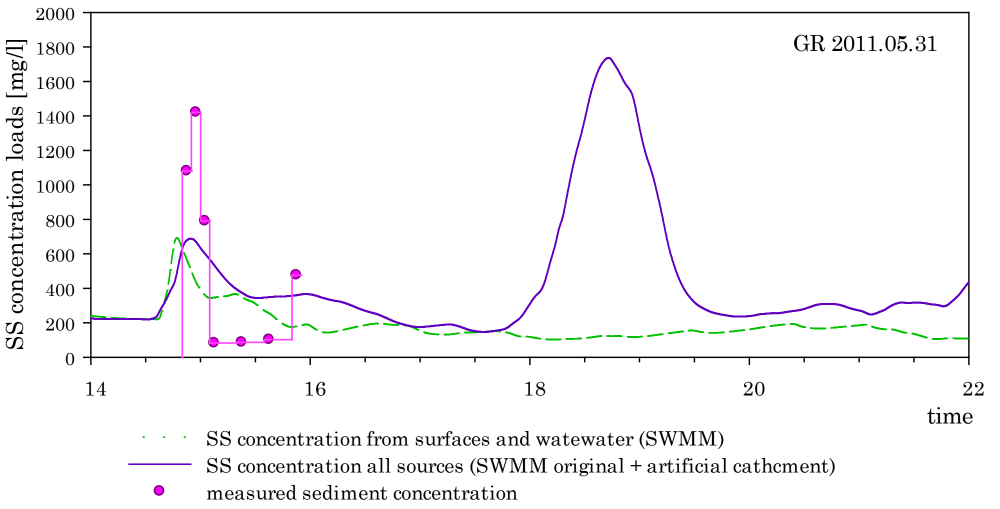


Figure 5-13 Suspended sediment loads evolution at the outlet of the urban catchemnt (Rain event: 31/05/2011). Comparison between simulation results by the conceptual methodology proposed and

measured values.

The results obtained at the control section of the catchment showed a significant delay with regards to the measured data. The effect of delay in the output of the eroded sediment in pipes is even more pronounced when the results of the whole basin are observed. Even, the possible effect of the sediment released from inside the pipes is noticed several hours later.

The results show then an unsatisfactory performance in the application of the proposed predictive model.

Despite the difficulties in the calibration of the integrated model, it can be observed that the sediments released from storage within the sewer network are significant higher than the contributions from the surfaces of the catchment, and significantly exceed the wastewater concentration (mean 182 mg/l).

The insufficient accuracy in the predictions obtained up to now with this methodology led to the search of new alternatives. It is proposed the use of an erosion relationship that better predict the erodibility of particles with cohesive-like behaviour. It will be seen in Chapter 6 a new proposed approach to lead with it that can be later, as future work, coded in SWMM5 for the improvements in the release of organic solids from in-pipe deposits discussed here.

5.4 Discussion of the results and Conclusions

The simplified approach proposed is based on a conceptual modelling of a pipe and the mobilization of the deposits of sediments, by using parameters that have not a direct correlation with the real physical process simulated. This lack of physical meaning in the representation of the transport process increases the difficulties in the consideration of the cohesive behaviour of the sediment. The erosion and transport process of highly organic sediment should also consider the consolidation of the bed and transformations processes during dry-periods.

To calibrate the erosion/transport model, data about the evolution of sediment mobilized just from the deposited sediments beds is needed. Even if it possible to have measurements of the suspended sediment evolution in the pipes of the system, the individualization of the contribution of each type of sediment sources that achieve the outlet of the pipe during rainfall runoff is extremely hard to obtain. Thus, predicting these process in pipes is quite complex and will require a great number of calibration data that mostly nowadays is only obtained in research stage.

Due to the difficulties in obtained individualized measured data; the involved parameters were calibrated by applying predictive empirical formulations. The calibration process for the proposed methodology is quite complex. The adjustment in the parameters must be done iteratively until found a set of values that characterize the process in all the pipes with sediment deposited, and later verified for different rain events in the whole system. Additionally, as a conceptual model with coefficients that have non-direct physical meaning, it can be possible to have several combinations of coefficients to adjust the results of the model. As a consequence, the assessed parameters are site specific and the application of the module need a later verification.

On the other hand, the obtained evolution of sediments released from the sub-catchments in the SWMM5 methodology is a result of a direct relation with the runoff flow, that do not consider the shear stress ejected by the flow on the particles and the boundary shear stress for the initiation of the motion. It is not possible to consider neither changes in consolidation of the bed because the composition of the sediment or because physical reasons. So then it can be suggested that the differences in the evolution of SS obtained from the artificial sub-catchment compared with the simulation obtained from a formulation developed for fine cohesive sediments (Skipworth) are related with the cohesive behaviour of the sediments.

Then, it was concluded that the introduction in SWMM5 of a user-defined function for the wash-off process (now just available for build-up) will allow for the consideration of different processes of erosion that can better adjust to the results obtained in this methodology.

Also, the measurements of the concentration of sediment during rainfall in different point of the network are necessary for a better calibration and adjustment of the methodology.

The wide use of SWMM5 in Spain, make this software package, a good media for arriving with the awareness and quantification of the pollutant problem during CSOs to small municipalities. Nevertheless, it is necessary to continue working both, in the improvement of the reliability of the methodology in the assessment of the pollutant loads evolution, as on an easier implementation in SWMM5 intended to facilitate the end user application.

The weakness of the approach is that do not consider the sediment characteristics. When intended to predict the transport potential it was seen that the parameters that characterize the sediments are of relevance.

The insufficient accuracy in the predictions obtained led to the search of new alternatives for the prediction that better predict the erodibility of particles with cohesive-like behaviour. It will be seen in Chapter 6 a new proposed approach to lead with it that can be later as future work coded in SWMM5 for improvements in the release of solids from in-pipe deposits discussed here.

The analogy pipe – artificial sub-catchment need the prior individual calibration of the erosion evolution at each pipe. Information of the evolution of the sediment concentration loads eroded from the deposits is not actually available.

Modifications in the methodology can be considered for further improvements in the prediction. The adaptation of the SWMM5 code to allow the inclusion of alternative sediment transport equations that perform better for cohesive sediments or of a user-defined function for wash-off process is suggested. Both possibilities are thought that can improve the better representation of the erosion process of organic sediments (low density and the influence of the organic behaviour).

5.5 Summary

Strong first pollutants flushes are frequently observed in small impervious catchments during rainfall that can be discharged into the receiving natural waters. There is a need to improve the prediction of sediment released in combined sewer system, but also in arrive with these predictions to the smallest sewerage managers and consultants.

This chapter described the implementation of a proposed conceptual methodology that, using the SWMM5 tools, might allow the consideration of the transport of sediments previously deposited in the pipes during dry-periods. This source of sediments and pollutants is considered the highest contributor to the pollution that arrives to watercourses during storm events, and is not currently considered in the calculations by SWMM5 quality model.

The proposed quality model intends to provide a first approximation of the evolution of sediments whose source was the dry-weather deposits within the network. The eroded pollutants, conveyed through the system by stormwater runoff, are later combined with sediments washed from surfaces and wastewater sediments.

The model is based on a hydrologic and hydraulic previous calibrated model of the studied catchment. The analysis of the pipes with highest trend to accumulate deposited sediments was made by Pisano methodology. This last was also used in a prior estimation of the total mass of sediment accumulated during a dry-period.

The verification of the implementation of the proposed methodology was made by using data collected in the urban catchment, described in Chapter 3. Due to the lack of data regarding evolution of the eroded/transport sediment from in-pipe deposits at each analysed pipe, results of the application of known transport formulations were used for the comparison of the results and calibration. The relationships of van Rijn (1984) and Skipworth (1996) were used in that regards.

Calibration process for this methodology is quite complex. Measurements of the SS concentration in different points of the network are necessary for a better performance of the model. An adequate and reliable calibration of a sediment erosion/transport model from deposits at each pipe is currently unfeasible with the data available.

Also the implementation of the methodology in SWMM5 in a real system is labour intensive. Improvements are necessary on the methodology to better predict the total sediment transport loads and on the easiness of its implementation.

Bibliography of the chapter

Arthur, S., 1996. *Near-bed solids transport in combined serwers.*

Arthur, S., Ashley, R.M., 1998. The influence of a near bed solids transport on firts flush in combined sewers. Water Science & Technology **37** (1), 131–138.

Arthur, S., Ashley, R.M., Nalluri, C., 1996. Near bed solids transport in sewer. Water Science & Technology **33** (9), 69–76.

Arthur, S., Ashley, R.M., Tait, S.J., Nalluri, C., 1999. Sediment Transport in Sewers - a Step Towards the Design of Sewers To Control Sediment Problems. Proceedings of the ICE - Water Maritime and Energy **136** (1), 9–19, DOI:10.1680/iwtme.1999.31264.

Ashley, R.M., Bertrand-Krajewski, J.-L., Hvitved-Jacobsen, T., Verbanck, M.A., 2004. *Solids in Sewers. Characteristics, effects and control of sewer solids and associated pollutants. Scientific and Technical Report No.14*, First. ed. IWA (International Water Association) Publishing. Joint Commitee on Urban Drainage, London, ISBN: 1-900222-91-4.

Chebbo, G., Ashley, R.M., Gromaire-Mertz, M.C., 2003. The nature and pollutant role of solids at the water-sediment interface in combined sewer networks. Water Science & Technology **47** (4), 1–10.

EPA Environmental Protection Agency, ., 1983. *Results of the Nationwide Urban Runoff Program: Volume 1 - Final Report.* NTIS PB84-185552U.S. Environmental Protection Agency, Washington, DC.

Gironás, J., Roesner, L.A., Davis, J., 2009. *Storm Water Management Model. Applications Manual EPA/600/R-09/077*, Journal of the American Water Resources Association. Cincinnati.

Huber, W.C., Dickinson, R.E., 1992. *EPA/600/3-88/001a. Storm Water Management Model, Version4: User's Manual*, Environmental Protection. EPA. United States Environmental Protection Agency.

Krebs, G., Kokkonen, T., Valtanen, M., Koivusalo, H., Setälä, H., 2013. A high resolution application of a stormwater management model (SWMM) using genetic parameter optimization. Urban Water Journal **10** (6), 394–410, DOI:10.1080/1573062X.2012.739631.

Van Rijn, L.C., 1984. Sediment Transport, Part II: Suspended Load Transport. Journal of Hydraulic Engineering **110** (11), 1613–1641, DOI:10.1061/(ASCE)0733-9429(1984)110:11(1613).

Rossman, L.A., 2009. *EPA/600/R-05/040. Storm Water Management Model. User's Manual. Version 5.0*, Water Management. EPA. United States Environmental Protection Agency, Cincinnati.

Seco, I., Gómez-Valentín, M., 2011. Estimación mediante SWMM 5.0 del transporte de sedimentos depositados durante tiempo seco en conductos de alcantarillado unitario. In: II Jornadas de Ingeniería Del Agua, JIA2011 Modelos Numéricos En Hidráulica Fluvial. Barcelona.

Seco, I., Gómez-Valentín, M., 2012. Transporte de sedimentos depositados en alcantarillado unitario.Estimación mediante SWMM 5.0. In: Congreso Latinoamericano de Hidráulica. ISBN: 978-9968-933-06-3, San José de Costa Rica. Costa Rica.

Skipworth, P.J., 1996. *The erosion and transport of cohesive-like sediment beds in sewers.* PhD Thesis.Department of Civil Engineering. University of Sheffield. U.K.

Temprano, J., Cagiao, J., 2006. Stormwater quality calibration by SWMM : A case study in Northern Spain. Water SA **32** (1), 55–63.

Verbanck, M.A., 2000. Computing near-bed solids transport in sewers and similar sediment-carrying open-channel flows. Urban Water **2** (4), 277–284, DOI:10.1016/S1462-0758(01)00011-5.

Chapter 6

The erosion and transport of high-organic sediments in combined sewer Water quality modelling

Chapters 1 and 2 highlighted the quality problems in receiving waters caused by the sediments and associated pollutants that might arrive to a river through combined overflow discharges. In Chapter 2 it is also analysed the state-of-the-art on the sediment transport predictive methodologies that can currently be applied to cohesive sediments. Chapter 4 identifies the main factors that have influence on the erosional resistance of the sediment deposited at the invert of the sewer pipes during dry-weather conditions, and the site data collected were presented in Chapter 3.

The main goals set for this dissertation were to analyse the behaviour and assess the mobilization of sediments from in-sewer deposits emphasizing on the need for better understanding of the mobilization process occurring in bed-deposits composed mainly by highly-organic sediments. To achieve them this chapter builds on the previous analysed information and data in order to design an implementation module applicable to a real case. Thus, we propose the application of the sediment transport relationship of Skipwoth (1996) by implementing a new set of transport parameters previously assessed from laboratory testing. In this way, it was suggested that it is possible to introduce the key aspects of the transport of cohesive and highly organic sediments in the relationship.

The herein chapter is organised as follows. Section 6.1 provides an overview of the fundamental aspect on the cohesive transport modelling previously detailed in Chapter 2. The steps followed for the application of the Skipworth's method are described in Section 6.2, where firstly a review on the subsequently used collected data in the study case is made in Section 6.2.3 and 6.2.4. The erosion testing results obtained in Chapter 4 were used in Section 6.3.1 to establish the values of the transport parameters needed for the Skipworth's method application. As a final point in this section, the implementation of the method in the studied urban catchment is explained in Section 6.2.5, and the results and discussion of the outcomes are presented in Section 6.3. Finally the conclusions and a summary of the chapter are given in Section 6.4 and 6.5.

6.1 Overview on the sediment release and transport of sewer sediment deposits

Most of the current sediment transport equations particularly developed for sewerage (see Chapter 2, Section 2.4) are site-specific and heavily dependent on the sediments characteristics and on the conditions of deposits formation. Therefore their application in a general context might be unsatisfactory without a detailed analysis of sediment properties and the "initial conditions" at which deposits were subjected.

Nowadays, available relationships and software packages for urban sewer and drainage systems show good performance and high degree of confidence regarding flow routing. However, while the dynamic aspects of non-cohesive sediment erosion and transport are well studied, the erodibility of cohesive sediments has shown greater difficulties in achieve an adequate prediction, and the accuracy in the application of the existing transport models is still limited.

Most of the research in the field of sediment transport was developed for the hydrodynamic conditions of rivers and open channels. The use of the classical equations of sediment transport like Ackers (1991), Ackers and White (1973) and May (1993), developed for non-cohesive inorganic particles, do not give in sewers as good fitting as it was found in riverine environments when dealing with cohesive sediment deposits (De Sutter *et al.*, 2003; Ashley *et al.*, 2004; McIlhatton *et al.*, 2005; Schellart, Tait, *et al.*, 2008). The low accuracy achieved is basically related with the differences in nature and behaviour of the sediments, and dynamics of the flow in a sewer network. The transformation processes because the cohesive nature that the sewer sediment generally exhibits in highly dense and impervious urban areas, together with interactions between particles and microbiological activity (see Chapter 4, Section 4.3.3) can have also a significant influence on the in-pipe deposits behaviour regarding resistance to erosion (Vollertsen and Hvitved-Jacobsen, 2000; McIlhatton *et al.*, 2005; Sakrabani *et al.*, 2005; Banasiak and Tait, 2008; Seco, Schellart, *et al.*, 2014).

The sediment transport methodology developed by Skipworth (Skipworth, 1996; Skipworth *et al.*, 1999; Rushforth *et al.*, 2003; Freni *et al.*, 2008) gives results more adjusted to the behaviour of cohesive sediment mobilized in sewers. The model developed allows the assessment of the sediment erosion rate linked to a runoff hydrograph, for what consider the release and re-suspension of cohesive-like sediment previously accumulated in-pipes. The developed methodology, explained before in Chapter 2, Section 2.4.6, is derived from laboratory results obtained from the erosion and transport of cohesive-like synthetic sediment previously deposited in-pipe subjected to steady flow conditions.

The proposed method by Skipworth is based in an excess shear stress relationship first suggested by Parchure and Mehta (1985) for estuarine deposits. In this way, a combination of the shear stress directly related to the hydraulic boundary conditions and empirical parameters depending on the sediment bed characteristics are used to describe the remobilization process. Despite the potential improvements in the sediment erosion rates prediction that can be made by its application, the quantification of the model parameters is still necessary and difficult to establish due the high dependence on the sediment characteristics.

Additional difficulties will be found in the sewers sediment collection procedures and in determination of the sediment properties, because their own nature and also because the highly variable distribution in the system that change with space and time. These difficulties greatly limit the understanding of the transformation and consolidation phenomena and the reliability of the prediction that can be made with models.

The wideness of variations on the sediment characteristics deposited in sewers, and on the hydraulic operation of the system, together with the complexity of the overall transformation process for which there is a limited scientific knowledge, make that the application of transport predictive methodologies must be subjected to a process of calibration and verification against locally measured data.

6.2 Predictive sediment release and transport model

Application in a study case

6.2.1 Objectives and considerations

With the purpose to analyse and assess the mobilization of sediments from in-sewer deposits composed by highly-organic sediments and validate the applicability of the relationship developed by Skipworth's (1996), a detailed network model approach of the sewerage system of the urban catchment under study in the herein dissertation was implemented through the software package MATLAB®.

The aim of the modelling is to calculate the sediment transport rate from the deposits erosion in combined sewer system based on the hydraulic conditions during rainfall and considering the behaviour of cohesive sediments that have been accumulated during previous periods without rainfall.

The required hydrologic inputs linked to the shear stress imposed by the flow (τ_b) used for the transport rate calculation are obtained from a model of the catchment previously implemented in SWMM5.

The determination of the shear stress at the threshold of motion (τ_c) exerted on the sediment bed surface is crucial in the evaluation of the release of deposited sediments and for a good performing of a sediment transport model. For it adequate assessment, the evaluation of the parameters involved in the model proposed by Skipworth (1996) that describe the increase in the deposit strength with depth of the bed are necessary. These parameters were experimentally assessed based on findings of the erosion tests previously detailed in Chapter 4 and explained later in this section.

Remobilization process is highly dependent on the hydraulic boundary conditions and on the updated area covered by the sediment at the invert of the pipe, and both vary constantly during a rain event. Despite the coupling between SWMM5 hydrological results and the network model approach developed in MATLAB® are not online, the small time step selected permits the more accurate update of the necessary parameters.

Physical and biochemical consolidation and transformation processes occurring in the sediment deposits during dry-weather periods are suggested that can be indirectly considered by applying transport parameters values assessed for sediment collected in the site, based on laboratory erosion tests findings. Aerobic environment conditions and dry-weather periods longer than 24 hours are selected as representative conditions of the analysed network.

The use of real sewer sediments for the determination of the transport parameters and sediment characteristics, as well as the field data measurements regarding hydrologic, hydraulic and quality aspects allow for the verification of the application of the sediment transport model developed by Skipworth (1996). The validation of the approach to describe the release and mobilization process was performed using rainfall, sewer flow and sediment concentration load gathered at the outlet point of the urban catchment in Granollers, Spain.

Non sedimentation process during the performance of the model during rainfall runoff inside pipes is assumed as hypothesis. The low density displayed by the sediment and the highly variable water velocity during rainfall runoff inside pipes can be translated in turbulent flows that might maintain light particles in suspension with non-deposition during these short analysed periods. Despite sedimentation might occur when storm flows are receding, non-consideration is made in the modelling in that respect. This assumption is also based on that it is our interest to focus on the sediment and pollutants remobilized during the beginning of the storm event, associated with the first flush pollution phenomena. The considerations regarding the sedimentation process in the model are set later as one of the future work topics.

In this way, the erosion and transport model allows for both spatial and temporal prediction of the sediment concentration loads conveyed through combined sewers, originated in the released and remobilization of sediment previous deposited in the system for cases of studies where deposited sediments display high organic concentrations. The prediction of the sediment deposit level evolution in the sewer system in the whole catchment during the rain event is also obtained.

6.2.2 Brief description of the procedure

The implementation of the model was conducted in the following steps that are explained below:

- Assessment of the transport parameters from laboratory results
- Implementation of the hydraulic and hydrological model (catchment surface and combined sewer system) in SWMM5 for the simulation of the hydraulic conditions required as inputs for the transport model.
- Hydraulic calibration and validation of the hydrodynamic SWMM5 model from flow data collected at the outlet of the catchment and rainfall information (independents events)
- MATLAB® implementation of the sediment transport model module based on Skipworth relationship (1996)
- MATLAB® implementation of the network system approach module
- Coupling of the sediment transport model, the network module and the SWMM5 hydraulic results
- Sensitivity analysis
- Evaluation of the performance of the transport model in the assessment of sediment concentration loads against locally measured data

6.2.3 Review of the study site and monitoring programme

6.2.3.1 Study site location and description.

The small urban catchment covering an area of approximately 10 hectares (Figure 6-1) situated in the north-east of Spain, in the city of Granollers (35 km northerly from Barcelona in Catalonia, Spain) monitored during the research project and previously described in Chapter 3 is selected for the validation of the sediment transport model.

Given the high impervious conditions of the urban catchments of the region, and the limited existence of natural or green areas, inorganic sediments are a minor contribution during storm runoff. Additionally, the low wastewater flow due to the low drinking water consumption rates that have been decreased the last years (from 129.6 l/inh/day in 2001 to 105,1 l/inh/day in 2012 according to the data published by the local water management company) and intensive food commercial use of the area mean a significant risk of accumulation of organic sediments in the combined sewer pipes during the prolonged dry periods usually longer than a week. The low wastewater flow influence the reduction of the sediment transport capacity during dry periods, increasing the sedimentation in-pipes of rich-organic sediments particles from domestic sources. The long dry-weather periods are usually followed intense storm events, which promote the release of the previously deposited sediments.

General characteristics of the catchment and the combined sewer network can be queried in Table 3.1 from Chapter 3.

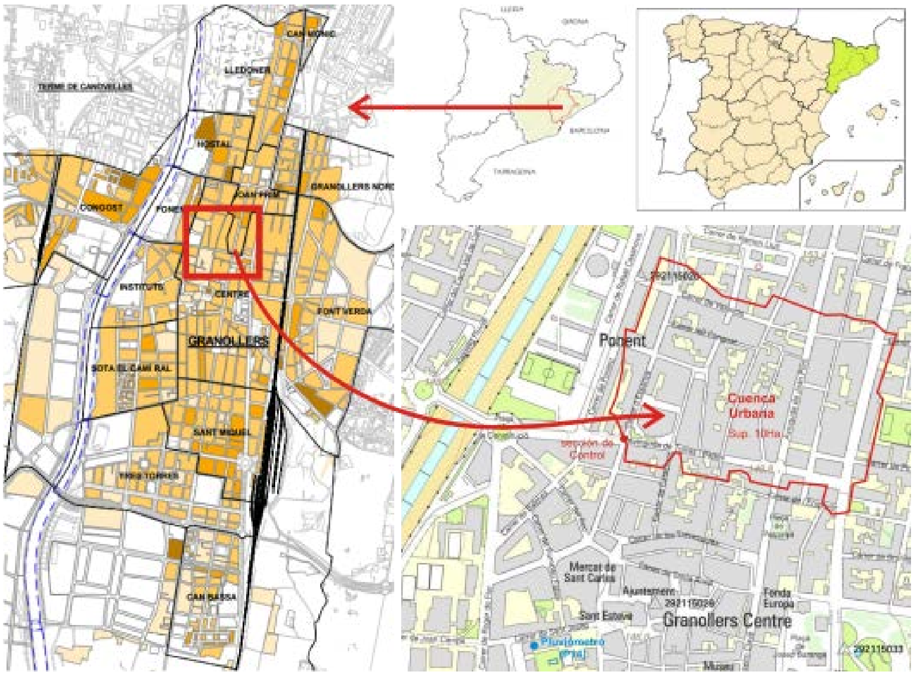


Figure 6-1   Location of the study urban catchment.

6.2.3.2 Hydrological, Hydraulic and quality monitoring

Monitoring programmes have been carried out along a 18-month period in the mentioned urban catchment based on automated sampling and flow rates measurements presented in Chapter 3. Rainfall data was also registered simultaneously with flow and quality monitoring. The purpose of the monitoring programme was to obtain local specific data to model the hydrodynamic and pollutant transport behaviour in a typical urban catchment in the region that can be applied to similar conditions.

Two rainfall-flow measured data were registered and used for the calibration of the hydrodynamic model performed in SWMM5. The detail of the events is shown in Table 6-1 and Figure 6-3.

Five additional rainfall events were recorded gathering rainfall-flow data at the outlet of the urban catchment and collecting samples for quality analysis.

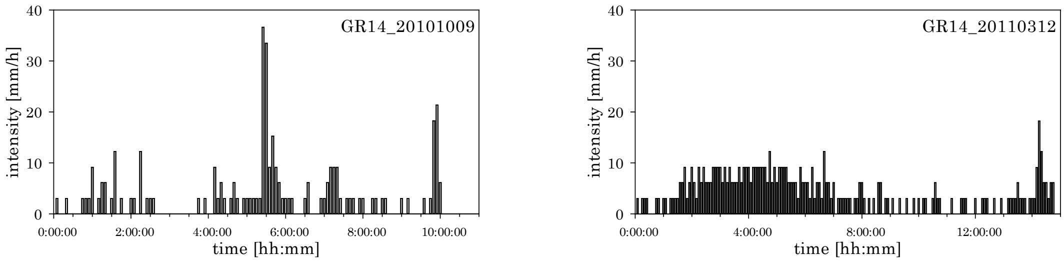


Figure 6-2 Rain events used for calibration of the hydrodynamic model.

Table 6-2 lists the characteristic values of these events and the distribution of the rainfall can be observed in Figure 6-4.

Table 6-1: Rainfall events registered in the study site and used for the hydrodinamic modelling calibration.

Date	Total volume [mm]	Maximum intensity [mm/h]	Total duration [hh:mm]
09/10/2010	33.5	36.6	10:05
12/03/2011	71.6	18.2	18:50

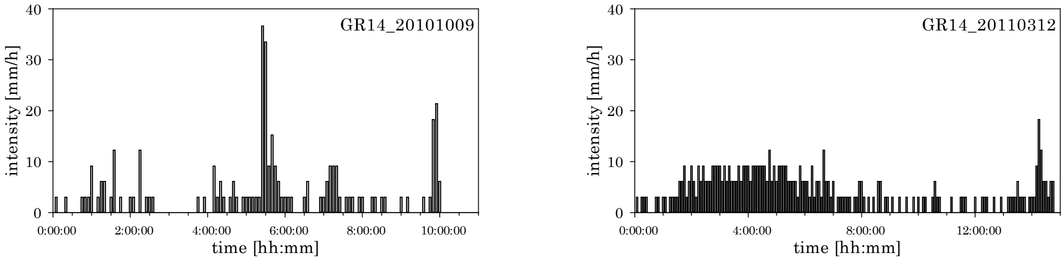


Figure 6-3 Rain events used for calibration of the hydrodynamic model.

Table 6-2: Rainfall events registered in the study site and used for the sediment transport modelling validation.

registered data	Date	total volume [mm]	maximum intensity [mm/h]	duration [hh:mm]	previous dry-weather period length [days]
rainfall, flow and quality	17/09/2010	19.0	36.2	2:10	28
	31/05/2011	26.2	33.5	5:15	16
	13/07/2011	5.6	27.5	0:50	32
	24/10/2011	6.4	37.0	1:20	39
	13/11/2011	11.1	18.2	3:55	6

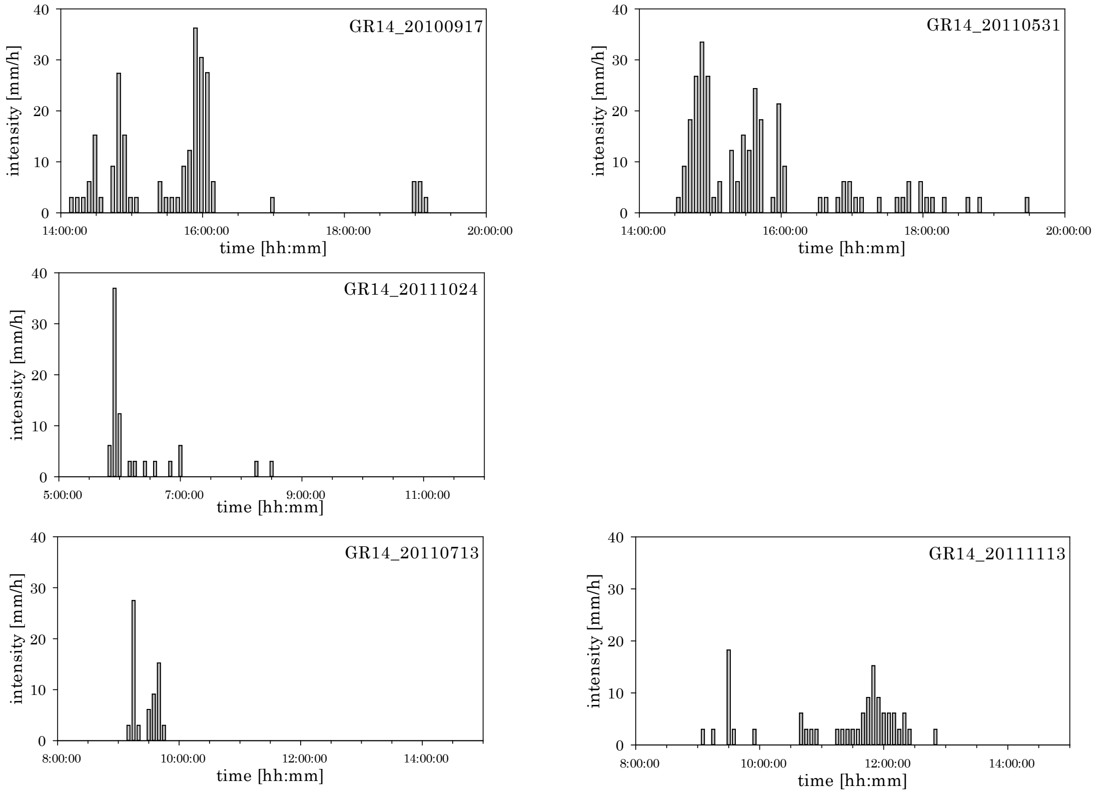


Figure 6-4 Rain events used for calibration and validation of the quality modelling.

6.2.4 Deposited sediment characteristics and behaviour

6.2.4.1 Sediment deposit sampling and analysis

Highly-organic sediments are typically observed in the Mediterranean region where densely populated urban areas with a high level of imperviousness are usual.

A batch of in-sewer sediment has been collected on three occasions from the combined sewer system of the study case. The sediment samples displayed non-homogeneous composition and size distribution, exhibiting a high presence of fat, oil and greases (FOGs). The sediments were used for analysing the sediment properties itself and in the performing of a series of laboratory erosion tests, both previously detail in Chapters 3 and 4.

A brief summary of the sediment characteristics is shown in Table 6-3 and compared with the main characteristics of the synthetic sediments used in the developing of the sediment transport methodology by Skipworth. The organic content percentage is related with the relation between volatile solids (*VS*) and the total dry mass of suspended sediments (*TSS*).

Table 6-3: Characteristics of sediments used by Skipworth (1996), Rushforth (2001) and Seco (2014) experimentation.

sediment type	characteristic particle size d_{50} [mm]	sediment density [kg/m^3]	organic content [%]
sewer sediment from urban catchment in Granollers. Spain (Seco *et al.*, 2014)	0.31(± 0.16) (***)	1310 (± 146) (***)	74 ±5 (VS/TSS) (*) 93 ±2 (VS/TSS) (**)
crushed olivestone (Skipworth, 1996) and (Rushforth, 2001)	0.047	1445	100

(*)batch collected on the 26/06/2012
(**)batch collected on the 29/11/2013
(***) average of the values assessed from the three different batch of sediments collected in the system

6.2.4.2 Laboratory erosion tests procedure

An oxygenated environment in the sewer network might be produced under conditions of varying flows or high velocities. Aerobic atmosphere might be usually developed on upstream pipes of a sewer network where turbulent flows promote the reaeration of conveyed waters. The data reported in this Chapter focus therefore on the erosion and transport of sediments subjected to aerobic conditions during dry-weather periods prior to a storm.

Laboratory tests for the assessment of the critical threshold of motion at the solid-fluid interface were carried out with supplying oxygen and varying the simulated dry-weather periods using an *erosionmeter* device. The set of erosion tests were performed in a controlled temperature laboratory facility at 20 ºC.

Details of the experiment and tested conditions were explained in Chapter 4. A detail about the equipment and calibration process were also explained at Seco, Gómez-Valentín *et al.* (2014).

6.2.5 Modelling the sediment transport in the study case

The termed critical bed-shear stress is referred to the lowest value of the shear stress that will produce the release and re-suspension of the particles laying on the superficial layer of the sediment deposit at the interface solid-water. It is therefore a relevant factor in erosion process modelling. Its accurate assessment is crucial because the movement of the particles depends basically on the excess of shear stress between the critical and the applied value. On the other hand, the applied shear stress distribution linked with the varying circulating flows (and water depth variation) needs to be updated at each time step of calculation.

In that sense, the better prediction of the hydrodynamic during a rain event, that will be the inputs of the quality model, will allow the more accurate assessment of the boundary shear stress parameter and therefore, the more reliable sediment erosion and transport prediction.

6.2.5.1 SWMM5 hydrodynamic modelling

The SWMM5 (Storm Water Management Model, version 5.1) software package was selected for the rainfall-runoff and flow routing modelling through the combined sewer system in the study case.

The hydrological model is defined based on a sub-catchment delineation associated to the combined sewer network complemented with topography information and in-situ observations (Figure 6-5).

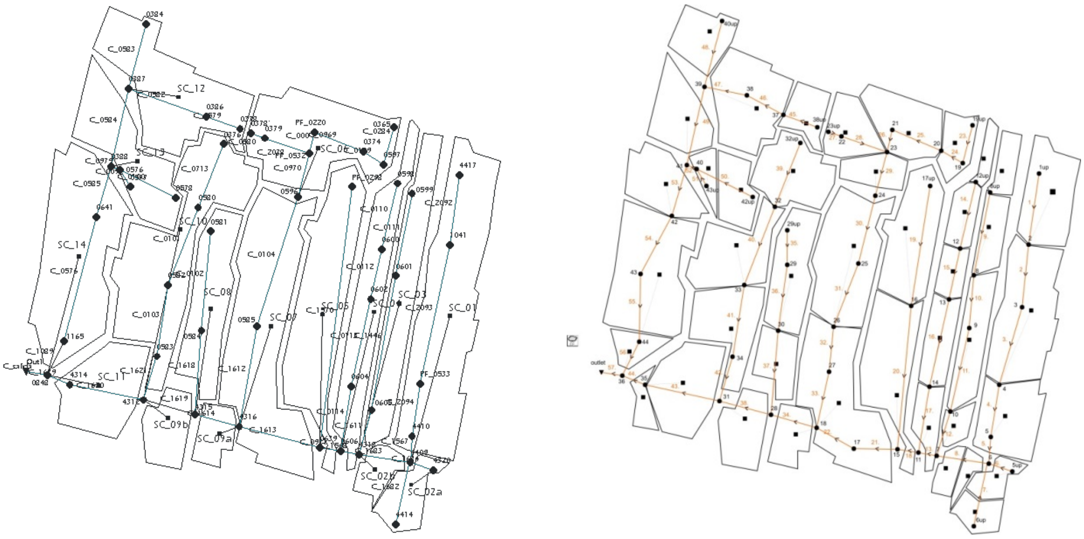


Figure 6-5 Layout of the combined sewer network implemented in SWMM5 showing manhole locations and catchment subdivision for the hydrodynamic modelling. Comparison between original SWMM5 model from Chapter 5 (on the right) and discretization of the catchment and conduits for modelling improvements (on the left).

Later, the hydraulic parameters obtained from the SWMM5 model will be introduced as inputs in the nodes of the network in the detailed network module. Regarding the frequency of the hydraulic data introduced, it was analysed that the routing time in the network model in MATLAB® might be similar to the time-step used for the simulation in the SWMM5 model. In this way, the hydraulic data inputs in the upstream node of the analysed pipe in the network is introduced as pulses with the time-step delay, which in turn will be similar to the time necessary for the water to arrive until the outlet of the pipe. To take this into account, the original sewer network system in the catchment was adapted in the SWMM5 model in order to have as uniform lengths of pipe as possible that allows a more uniform routing time for all the pipes. For this purpose, fake nodes were entered keeping the original slopes of the conduits. In this way, the original network of 48-pipes becomes in a 57-pipes network just dividing the longest pipes in 2 or 3 sections with a final average length of 39m. This modification gives the possibility of define a 20 seconds time-step for the hydraulic calculation in SWMM5, that will more closely represent the routing time in an average length pipe with average water velocity.

A more detailed division in the sub-catchments contributing with superficial runoff at each node is also implemented (left side in Figure 6-5) with respect to the SWMM model used in Chapter 5. This modification allows better representation of the inputs from the runoff and from the wastewater contributions.

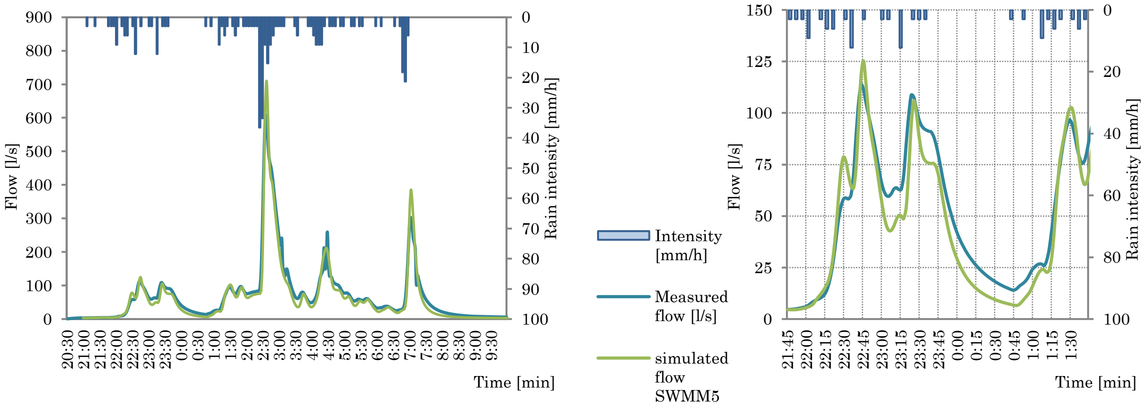
A calibration-validation process of the hydrodynamic model is performed through the comparison between the simulated results against locally measured data. Firstly a calibration step is carried out through the application of two set of rainfall data corresponding with the rain events occurred on dates 09/10/2010 and 12/03/2011 (Figure 6-1). Subsequently the model is validated by applying a new independent data set for which the event of the 31/05/2011 was applied, later used in the quality model.

The adjustment in the roughness coefficient for the pipes and sub-catchment properties was based on the criteria of minimization of the sum of squared errors in terms of water flow and volume. The calibration-validation results in term of flow evolution against time are shown in Figure 6-6.

Having observed the strong influence on sediment erosion of the first minutes of in-pipe runoff associated with the rain event, hydrodynamic model calibration for the present study was based on optimizing the performance of the model with regards to the first peak flow rate and the time at which starts the in-pipe runoff.

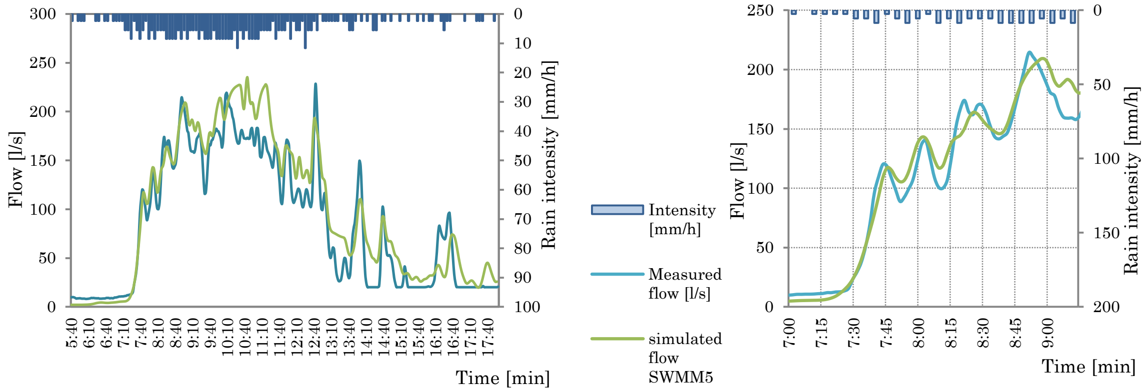
After a calibration process, it was noticed for all the events a slight temporal delay (2 to 10 minutes) in the start of the runoff at the outlet pipe between the measured flow and the simulated flow. It was assumed that the noted differences might be related with two issues: Firstly, because differences in the rainfall data measured and the flow measurements intervals might influence in the observed delay (the rainfall data was measured with a time-step of 5 minutes and the flow measurements were registered every 2 minutes interval). Secondly, having observed high variation in the spatial distribution of the rain in the area, the location where the nearest rain gauge was installed (outside the area of the analysed catchment and at about 300 meters from the outlet) might also have influence in the slight delays observed in the hydraulic results.

Since this temporal delay in the flow routing might cause a much bigger influence on the mobilized sediment mass simulated, it was introduced a correction in the starting time of the rain data in order to better represent the beginning of the flow routing. The applied delay is shown in the caption in Figure 6-6 and is lower than 10 minutes in all the cases. On the right side of the Figure, a detail of the initial part of each hydrograph is displayed where it can be appreciated the temporal correspondence between the simulated and the measured flow beginning.



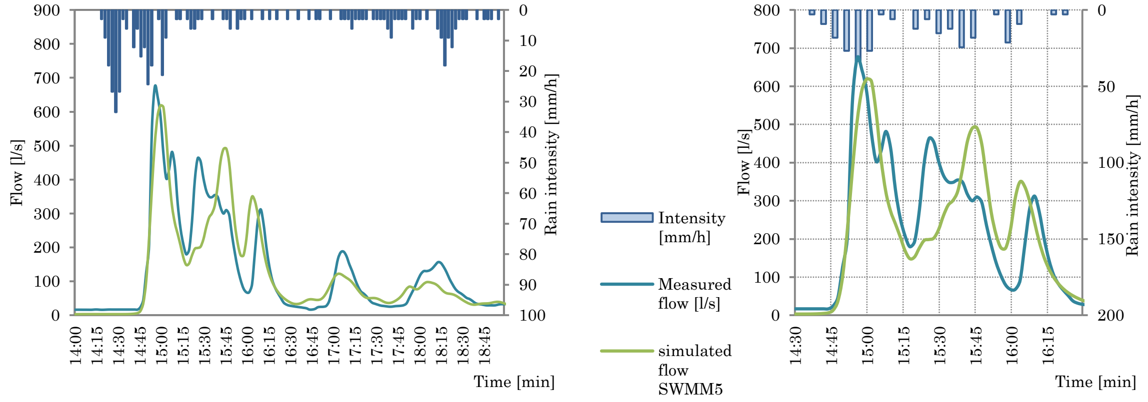
(a.1) whole rain event hydrograph
rain event: 09/Oct/2010 (delayed 2min)

(a.2) first 2hours rain event hydrograph
rain event: 09/Oct/2011 (delayed 2min)



(b.1) whole rain event hydrograph
rain event: 12/March/2011 (delayed 10 min)

(b.2) first 2hours rain event hydrograph
rain event: 12/March/2011 (delayed 10 min)



(c.1) whole rain event hydrograph
rain event: 31/May/2011 (delayed 8 min)

(c.2) first 2hours rain event hydrograph
rain event: 31/May/2011 (delayed 8 min)

Figure 6-6 Hydrographs corresponding with the calibration and validation of the hydrodinamic model performed with SWMM5.

For the hydraulic calibration-validation, a quite accurate adjustment in terms of first peak flow (between 2 and 10% error) and time to the peak (2 minutes average error) was obtained. The hydrologic-hydraulic adjustment in volume between the measured and the SWMM simulation is adequate (<10% in volume). A detail of the errors is displayed in Table 6-4.

Table 6-4: Observed errors between measured and simulated hydrodinamic results afted calibration process.

Errors	12/03/2011		09/10/2010		31/05/2011	
	Measured data	SWMM simulation	Measured data	SWMM simulation	Measured data	SWMM simulation
total Volum (m3)	3780	3822	3356	3030	2400	2256
percent volume error VE	1%		10%		6%	
overall Peak (l/s)	228	235	607	710	673	624
percent peak error PE	3%		17%		7%	
1rst Peak (l/s)	120	117	114	125	673	624
percent peak error PE	2%		10%		7%	
time to 1rst peak (hh:mm)	7:44	7:46	22:44	22:46	14:56	14:58
Error	00:02		00:02		00:02	

6.2.5.2 Sediment transport model module

Further details of the sediment transport method by Skipworth (1996) can be found in Chapter 2. In this section, the purpose is just to review on the parameters defined in the model that are necessary to be assessed by experimentation.

The methodology is based on the consideration of several sediment layers forming a bed structure that displays an increasing resistance against erosion with depth. The structured bed deposit shows a weakly upper layer and a stronger underlying layer. Once the lower layer is achieved, the deposit presents a uniform resistance to erosion.

The variation of the critical strength in the upper weak layer is described then with a power equation (equation 2-11) meanwhile the upper layer depth is not exceeded (d'). At the upper layer, the erosional strength increases in depth from a surface strength (τ_{cs}) until a value of strength (τ_{cu}). Once the thickness of the upper layer (d') is exceeded, the boundary shear stress is constant and equal to τ_{cu}. Subsequently, the evaluation of the sediment erosion rate is made by applying an excess shear stress relationship (equation 6-2), where the parameters involved are: d, the cumulative depth of erosion, E the erosion rate (in g/m^2/s) for the applied bed shear stress τ_b [N/m^2]. τ_c is the critical shear stress also in [N/m^2], and M is a transport parameter used as calibration factor.

The values of the parameters τ_{cs} ,τ_{cu}, d' and the parameter b are related with the structure of the bed deposit and the characteristics of the sediment (particle size and density). Despite the named transport parameters b and M do not have a physical meaning; they are directly related with physical features. In that regard, b is a parameter which allows the description of the change in bed strength with depth. M is a parameter suggested as dependent on the hydraulic conditions (flow regime and slope of the pipe), but also related with the sediment characteristics.

$$\begin{aligned} \tau_c &= \left[\left(\frac{d}{d'}\right)^{1/b} . (\tau_{cu} - \tau_{cs})\right] + \tau_{cs} && for \quad 0 \leq d \leq d' \\ \tau_c &= \tau_{cu} && for \quad d > d' \end{aligned} \tag{6-1}$$

$$E = M \,.\left(\frac{\tau_b - \tau_c}{\tau_c}\right) \tag{6-2}$$

The high dependence of these parameters on the sediment bed properties makes that the value of all of these five parameters must be experimentally determined to obtain a more realistic prediction of the sediment transport.

As a result of the erosion test performed with highly organic sediment deposits (Chapter 4), it was experimentally confirmed that the upper layer exhibits a variation of the erosional strength with depth, and the values of the mentioned parameters can be assessed from the testing results. The procedure and obtained values are explained below in Section 6.3.1.

6.2.5.3 Coupling of the sediment transport model, the network module and SWMM5

The sediment transport relationship developed by Skipworth (1996) can be easily implemented in an individual pipe. In order to analyse the performance of the method in a combined sewer network, under the complex hydraulic conditions, the relationship of Skipworth with the adapted parameters in order to represent the sediment commonly found in the study case site, was coded using the dynamic programming package MATLAB® and then coupled with a simplified network model also coded in MATLAB®.

The implemented sediment transport module allows the assessment of the sediment erosion rate linked to an instant flow at each pipe and the update of the sediment depth and area covered by the sediment bed necessary for a next time-step calculation.

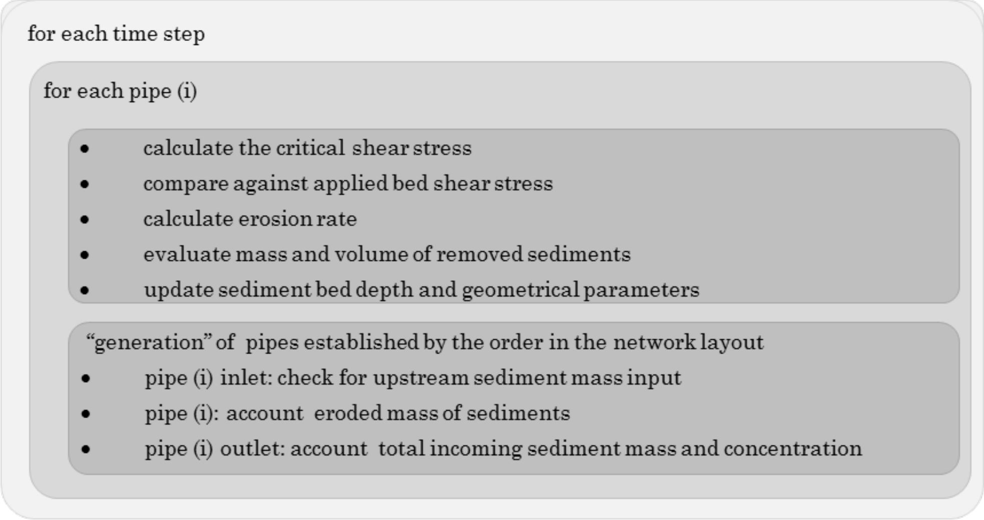
The network module is a physically based code, based on a model previously proposed by Schellart (Schellart *et al.*, 2008). The network code allows the evaluation of the movement of sediment from the in-pipe erosion at all pipes of the system, and their subsequent movement until arriving to the outlet of the catchment were measurement of the sediment concentration was registered. In this way, the transference of the mass of sediments eroded through different conduits at different times is considered following the network layout. The layout of the network coded for the transport module is the same as previously shown in Figure 5-6 (right side).

The hydraulics inputs for the MATLAB® network model were generated from the same study case urban catchment previously implemented in SWMM5 as was explained above in Section 6.2.5.1. The catchment model comprises 57 pipes and manholes, and 42 sub-catchments. The hydraulic prediction by SWMM5 was previously calibrated and validated using local flow measurements generated from independent rainfall data.

The coded module allows the update of the area covered by the sediment that varies constantly during the remobilization process linked to a runoff hydrograph.

The composite roughness and side wall effects on the hydraulics during sediment release and transport were considered through the side-wall correction method according to Einstein (1943) (Chapter 2, Section 2.4.5.2.2)

In this way, the coupling of the individual aforementioned modules allows integrated simulation of processes in a network system. The coupled modelling structure between the *Skipworth transport model* - *network module* - *SWMM5* is shown in Figure 6-7.



for each time step

for each pipe (i)

- calculate the critical shear stress
- compare against applied bed shear stress
- calculate erosion rate
- evaluate mass and volume of removed sediments
- update sediment bed depth and geometrical parameters

“generation” of pipes established by the order in the network layout

- pipe (i) inlet: check for upstream sediment mass input
- pipe (i): account eroded mass of sediments
- pipe (i) outlet: account total incoming sediment mass and concentration

Figure 6-7 Scheme of the simplified network sediment transport module coded in MATLAB®.

The results and the analysis of the sediment release, erosion and transport from in-sewer deposits generated in the study case urban catchment under the occurrence of different storm events are presented in the following sections.

6.2.5.4 Performance evaluation criteria

The goodness of the fit between observed and simulated quality parameters was evaluated by using the following criteria: the sum of squared errors *SSE* (equation 6-3), the percent peak error *PE* (equation 6-4), and the percent volume error *VE* (equation 6-5), where $C_{SS,m,i}$, $C_{SS,s,i}$ are the suspended sediment concentration measured and simulated respectively; $C_{SS,m}$ is the mean suspended sediment concentration measured.

$$SSE = \sum_{i=1}^{n} \left(C_{SS,m,i} - C_{SS,s,i}\right)^2 \tag{6-3}$$

$$PE = \frac{\left(C_{SS,m,peak} - C_{SS,s,peak}\right)}{C_{SS,m,peak}} . 100 \tag{6-4}$$

$$VE = \frac{\left(V_{m,i} - V_{s,i}\right)}{V_{m,i}} . 100 \tag{6-5}$$

6.3 Results and Discussion

6.3.1 Assessment and optimization of transport parameters based on laboratory results

In this section, transport parameters involved in the sediment transport relationship proposed by Skipworth (1996) were assessed based on laboratory erosion tests findings. Highly-organic sediment samples deposited during dry-periods in a combined sewer system were used in that regards. The assessed parameters were later applied for the sediment transport prediction / validation through the modelling of a small urban catchment from where hydrologic, hydraulic and quality data is available.

Erosion test were performed over the real high organic sediment deposit using an erosionmeter device (see details in Chapter 4). The determination of the sediment transport parameters used in the transport model was obtained for the tests performed at aerobic conditions at 20ºC under different length of dry-period simulation, corresponding with the second set of erosion tests carried out and previously explained in Chapter 4. Thereby, the assessed values of the parameters are supposed that consider the intrinsic characteristics of the sediments (particle size distribution, density and cohesive properties) and the existence of underlying in-sewer biochemical processes that both influence on the sediment bed properties over time and transformation effects.

The determination of the erosional strength linked to each stepwise of applied shear stress is calculated from the suspended sediment concentration (*TSS*) for each collected sample during the erosion test after applying a weight correction.

The mentioned weight correction applied to the *TSS* measured values allows the calculation of the fresh sediment mass. The measured values of *TSS* were obtained following the Standard Methods, and this meant a process of drying of the sludge in oven until the water contained in the sediment mass evaporates. As here we are interested in considering the mass of sediments in the fresh state that is released from the deposit in the erosionmeter, it was suggested the application of a correction factor (c_w). This value is calculated as an average of the relation between the *TSS* values for each collected sample and the first weight of these samples after filtering with the vacuum pump. A $c_w = 1.77$ was found in that way.

The relationship between applied shear stress and erosion rate from the laboratory measurements is shown in Figure 6-8 (left side), for tests carried out under aerobic conditions and different durations of dry-weather period. Through a regression analysis, the best fitting was obtained with power trend functions. The right side of Figure 6-8 shows the regression functions found.

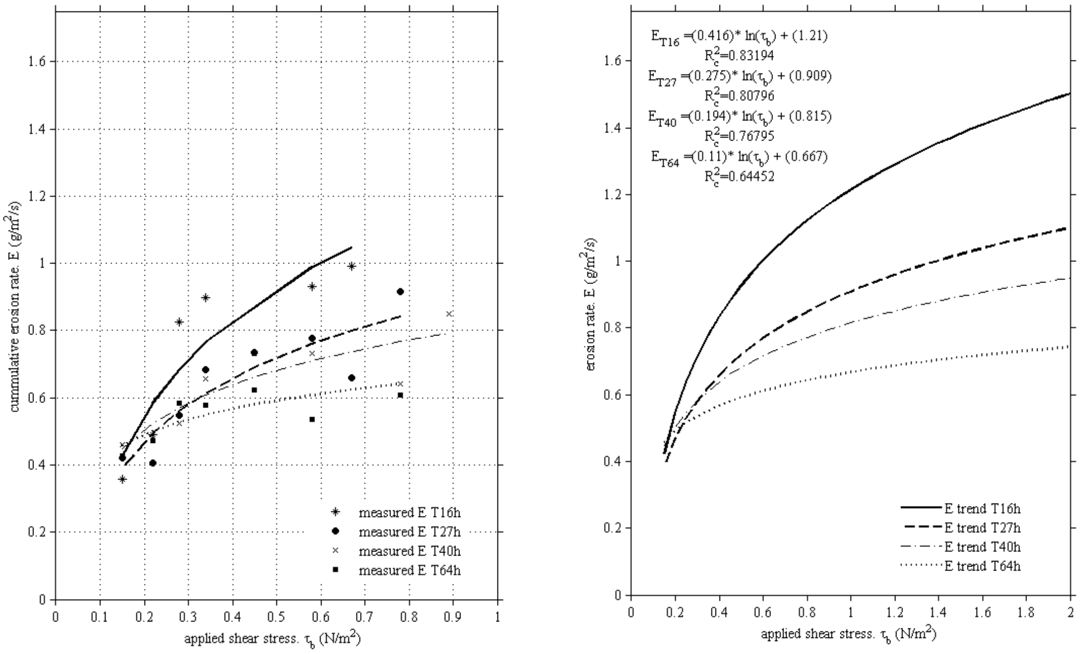


Figure 6-8 Erosion rate against applied shear stress. Measured data and regression function.

6.3.1.1 Assessment of parameters τ_{cs} ,τ_{cu}, d'' and d'

At the end of each time step during the erosion test, the mass of sediments obtained from the suspended sediment sample can be set in terms of depth of sediment eroded (d_e), and linked to the applied shear stress (τ_b). The depth of the eroded sediment bed can be assessed from the sample sediment concentration at the end of each time step using equation 6-6, where C_{SSc} is the corrected value in weight of the sediment concentration in the collected sample, V_s is the volume in the device reactor and $A_{s\text{-}e}$ the superficial area of the bed deposit in the erosionmeter device.

$$d_e = \left(C_{SSc}\cdot\frac{V_s}{A_{s-e}}\right)\cdot\frac{1}{\rho_m} \qquad 6\text{-}6$$

The density of the sediment (ρ_s) of 1310 kg/m^3 (± 146 kg/m^3), determined from previous laboratory work (see Chapter 3, Section 3.4), was used for the calculation of the sediment-water mixture density (ρ_m) using equation 6-7, assuming that remains constant during the test.

$$\rho_m = \rho_w + C_{SSc}\left(1-\frac{\rho_w}{\rho_s}\right) \qquad 6\text{-}7$$

The applied shear stress against the depth of erosion trend can be assessed from the measured results as it is shown in Figure 6-9.

It can be hypothesised that the value of the critical shear stress at the superficial layer (τ_{cs}) can be considered equal to the applied shear stress during the simulated dry-period (τ_{DW}=0.15 N/m^2). This dry-weather shear stress is linked to the average wastewater velocity at the outlet pipe in the studied network.

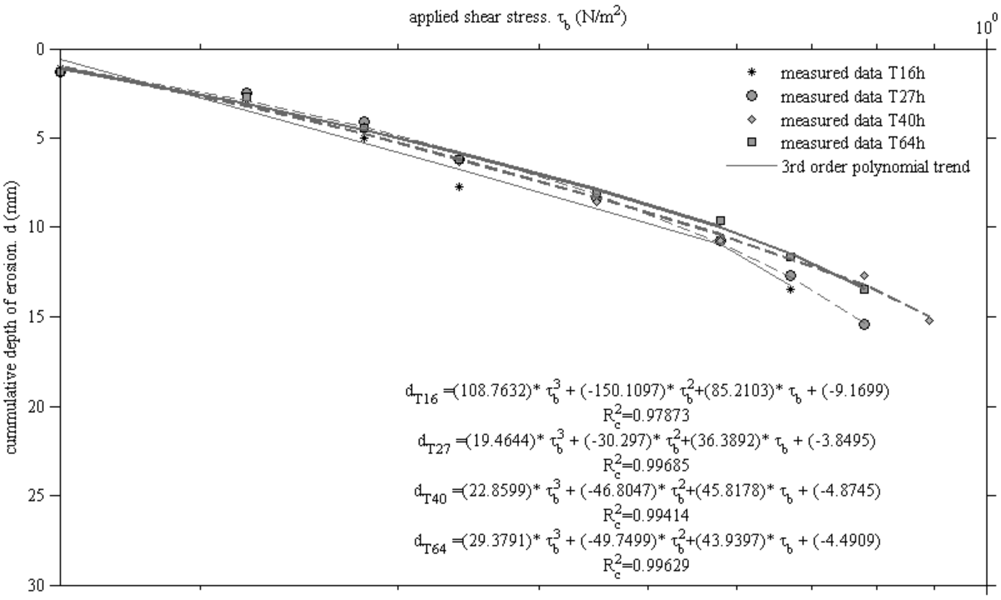


Figure 6-9 Sediment bed depth strength against applied shear stress. Measured data from erosion tests and trend.

The depth of the eroded sediment bed during the dry-weather period simulation (*d"*) can be assessed from the sample sediment concentration at the end of the dry-period by applying the equation 6-6 previously defined. It can be noticed that for all the lengths of dry-period tested, the parameter *d"* (depth superficial layer) results in a quite constant value being *d"*=1.25 mm (standard deviation *SD* = 0.13 mm). This finding meant that the τ_{cs} and *d"* can be considered independent on the length of the dry-period when consolidation of the sediment deposit take place.

Analysing the profile of variation for the resistance of the sediment deposit in depth suggested by Skipworth, it follows that the value of τ_{cu} is reached when the resistance strength becomes uniform in depth. From the experimental results, the determination of the thickness of the upper layer of sediments (*d'*), is found by considering a critical gradient of 0.01($\Delta\tau_b/\Delta d$), due that the constant value of the critical shear stress is not actually achieved. Once this critical gradient is reached, it is hypothesised that from that depth of the sediment bed the critical shear stress is uniform and the value of τ_{cu} is set. Figure 6-10 shows the different pair of values (*d'*- τ_{cu}) obtained for the erosion test performed with different dry-weather period simulated. The values of τ_{cu}, and *d'* obtained through the explained methodology are shown in the graph on the left side of the Figure 6-12.

For the analysis of the results obtained that show the relationship between depth of erosion and shear stress, it is necessary to consider the errors in the assessment of the sediment depth combined with the accuracy in the applied shear stress measurement. In order to make this consideration, the accuracy in the measurements was applied to the assessed values. A clear visualization of the influence of the measurement accuracy is presented in the right plot in Figure 6-10. The representation of the accuracy through shadow graphs was created in MATLAB® using the toolbox *herrorbar* © 2009. Analysing the shadow error curves in this plot, it can be suggested that from around 24 hours of consolidation period, the increment in the resistance against erosion of the sediment bed is quite slow.

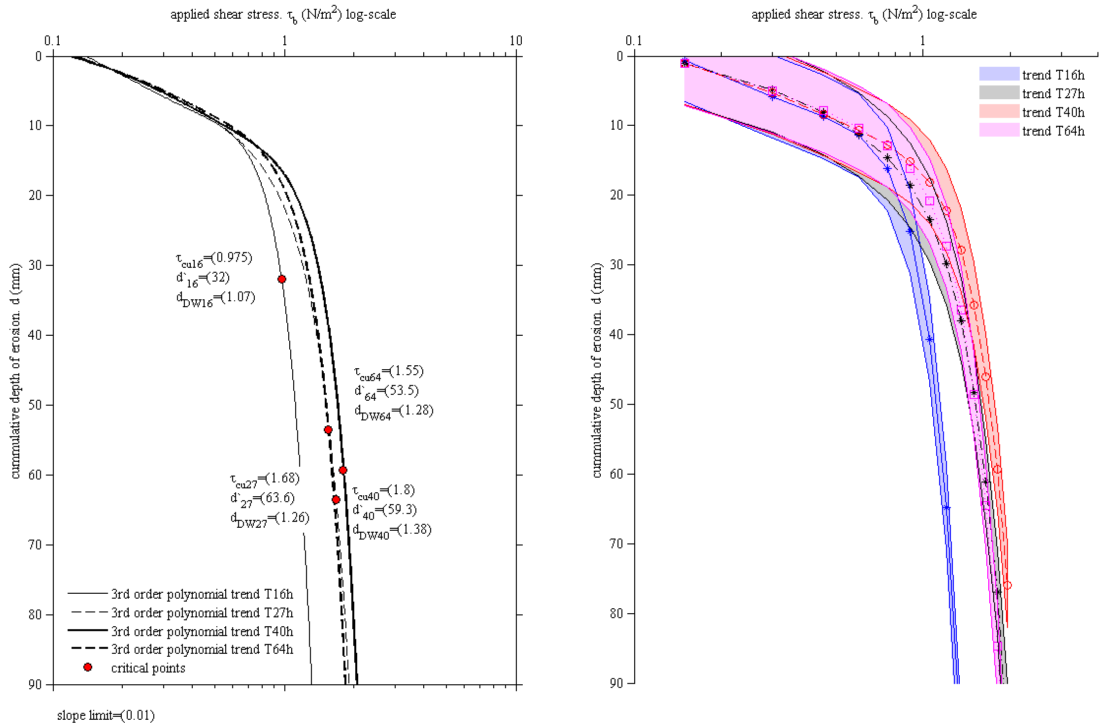


Figure 6-10 Bed strength profile in depth of the sediment layer calculated by using the 3rd order polynomial regression functions obtained from experimental data.

6.3.1.2 Determination of the parameters *b* and *M* values

The application of equation 6-2 implies the previous determination of the critical shear stress τ_c value from equation 2-11, and the knowledge of the value of the parameter M. On the other hand, in order to calculate τ_c, the value of the until now unknown parameter b is also necessary. In this way, the calculated erosion rate E_c at each applied shear stress interval τ_b is obtained and can be compared against the value of erosion rate obtained from measured data (E_m).

Since the determination of a value of the erosion rate E_c (calculated rate) implies the knowledge of the calibration parameters b and M, and the assessment of the value of M implies the previous knowledge of the value adopted by the b-parameter, the values of them are adopted by varying both in a loop to obtain the lowest value for the quadratic error e (equation 6-8). The initial range of parameters b and M introduced in the mentioned loop were those determined by Skipworth and presented below in Table 6-5.

$$e = \sqrt{(E_c - E_m)^2} \qquad 6\text{-}8$$

Considering increasing values for the unknown parameters b and M, and calculating the quadratic error e of the erosion rate, a 3D plot as shown in Figure 6-11 (for the 16-hours dry-period) is obtained for each τ_b step and each b_i-value adopted (linked with a $\tau_{c\text{-}i}$ value).

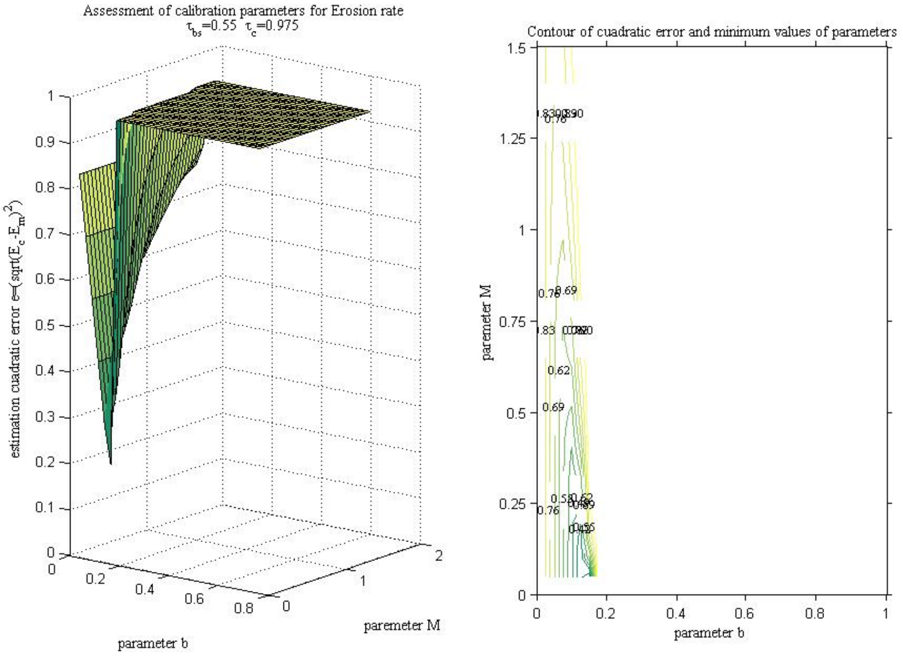


Figure 6-11 Cuadratic error versus calibration parameters. Minimization of the error procedure.

The relationship between the applied shear stress and the values of the assessed parameters b and M based on a minimum quadratic error criteria are comparatively shown in Figure 6-12 corresponding in this case for the results obtained for the test performed with 16 hours of dry-weather period, taken here as an example.

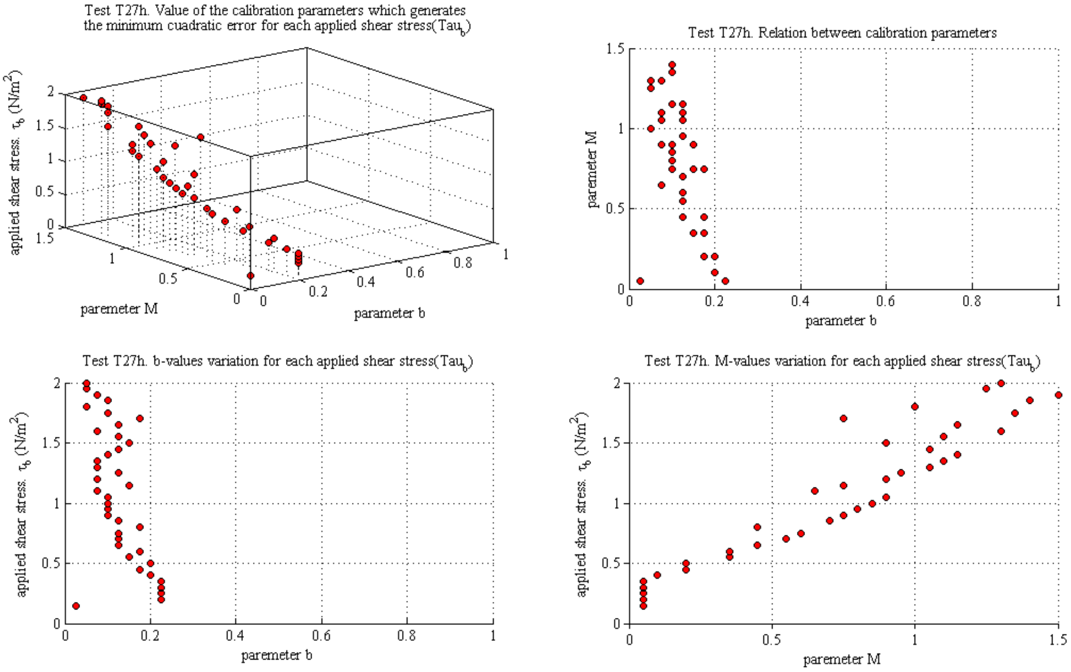


Figure 6-12 Assessment of the parameters b and M from the minimum quadratic error in the calculation of the erosion rate E.

So that, assigning different values to the parameters b and M and calculating the critical shear stress τ_c and erosion rate E_c by applying the equations 6-1 and 6-2 at each step of applied shear stress, and for each test conditions (consolidation period), it is possible to find a range of values of these parameter where the quadratic error *e* achieve a minimum value.

The analysis of the results of minimum error *e* for all the four performed tests allows to confirm a narrow range of values for the *b* parameter (Figure 6-13, left) where the mean is *b* = 0.125 (SD = 0.071). As it was mentioned before, although the parameter *b* do not directly represent a physical characteristic of the sediment deposit, its value depend on the structure of the bed of the deposit and on the degree of consolidation which means that there is a link with changes of the bed strength with depth. The quite uniform distribution of the values assessed for *b*-parameters for all the dry-periods tested suggests a stable degree of consolidation of the bed in the samples tested, and homogeneity in the material that formed these deposits.

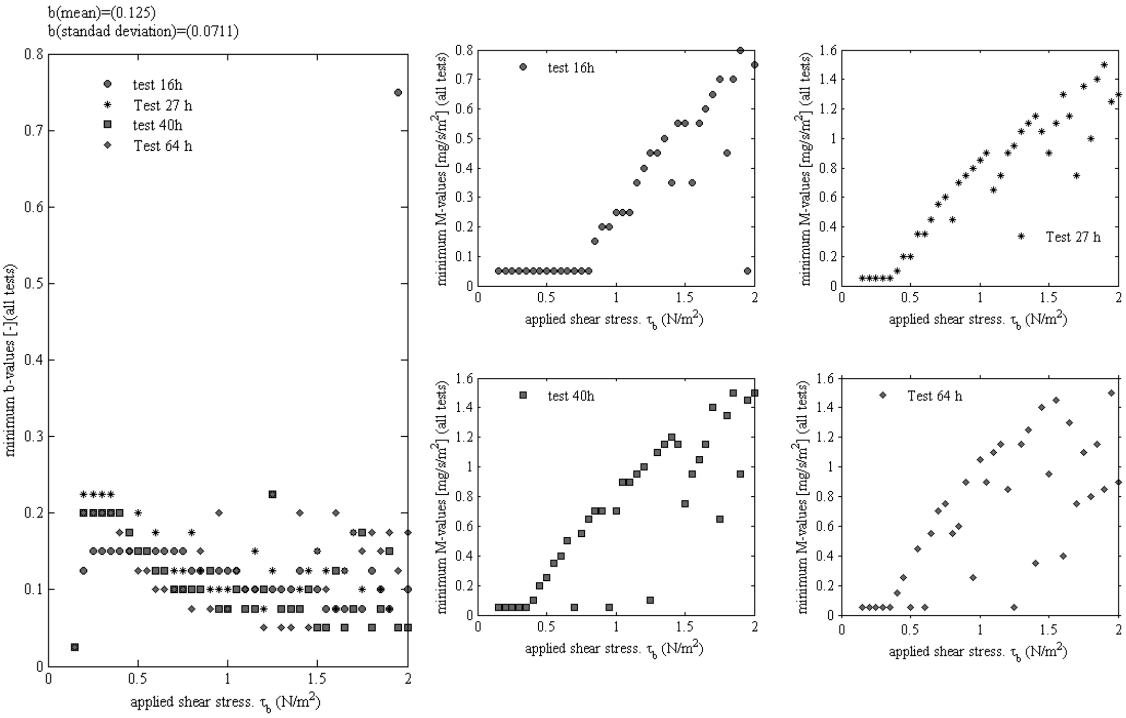


Figure 6-13 Variation of the values of the parameters b and M against applied shear stress for all the dry-period tested.

Regarding the assessment of the parameter *M*, the variation is wider (Figure 6-13, right). However, it can be observed a clear proportional relationship between the value adopted by the *M*-parameter and the applied shear stress for each test. It can also be noted that the mentioned trends change with the length of the dry-period analysed. Thus, it can be suggested that there exist a relationship between the duration of the consolidation period and the parameter *M* (coefficient of proportionality between 0.51 and 0.74). It can be also suggested that the variation of the parameter *M* might be linked with and increasing mean particle size or increasing particle fall velocity during deposition period when the bed is formed.

Table 6-5 summarize the obtained values of all the parameters involved in the calculation of the erosion rate by applying the equations given by Skipworth (1996). The table also shows a comparison against the values obtained from laboratory experimental work developed by Skipworth and Rushforth using crushed olivestone bed (uniform and homogeneous sediment) and same material mixed with sand respectively.

In this way, with the assessed values for the transport parameters, it is possible to implement now the sediment transport predictive module.

Table 6-5: Comparison of the values of transport parameters obtained from Skipwort and Rushforth experimentation (Skipworth, 1996; Rushforth, 2001) and the obtained from the experimentation described in this work.

Parameter		values obtained in this work	Rushforth (2001)	Skipworth (1996)	
			optimum for olivestone	1:500 slope	1:1000 slope
M	[g/s/m^2]	0.5 - 1.5	0.73	2.0	0.35-0.65
b	[-]	0.125	0.93	0.45	
d'	[mm]	32 - 64	7.2	7	3.8
τ_{cs}	[N/m^2]	0.15	0.07	0.20	0.10
τ_{cu}	[N/m^2]	1.07 – 1.38	0.37	0.50	0.20

6.3.2 Sediment transport model applied to a single pipe

The model of Skipworth (1996) is based in the analysis of observed sedimentographs registered through a laboratory programme. As it was explained in Chapter 2, tests were carried out with in-pipe sediment deposits composed of crushed olivestone of the same particle size and density.

Here in this section, the methodology followed for the application of the transport rate equations in a single pipe is explained and applied by using the original parameters assessed experimentally by Skipworth for olivestone material and the new set of parameters assessed in this work for real organic sediment collected from the study case combined sewer system.

The calculation methodology involves assessing the erosion rate per time interval (here 20 seconds) and the critical shear stress value (τ_c) using the equations 2-11 and 6-2. At the end of each time interval, the mass of mobilized sediment is obtained, and can be translated into depth of erosion from the bed deposit and update the remained bed depth. The updated sediment depth will be the initial value for the next time step calculation that enables the assessment of a new τ_c value. Once the depth of erosion exceeded d', τ_c became constant and equal to τ_{cu}. In this process, it is assumed that the density of the sediment remained constant throughout the cross-section and in depth of the in-pipe deposit. Finally, Skipworth proposed a correction to be applied to the erosion rate which considers the changes in the width of the superficial layer of sediment due to the pipe geometry (circular cross section) as the bed depth is reduced.

A flow diagram for the explained methodology is provided in Figure 6-14.

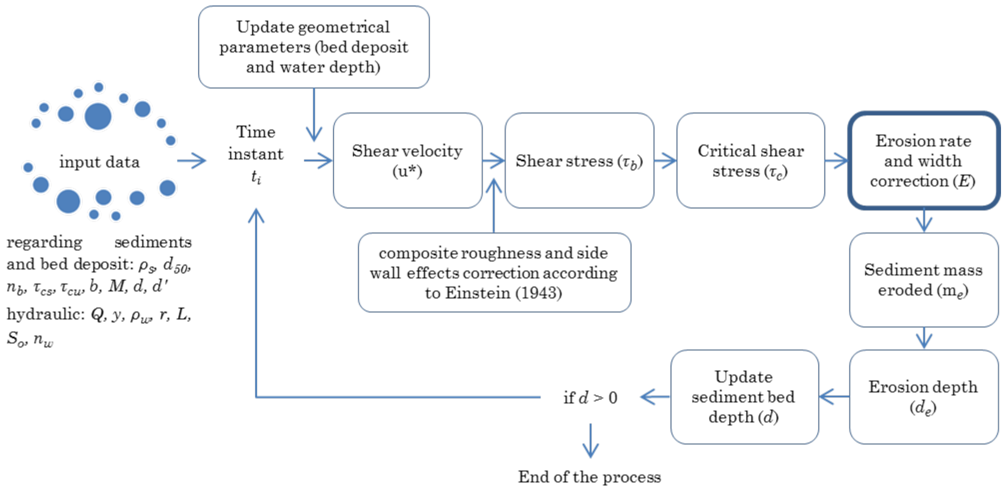


Figure 6-14. Schematic overview of the methodology for the application of the transport method by Skipworth(1996) to a single pipe.

6.3.2.1 Comparison of results obtained for the single pipe case using original Skipworth parameters and locally assessed parameters

Values of the parameters M, b, τ_{cs}, τ_{cu} and d' previously estimated were applied in the transport model.

The predicted erosion rates resulting from the application of the new assessed parameters and sediment characteristics for the high organic particles here analysed in the model were compared with the simulated results by applying the original parameters. Figure 6-15 shows the comparison that also includes the experimental measured values suspended sediment erosion rates by Skipworth (1996). The flow hydrograph used in the test is also shown in the figure.

As expected, differences in the sediment bed properties influence on the sediment erosion rate. It can be seen from the results of the simulation considering the properties of new sediment that erosion rates are greater than those simulated (or experimental measured) for olivestone material, and the difference seems higher as greater the applied flow. It is suggested that these results are influenced by the lowest density of the organic sediments and differences in the structure of the deposited bed.

It can also be observed from the graphs that the rising limb of the hydrograph is the period of the simulated storm where re-suspension of sediments from the bed is the highest. The erosion rate is declining as the flow becomes steady.

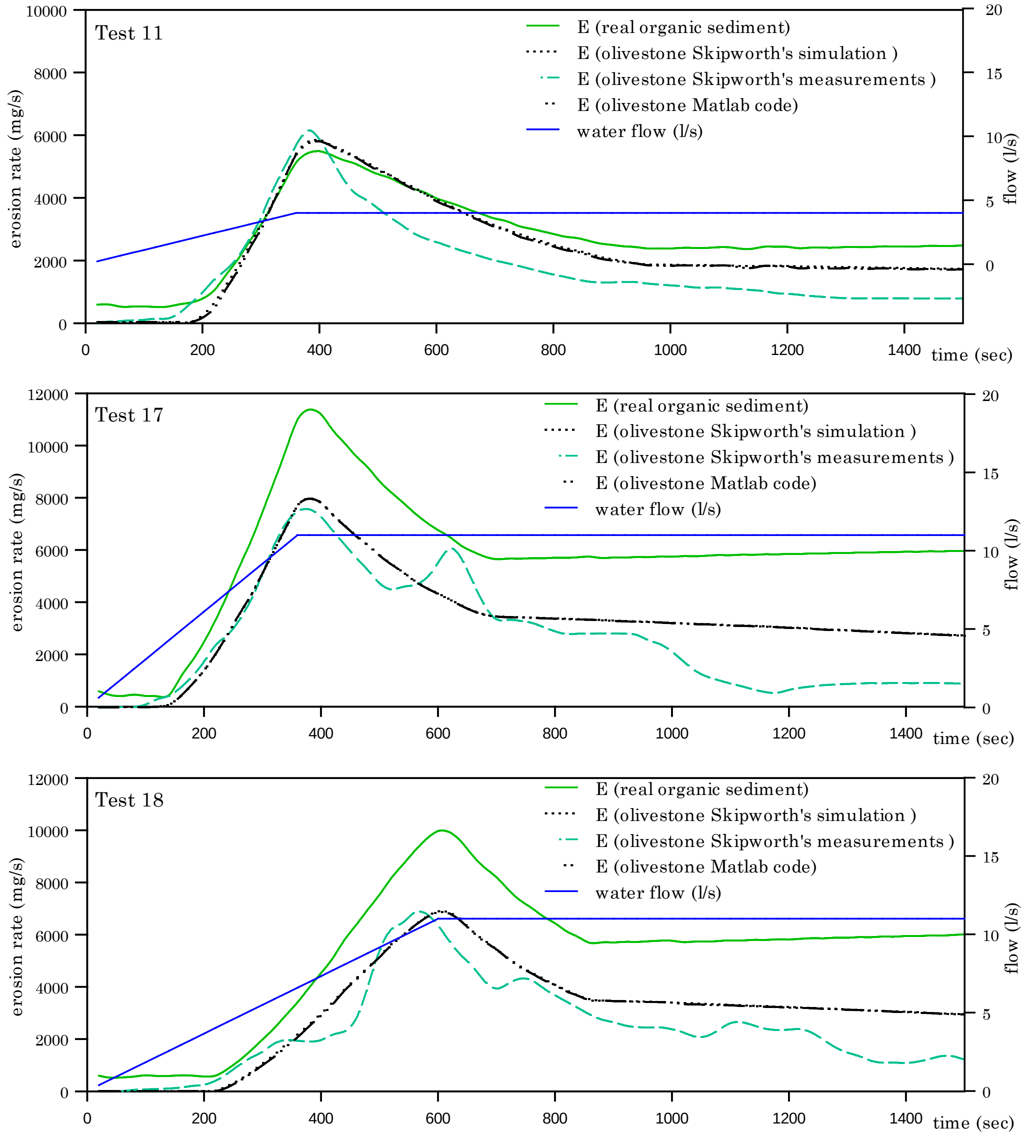


Figure 6-15 Observed and simulated transport rate profile for test T11, T17 and T18 from Skipworth (1996). Comparison with application of the model with organic sediment.

6.3.3 Validation of performance of Skipworth (1996) method in a combined sewer system

The goodness of the fitting will depend on the applicability of the relationship to the conditions in the evaluated site, on the assessment of adequate values for the parameters and on the performing of an adequate calibration process. The wide range of variation in the nature and behaviour of the sediment deposited, the highly variability in the hydraulic conditions and the complexities of the processes occurring in-sewer makes essential a calibration process and validation against locally measured data.

The hydrodynamic results obtained from SWMM5 for each five analysed events (Table 6-2) were coupled with a simplified network module based on a transport concept between adjacent pipes previously developed by Schellart (Schellart *et al.*, 2008).

The network model is generated for the combined sewer system mesh and allows the consideration of the conveyance of sediments through the network. The module includes the sediment erosion relationship of Skipworth (1996) but using the values found for the parameters for the analysed highly-organic sediments. In this way, the approach was applied to the mentioned case of study in Granollers, Spain.

The model outputs were compared with the five measured rainfall events previously mentioned in Table 6-2, for which flow data and samples were collected at the outlet pipe of the network and analysed for *TSS*.

Through the analysis of the shadow error curves at Figure 6-10, it was suggested that from around 24 hours of consolidation period the resistance against erosion remains almost invariable. Based on that finding, the pair of values of the sediment transport parameters *b* and *M* used in the model are those obtained as an average calculation from the assessed experimental values found for the tests with dry-period higher than 24 hours (what means tests with dry-periods 27, 40 and 64 hours). A linear relationship (equation 6-9 and Figure 6-16) was implemented for the evaluation of the *M*-parameter for each applied shear stress (τ_b) during the simulation, valid for values of τ_b higher than 0.40 N/m², before which the value of *M* is constant and equal to 0.05.

$$M = 0.725.\tau_b - 0.0487 \quad ; \tau_b > 0.40\ N/m^2 \qquad 6\text{-}9$$

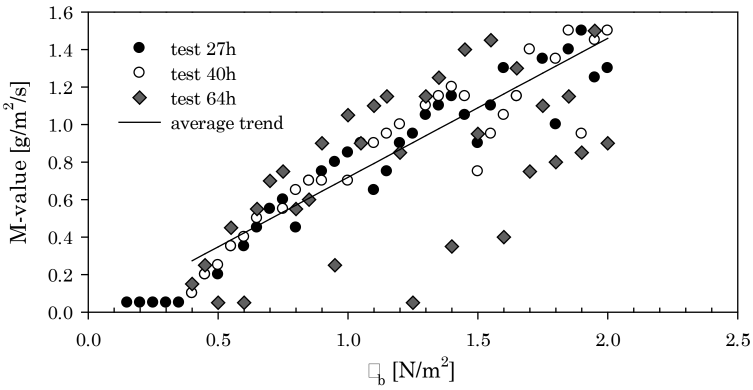


Figure 6-16 M-parameter assessment. Average linear trend of M value (for dry-weather period longer than 24 hours) against applied shear stress.

The initial condition for available sediment bed was established in 5 cm depth of sediment deposit. This depth of sediment in-pipes allows for the analysis of the sediment transport that is not influenced by the availability of sediments.

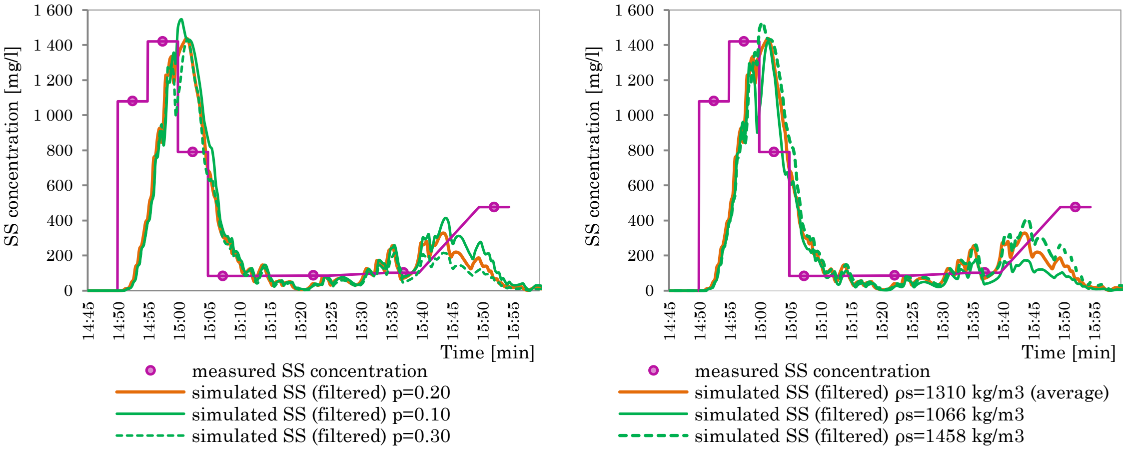
As it was explained before, the selection of the computational time-step affects the simulation results. A time-step of 20 seconds is established based on an average routing time through the network pipes.

6.3.3.1 Sensitivity analysis

In this section, for these parameters that cannot be assessed or measured, the sensitivity of the proposed model to the variations in these parameter values was examined. With that purpose, each parameter was varied around a considered optimum or in the usual range of values obtained from the literature review. The variation in the sediment concentration results were subsequently analysed in terms of the percent peak error (PE) and percent of sediment mass mobilized error.

In this way it was found that the release of sediment is not largely influenced by the porosity of the sediment deposits. Porosity of the sediments (p) was initially assumed as 0.20 despite it was considered a calibration parameter. After a sensitivity analysis changing the porosity value in the range from 0.10 to 0.30 (from literature review FOGs deposits porosity ranging from 0.10 to 0.24 (Keener *et al.*, 2008)), it was found non-significant influence on the sediment transport loads (Figure 6-17 (a)). Less than 8% of variation in sediment concentration peak and around 10% in sediment mass mobilized was verified regarding simulation results obtained with $p = 0.20$.

The effects of changes in the sediment density (ρ_s) in the assessed range of variation for the local sediments (1066 – 1458 kg/m^3; average 1310 kg/m^3) were also analysed (Figure 6-17 (b)). Variation from values calculated with the average sediment density were found between 1.5 to 6.4% regarding maximum sediment concentration, and between 9.4 and 16% regarding total mass of sediment mobilized.

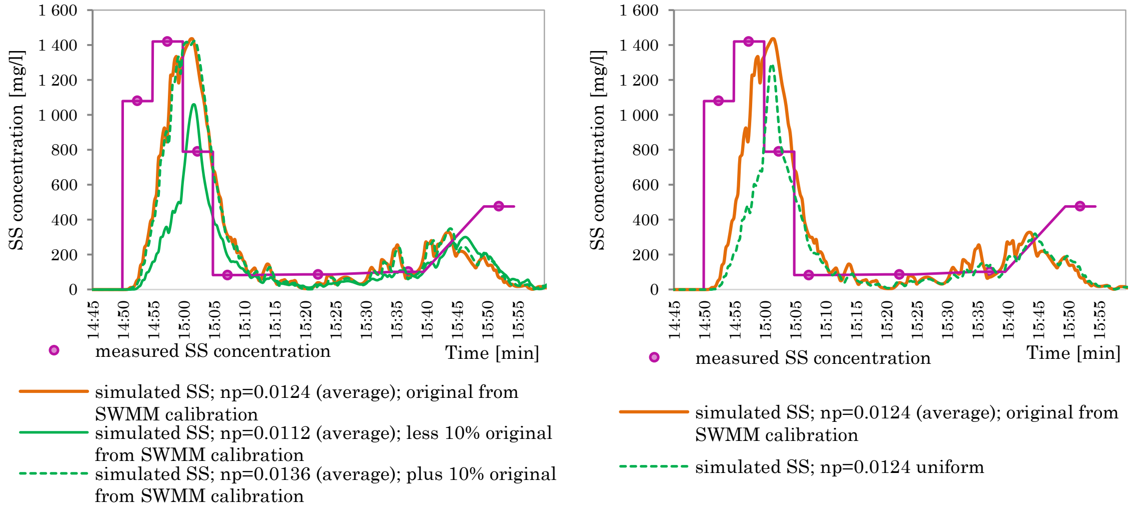


(a) influence of the porosity of sediments

(b) influence of the density of sediments

Figure 6-17 Influence of the variation of characteristic sediment parameters on the evolution of sediment concentration over time.

The highest influence on the sediment transport loads is exerted by the hydraulic conditions. Remobilization of sediments process is directly related to the hydraulic conditions that determine the boundary shear stress values (energy slope linked to the water velocity, roughness and hydraulic radius). Significant variability on the suspended sediment concentration is observed with regards to changes in the Manning roughness coefficient for the pipes shown at Figure 6-18 (a) and (b).



(a) influence of the roughness of the pipes *(b) influence of the roughness of the pipes*

Figure 6-18 Influence of the variation of pipe roughness on the evolution of sediment concentration over time.

6.3.3.2 Model results and performance

The optimization of the parameters involved in the sediment transport model in the present study was based on the minimization of the sum of squared errors (SSE) for the sediment concentration peak, and a minimization in the time at which these peak values are reached. The total mass of sediment was also analysed but cannot be considered limiting for the optimization because the sampling was performed for short periods and do not allow for a reliable calculation of the mobilized mass during the event because the sampling frequency.

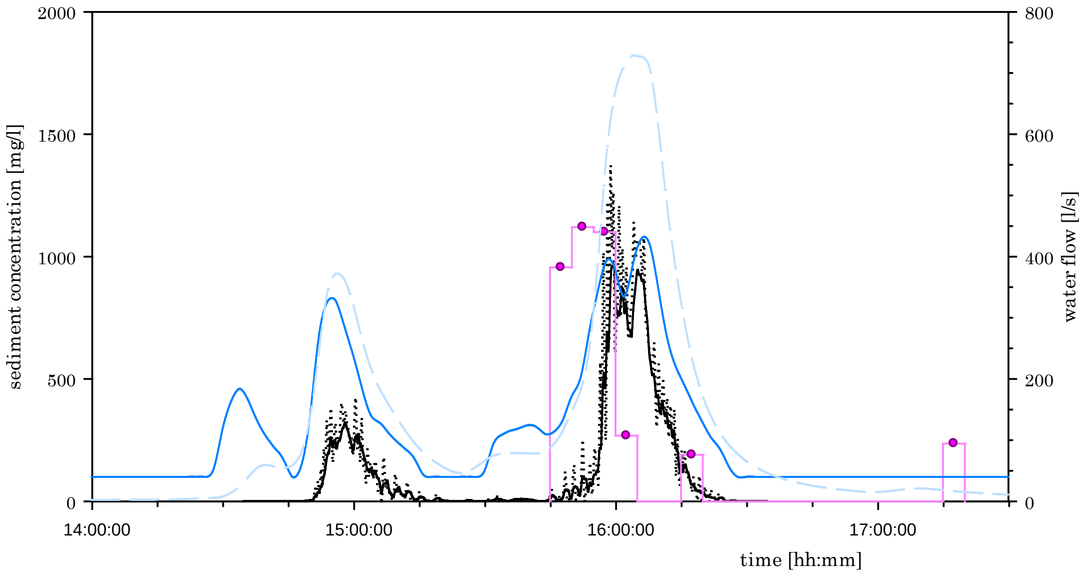
Performance of the sediment transport model application for each event is analysed in the periods for which suspended sediment concentration was measured and shown at Table 6-6. A relatively good fitting is observed analysing the evolution of suspended sediment concentration over time shown in Figure 6-19 and lower adjustment for the events showed in Figure 6-21 to Figure 6-23.

During the 17/09/2010 rain event (Figure 6-19 a), the first phase of runoff arriving to the outlet of the catchment generates an increment in water depth that was lower than the threshold water depth established for the start of the operation of the automatic sampling collection. Thus, the first flush of sediment that can be observed in the modelling results were not covered by the measured data. The error in the total mass of sediment mobilized showed at Table 6-6 for this event was considered only during the same period of sampling.

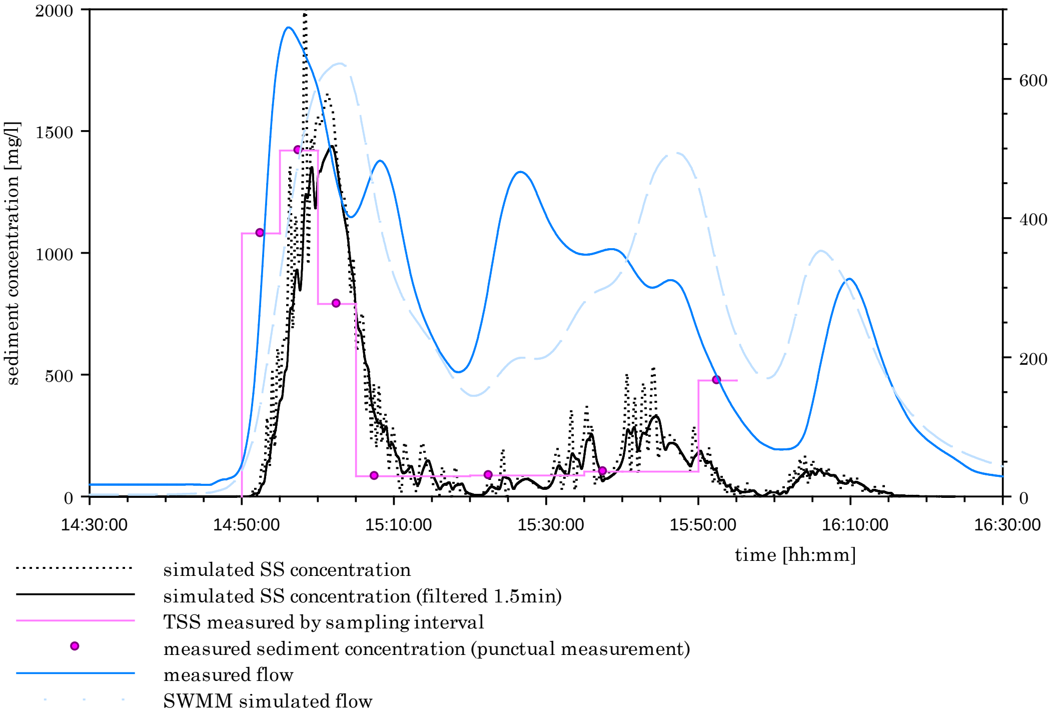
Table 6-6 Performance evaluation results between observed and simulated suspended sediment.

	Rain event 17/09/2010	Rain event 31/05/2011	Rain event 24/10/2011	Rain event 13/07/2011	Rain event 13/11/2011
PE (peak sediment concentration)	- 14.4%	- 1.1%	38.3%	89.1%	86.3%
Total mass of sediment mobilized	-8.1%	18.9%	- 4.0%	83.3%	79.8%

During the 31/05/2011 event, it can be observed at Figure 6-19 (b) that there is a slight delay (4 min) between the sediment concentration peak time measured and simulated. It can be hypothesised that the delay can be related with around the same delay (6 min) observed between the flow peak measured and simulated, despite the initiation time of the simulated and measured water runoff shows a good accuracy.

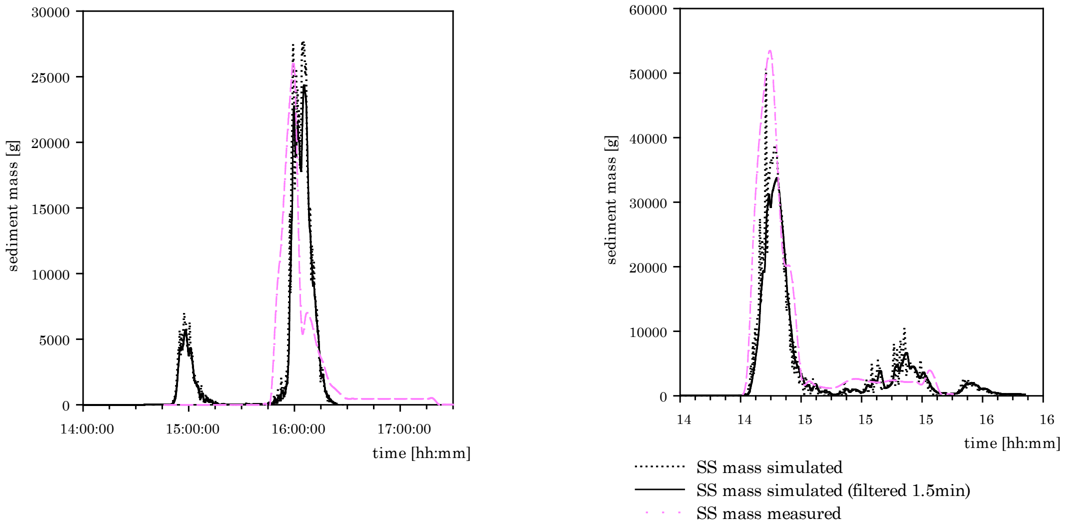


(a) Rain event: 17/Sep/2010



(b) Rain event: 31/May/2011

Figure 6-19 Sediment transport loads. Measured and simulation values based on the relationship of Skipworth (1996) with adapted transport parameters assessed for high organic sediments.



(a) Rain event: 17/Sep/2010 *(b) Rain event: 31/May/2011*

Figure 6-20 Sediment and mass transport evolution over time.

Figure 6-20 shows the evolution of the sediment mass mobilized during the previous analysed events that can be obtained from the sediment concentration evolution simulated with the proposed model and from the measured sediment concentration data from sampling during rainfall. A quite satisfactory adjustment in mass evolution can be observed from these graphs.

It must be noticed that the events of the 17/09/2010 and 31/05/2011 have the higher maximum intensity and total rainfall compared with the other rainfall events available for the analysis of the performance of the model (Table 6-6). These events also showed the highest intensities at the first third of the length of the event.

Poorest performance in the prediction of sediment transport loads was observed for the events of the 24/10/2011 (Figure 6-21), 13/07/2011 (Figure 6-22). Lower total precipitation and lighter storm-intensity for these rain events might influence on the prediction results.

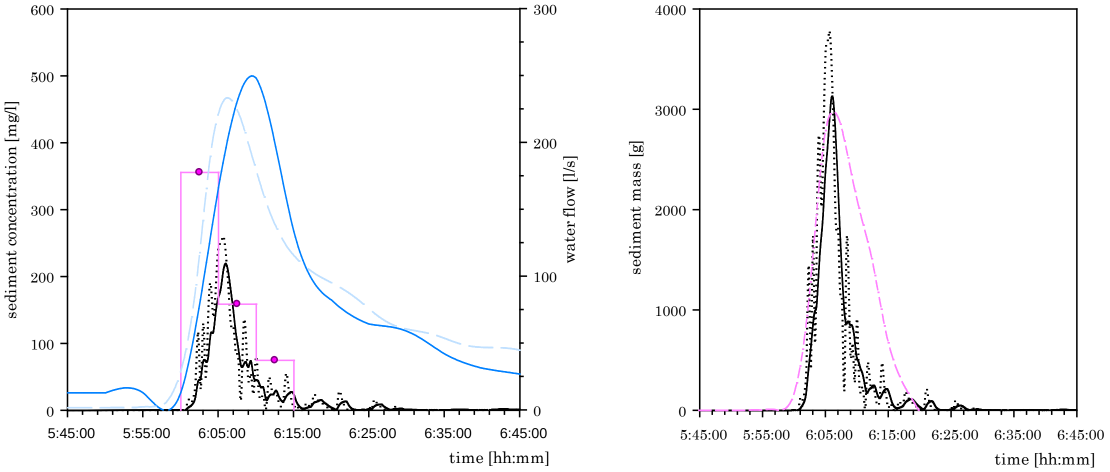


Figure 6-21 Measured and simulated sediment transport loads and mass transport evolution over time. Rain event: 24/Oct/2011.

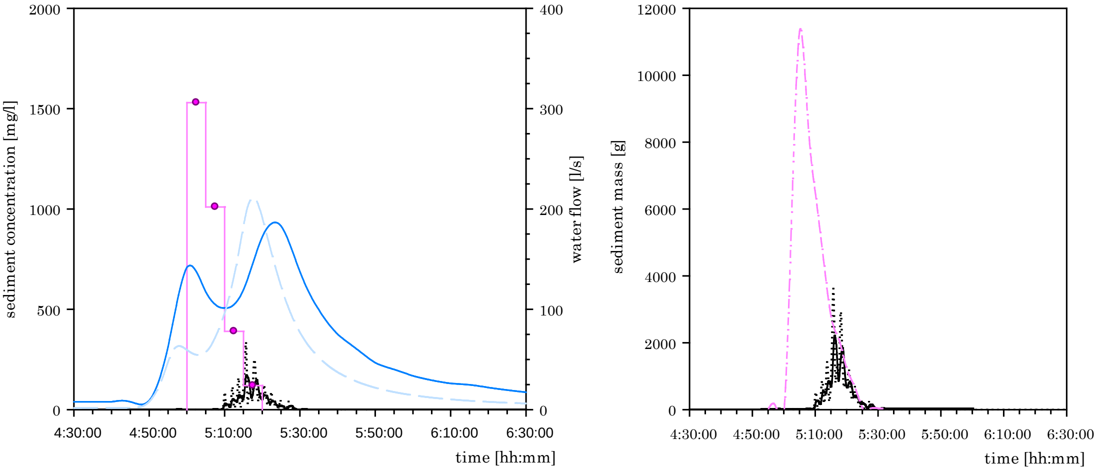


Figure 6-22 Measured and simulated sediment transport loads and mass transport evolution over time. Rain event: 13/July/2011.

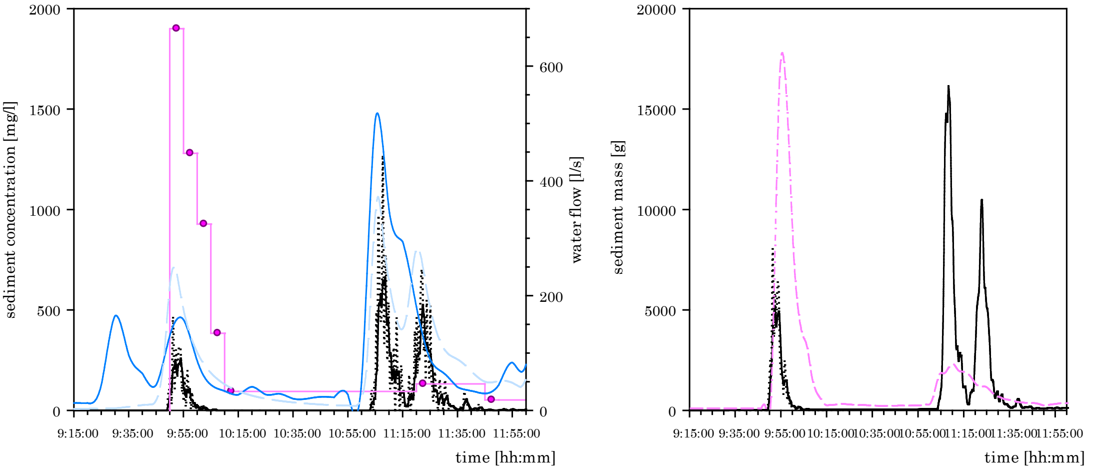


Figure 6-23 Measured and simulated sediment transport loads and mass transport evolution over time. Rain event: 13/Novt/2011.

Difficulties during sampling campaigns in 13/11/2011 and also a more uniform distribution of the rainfall observed during this event might be the related with the differences observed between measured and simulated sediment concentrations (Figure 6-23).

The evolution of the applied and boundary shear stress over time is also analysed for the five events in order to better understand the adjustment of the prediction. In that regard it can be seen from Figure 6-24 that for the events of the 17/09/2010 and 31/05/2011 the applied shear stress (τ_b) observed at the outlet of the analysed sewer system reaches values higher than the critical value of the upper layer (τ_{cu}). Even, the maximum applied shear stress reaches values more than the double of the τ_{cu} value. Meanwhile, analysing events of the 24/10/2011, 13/07/2011 (Figure 6-26), much lower values of applied shear stress are observed. It was suggested that the poorest performance displayed in the sediment transport prediction might be related with the lowest values of applied shear stress reached during light rain events.

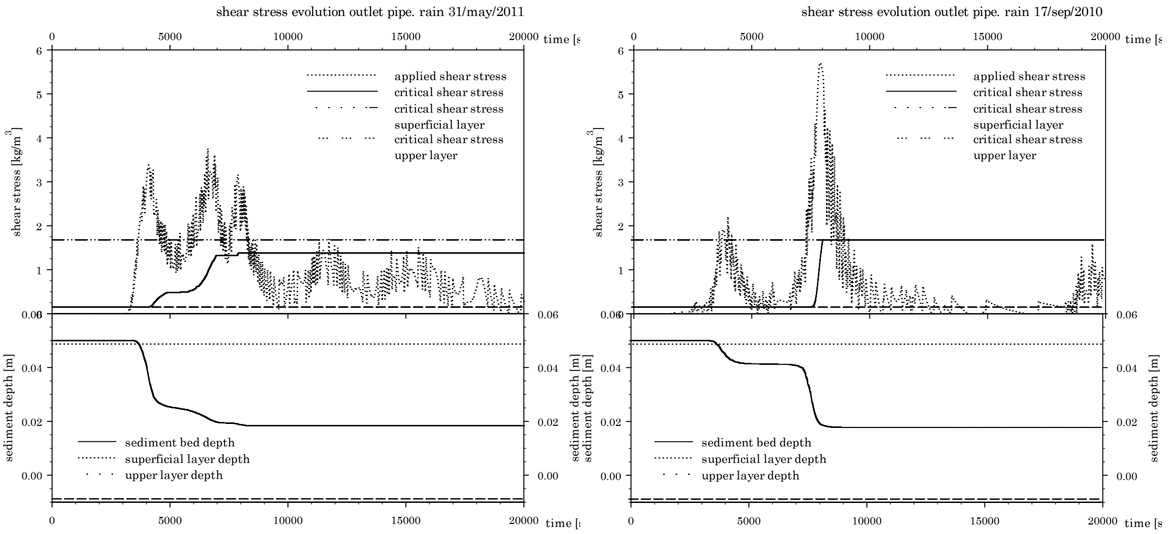


Figure 6-24 Applied and critical bed shear stress evolution and sediment bed depth evolution during erosion process for the 17/09/2010 and 31/05/2011 rain events.

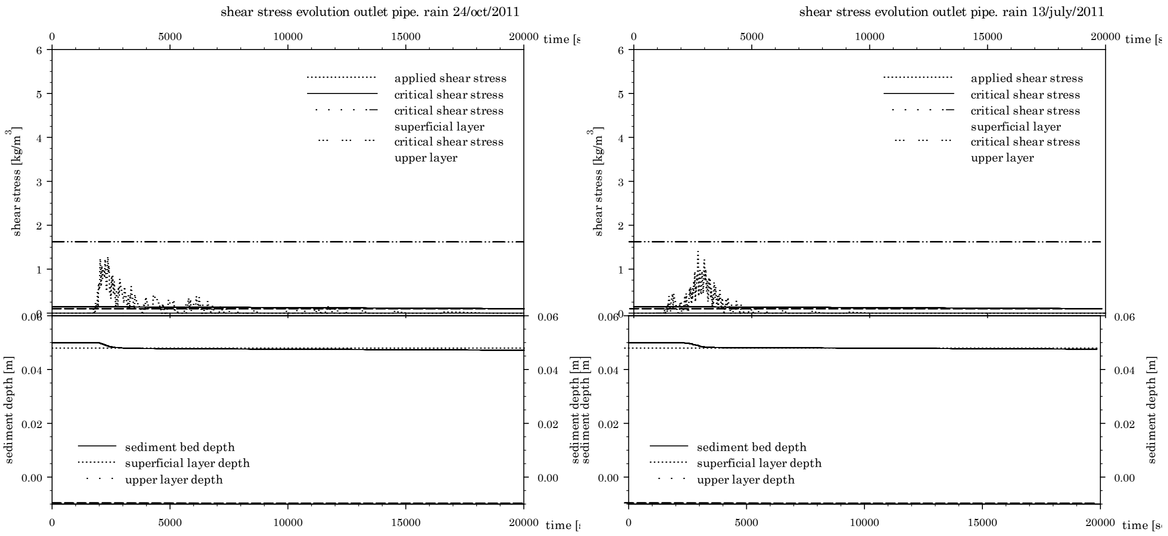


Figure 6-25 Applied and critical bed shear stress evolution and sediment bed depth evolution during erosion process for the 24/10/2011 and 13/07/2011 rain events.

Despite the 13/11/2011 event also displays values of applied shear stress higher than the τ_{cu} value (see Figure 6-26 right side), the samples collection from where the sediment concentration was measured, was during the period which presents shear stress values lower that τ_{cu} which can be observed from the plot on the left in Figure 6-26. Therefore, this would be a similar case to the previous analysed events with low rain intensity.

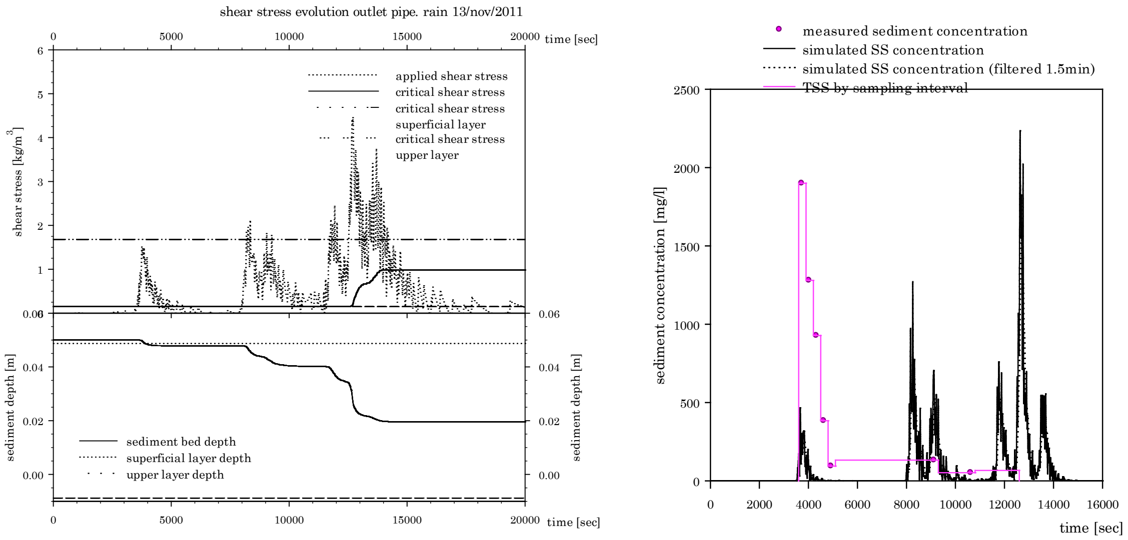


Figure 6-26 Applied and critical bed shear stress and sediment bed depth evolution during erosion process (right side). Sediment transport loads simulated and measured (left side). Rain event: 13/11/2011.

6.3.4 Contribution of wash-off from surfaces to the sediment concentration loads

Despite the measured concentration during rainfall provide information of sediments regardless the sediment source, in analysing the model results in this study, it was hypothesised that the first period of the runoff inside pipes do not account for sediments wash-off form surfaces, and the main source is associated to the re-erosion and mobilization of deposited in-pipe sediments. To confirm this hypothesis, a precise analysis of the contribution of each type of sediment sources that achieves the outlet point at the analysed combined sewer urban system during rainfall runoff is necessary. Nevertheless, in-situ monitoring to assess different sources of pollutants is hard to implement during rainfall.

Research carried out in “Le Marais” in Paris descripted by Ahyerre *et al.* (2001) performed in-situ direct measurements of sediment concentrations through water injection to simulate rainfall flows. This research confirm that the more significant source of organic matter is originated from the eroded sewer sediments deposits, and that the erosion occur since the start of the flushing flows, even at low shear stresses in the order of 0.5 N/m^2. Also from research in Paris (Ahyerre *et al.*, 2000), it was found that the eroded particles become increasingly less organics and denser as the flow increased during the erosion process, which might suggest the mixing with sediment washed from the surfaces as the time goes by.

Regardless the lack of data to calibrate a predictive model that only considers the sediment wash-off from the surfaces of the studied catchment, it is interesting to analyse a possible sediment evolution and their contribution in the total concentration loads. The quality simulation of the sediment loads possibly wash-off from the surfaces of the catchment was implemented in SWMM5 using quality parameters prior assessed for the study case from Chapter 5.

Figure 6-27 shows a comparison between a quality results from SWMM5 simulation that include the consideration of DWF sediment concentrations and sediment washed from surfaces of the catchment. From the observation of the measured concentrations and the results obtained with the transport model presented in this study, it is possible to suggest that the sediments re-suspended and transported from in-sewer deposits comprise the main source of solids arriving to the outlet during the first period of storm. The loads of mobilized sediments from the invert of the pipes are much more significant compared with the washed from the surfaces sediment loads. From the graph it is also observed that the variations in concentration of sediments washed-off is inversely correlated with the flow rate.

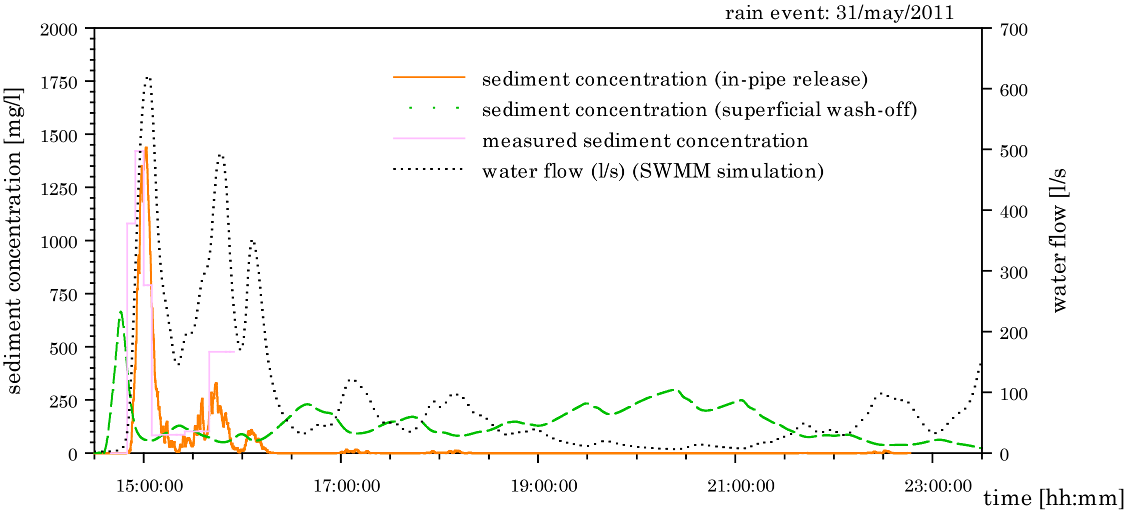


Figure 6-27 Comparison between sediment loads washed-off from surfaces (SWMM5 model simulation), measured data and sediment re-suspended from in-pipe deposits for the rain event of the 31/05/2011 at the outlet of the studied catchment.

6.3.5 Prediction of pollutants attached to solids

As it was mentioned in Chapter 2 (Section 2.2.7), several researchers in the field agreed that reliable "sediment-attached" pollutants loads can be simulated through the assumption of a correlation (potency factors) between them and the suspended sediments.

Potency factors reported in Chapter 3 (Section 3.2.3) were found between the measured data of suspended sediments (*SS*), chemical oxygen demand (*COD*) and total Kjeldahl nitrogen (*TKN*)

A correlation between the measured pollutants parameters and the suspended sediments concentration, simulated by the application of the proposed methodology, was confirmed and presented in the graphs of Figure 6-28 and Figure 6-29. The delay observed in the concentration evolution in the event of the 17/09/2010 in Figure 6-28 is the same observed in the sediment concentration evolution in Figure 6-19 (a).

The potency factor found for the measured events in Chapter 3 for *COD* loads, as a mean value (*COD* = 1.23 *SS*) for all the measured events, was readjusted here. The new value of the coefficient is 1.55, which provides a better adjustment in the analysed events. The potency factor regarding TKN correlation is maintained the same as from measured loads findings (*TKN* = 0.013 *SS*).

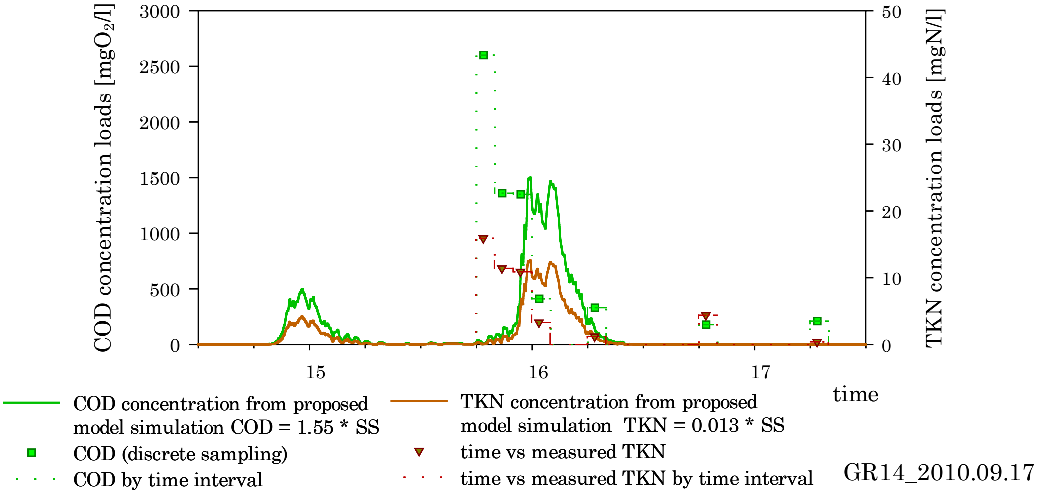


Figure 6-28 Comparison between measured and simulated COD concentration loads. Rain event: 17/Sep/2010.

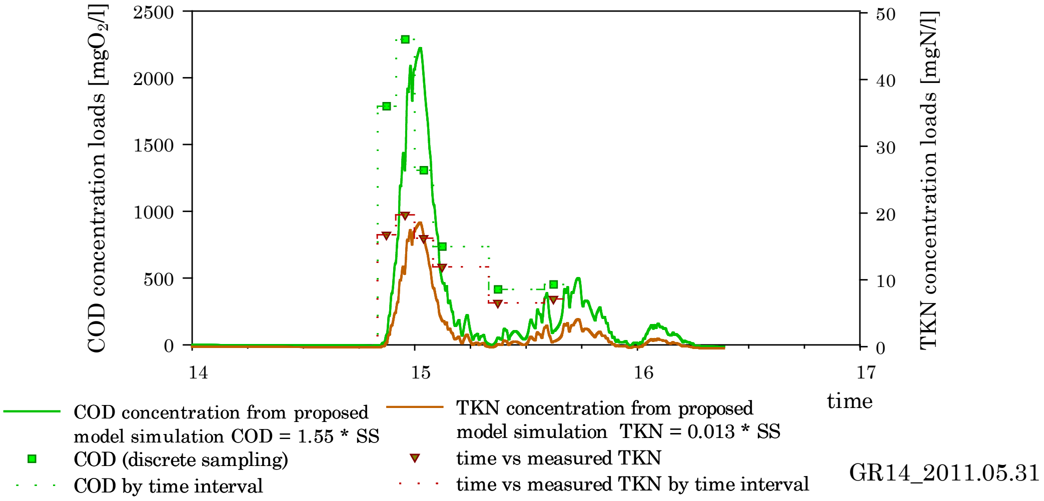


Figure 6-29 Comparison between measured and simulated TKN concentration loads. Rain event: 31/May/2011.

6.4 Conclusions

The available sediment transport relationships for cohesive particles considers, in general, oversimplifications of the process occurring in-pipes with a high level of uncertainties (Freni *et al.*, 2008; Schellart *et al.*, 2010; Mannina *et al.*, 2012). Physical and biochemical characteristics of the sediments must be known and its behavior considered in an attempt to improve the prediction of sewer sediment transport loads using quality models.

6.4.1 Transport parameters assessment

Erosion test were previously carried out using an erosionmeter device and real high organic sewer sediments. The values of the parameters involved in the Skipworth method (1996) were estimated from these laboratory results. The determination of the model parameters using real sediment allows the improvement in the assessment of the erosion rates of sediment obtained by applying the Skipworth method.

Based on laboratory findings, it can be confirmed that the critical shear stress values linked to the sediment bed depth and hence the values of the parameters d', τ_{cs}, τ_{cu}, b and M depend mainly on the characteristic of the sediment and on the structure of the bed deposited in-pipe.

From the analysis of the results obtained regarding parameters performance it can be suggested that the variation of the parameter M might be dependent on the mean particle size of the sediments that had been eroded under the application of a specific shear stress. The range of values adopted by b and M parameters might be also dependent on the density of the sediment bed eroded. The obtained model parameters showed in Table 6-5, are in the range of the values suggested for the synthetic sediment tested by Skipworth (1996).

Additionally, Skipworth suggested the existence of a weak upper layer where the resistant erosional strength is increasing in the depth of the bed. Results on the assessment of the critical shear stress through the erosion tests can also allow to confirm the hypothesis that the boundary shear stress increases in depth of the deposit, and that as longer the dry period, the higher resistance to erosion. A power trend was found in this work as a better description of the variation of the erosional resistance against depth of the deposit.

Furthermore, the obtained values in the present work for the critical shear stress τ_c, varying from 0.15 up to 1.4 N/m^2 (depending on the consolidation period for a deposit of 30mm depth), are in the range found from previous in-situ and laboratory work with real sewer sediments reported by Mclhatton *et al.* (2005) and Oms *et al.* (2008) who registered values in the range between 0.15 and 0.85 N/m^2.

It is also possible to suggest from the results obtained from erosion tests, that the behaviour of a sediment deposit subject to consolidation for up to around 24 hours shown a marked increasing resistance against erosion, meanwhile when the period of consolidation exceeds the 24 hours; the increment in resistance becomes increasingly slower (see results showed in Figure 6-10).

Although the validation of a pattern of release for high organic sediment deposits where biological consolidation might take place can be made based on the results presented here, further effort is needed aimed to identify a more direct relation between the parameter *b* and *M* with the sediment characteristics regarding consolidation period length. Also, it might be possible to find a relationship between sediment characteristics like d_{50} and density, more easy to experimental assess, will allow a more general application of the Skipworth formula for the prediction of the release of cohesive sediments.

It is necessary to consider additional difficulties with regards to the collection of samples from real sewerage that might influence on the parameters assessment. The high temporal and spatial variability regarding sediment distribution in the system might introduce a high level of uncertainties in the parameters values. The difficulties in performing laboratory analysis with real sediment to understand their behaviour together with the difficulties in sampling means that the determination of the parameters involved in water quality models becomes complex.

Because the site-specific sewer sediment characteristics the values adopted for the parameters that are involved in the transport model, must be locally determined prior the application of the model. The performing of erosion tests gives the possibility to assess the range of values of the transport parameters for a more realistic prediction of the transport loads of cohesive particles.

6.4.2 Sediment transport modelling application

For the case of study located in Granollers, Spain, it was verified that the initial conditions regarding sediment bed properties and hydraulic parameters are relevant in the prediction of suspended sediment loads released and mobilized from in-sewer pipes during rainfall runoff. Although the significance on the good evaluation of the critical shear stress of the sediment deposit, the difficulties in the *in-situ* determination and the variability of the time and space characteristics of the sediment deposits increase the difficulties in establishing the inputs and the initial conditions for modelling. Thus, field work studies for the assessment of local sediment characteristics and conditions are strongly recommended when the development of predictive models for a particular sewer system arises.

The results obtained show in general a considerable good performance in the predictive capacity of the selected sediment transport model. Despite that the short term variations predicted by the model (linked to the hydraulic variations) could not be appreciated from the measured data. It is conclude that the Skipworth model is adequate to be applied when the values of the transport parameters can be effectively assessed considering the local sediment characteristics. Nevertheless, calibration by the use of locally measured data is still crucial.

With the model, and the appropriate relationships, it is also possible to assess the evolution of other pollutants parameters by using the correlation factors found from in situ measurements.

Despite the limited data available for validation of the methodology, it can be suggested that the sediment modelling might be dependent on the storm total precipitation and intensity. The performance in the prediction of the sediment loads released from in-sewer deposits conveyed through the network is clearly better for intense storm events. The best performance of the predictive methodology was found for events with maximum rain intensity higher than 30 mm/h, for which shear stress linked to the water fluxes reaches values higher than the critical value of the upper layer (τ_{cu}). Relative low efficiency in the prediction results was evidenced during light intensity rain events.

The analysis of the simulation results leads to conclude that the initially adopted frequency for sampling (5 minutes interval at the beginning of the storm and greater as the rainfall time progress) seems too long when dealing with highly variable sediment evolution. The differences between the measured sediment concentration frequency and the time variability in the simulated sediment loads highlight the need of more detailed measured frequency in future works. More frequent measurement intervals at the start of the storm event might lead to better adjustment in quality modelling.

Additional difficulties in the correlation between measured and simulated sediment concentration might be linked with the sampling period (period needed for the automatic sampler for pumping the water samples to the container). The values of the sediment concentration assessed from the collected samples correspond to the average concentration of sediment in water during the pumping period, which add uncertainties in the prediction of the sediment concentration measured.

Many uncertainties are involved in the validation of the sediment transport mobilization method. Not just regarding errors in the measurement of the rainfall data, flow and the assessment of the sediment concentration, but also because the stochasticity in both time and space of all these parameters. The adequacy of the frequency at which these parameters are measured, and the perfect temporal synchrony that should be in all records, also influences on the results obtained. Even the definition of the physical parameters of the sewer system and catchments might add uncertainties in the sediment transport prediction because the high dependence on the hydraulic conditions. But maybe, the greatest uncertainty is introduce because the lack of knowledge on the biochemical processes and interactions between particles that produce transformations in the sediment deposits that are hardly difficult to consider in a model. Thus, no matter how complicate is the predictive model adopted, the improvements in the accuracy of the modelled results in terms of quality is hardly difficult to obtain. In this sense, locally measured data for calibration of the approach is relevant when any prediction study of water quality in sewers arises.

6.5 Summary

Modelling processes has become during the last decades an essential method for the prediction of the behaviour of a sewer system. Nevertheless the application of sediment transport models requires the prior extensive knowledge of the system and of the characteristics of the sediment particles involved, and is hardly difficult to achieve a fully detailed model that can also consider the transformation and interaction processes between particles. It is thus necessary to firstly improve the knowledge on the sediment behaviour to better represent them in a model and deal more efficiently with the processes involved during consolidation, release and mobilization.

The main objective proposed in the herein chapter is to validate the ability of the sediment transport model developed by Skipworth to estimate the release and transport when dealing with highly organic sediment deposits.

Once the transport parameters were assessed based on the characteristics of the sediments, in order to reach the objective, the validation of the method was proposed through the implementation of the sediment transport model coupled with a network module coded in MATLAB®. The physical model developed for the combined sewer system of the catchment linked to the mathematical approach proposed by Skipworth for the sediment remobilization, allows to simulate the movement of sediment through the system applied in a small urban catchment from where water quantity and quality data is available. Sedimentation process in the transport model is avoided. The hydraulic data for the analysed rain events was obtained from the catchment model in SWMM5.

Results shown that the Skipworth's model with the adapted parameters for high organic sediments has the ability to predict with good performance the sediment loads released from in-sewer deposits conveyed through the network for intense storm events. The best performance of the predictive methodology was found for events with maximum rain intensity higher than 30 mm/h, for which shear stress linked to the water fluxes reaches values higher to the critical value of the upper layer (τ_{cu}). Poorest performance was experimented with light intensity rain events.

The parameters adjustment by laboratory experimentation allows a more appropriate representation of the movement of solids in sewerage by considering a more realistic behaviour when dealing with non-homogeneous high-organic sediments. By means of the setting of the suitable initial conditions for the modelling it is possible to more adequately represent the processes occurring prior and during the release and mobilization of sediments.

Despite the limited data available for validation (field work studies are expensive not just in terms of resources, also in considering the difficulties in performing the data collection and analysis), results obtained confirm that the methodology accurately predict the cohesive high organic sediment transport rate under intense rain events conditions.

Improvements in the prediction of pollutant loads over time that can reach watercourses through urban overflow discharges become important for the receiving waters protection.

Bibliography of the chapter

Ahyerre, M., Chebbo, G., Saad, M., 2000. Sources and erosion of organic solids in a combined sewer. Urban Water **2** (4), 305–315, DOI:10.1016/S1462-0758(01)00012-7.

Ahyerre, M., Oms, C., Chebbo, G., 2001. The erosion of organic solids in combined sewers. Water Science & Technology **43** (5), 95–102.

Keener, K.M., Ducoste, J.J., Holt, L.M., 2008. Properties Influencing Fat, Oil, and Grease Deposit Formation. Water Environment Research **80** (12), 2241–2246, DOI:10.2175/193864708X267441.

McIlhatton, T.D., Ashley, R.M., Tait, S.J., 2005. Improved formulations for rapid erosion of diverse solids in combined sewers. Water Science & Technology **52** (5), 143–150.

Oms, C., Gromaire-Mertz, M.C., Saad, M., Milisic, V., Chebbo, G., 2008. Bed shear stress evaluation in combined sewers. Urban Water Journal **5** (3), 219–229, DOI:10.1080/15730620801924010.

Parchure, T.M., Mehta, A.J., 1985. Erosion of soft cohesive sediment deposit. Journal of Hydraulic Engineering **111** (10), 1308–1326, DOI:http://dx.doi.org/10.1061/(ASCE)0733-9429(1985)111:10(1308).

Rushforth, P.J., 2001. *The erosion and tranpsort of sewer sediment mixtures*. PhD thesis.Department of Civil and Structural Engineering. University of Sheffield. UK.

Schellart, A.N.A., Buijs, F.A., Tait, S.J., Ashley, R.M., 2008. Estimation of uncertainty in long term combined sewer sediment behaviour predictions, a UK case study. Water science and technology **57** (9), 1405–11, DOI:10.2166/wst.2008.299.

Seco, I., Gómez-Valentín, M., Schellart, A.N.A., Tait, S.J., 2014. Erosion resistance and behaviour of highly organic in-sewer sediment. Water Science & Technology **69** (3), 672–679, DOI:10.2166/wst.2013.761.

Skipworth, P.J., 1996. *The erosion and transport of cohesive-like sediment beds in sewers*. PhD Thesis.Department of Civil Engineering. University of Sheffield. U.K.

Chapter 7

Conclusions and Future work

The aim proposed for this project was described as developing a method for predicting the potential transport of organic sediment that can be applied in combined sewer system in the Mediterranean region. Thus, an overall objective of improving the awareness and quantification of the pollutant problem during CSOs was pursued. After the early analysis, the transport prediction was emphasized on the need for better understanding of the influence of the particularities of the sediments found in deposits within networks, which directly affect the transport predictions.

The developing of this dissertation intended to follow the stages to achieve the stated goals. A detailed account of what has been achieved was described at the conclusions of each chapter.

Firstly in this Chapter (Section 7.1), an overview of the research accomplished and the main findings is presented with a brief discussion on the applicability of sediment transport formulations. Then the following sections will summarize the main findings of each stage in the research.

At the end, many questions remain however without an answer. Pursuing the goals even has raised new questions. The future issues of research arising from this work are presented in Section 7.4.

7.1 Overview of the research accomplished and general conclusions

The research started with the selection of a study catchment in the area of the Mediterranean region: Significant pollution problems related with the overflows from CSOs mainly during storm events were evidenced in these watercourses. The project follows with the implementation of a monitoring programme in the catchment accomplishing a first analysis of the pollutants loads evolution. The knowledge gained in this phase of the field work and the literature review form the basis for the proposal of a simplified conceptual model implemented in SWMM5. The insufficient accuracy in the predictions obtained led to the search of new alternatives for the prediction.

An experimental work for the assessment of the sediment characteristics was subsequently planned for the better understanding of the properties and behaviour of the real sediments from combined sewer systems. The knowledge acquired allowed for the implementation of predictive formulas specifically developed for sewer cohesive particles.

A coupled model is designed and implemented, which integrate the hydrodynamics of the combined sewer system with the quality erosion and transport model. The quality module, by introducing the experimentally assessed sediment deposit parameters, considers a more realistic behaviour and the properties of the real organic sediments. Therefore, the implemented methodology is capable to more appropriately represent the variables that affect the entrainment of highly organic solids with cohesive behaviour.

A detailed model of the studied catchment that takes into account the hydrodynamics of the system was implemented for a final verification of the performance of the transport formulation. By applying the coupled model, a more accurately prediction of the mobilization and changes in sediment concentrations that can reach a watercourse by urban drainage overflow discharges was achieved for the test case.

As main conclusions are highlighted:

- the prediction of organic sediment mobilization and transport is complex but possible to accomplish
- the availability of consistent and detailed field data is one of the key factors in the achievement of reliable predictions. Nevertheless data acquisition, still limited, is one of the weaknesses in many quality projects

The field data collection requires intensive work and besides is expensive in terms of resources. However, the acquisition of quality data is essential in the calibration of these models and consequently, in the reliability of the results obtained.

Detailed quality data is required for the characterization of the sediment but besides for the hydrodynamics of the combined sewer systems, which significantly influences on the sediment and pollutants incipient motion. The more detailed the hydrodynamic information of the system is, the better sediment entrainment and mobilization prediction will be.

A general outline of the key factors that significantly influence on the results that can be obtained from the modelling predictions is represented in Figure 7-1.

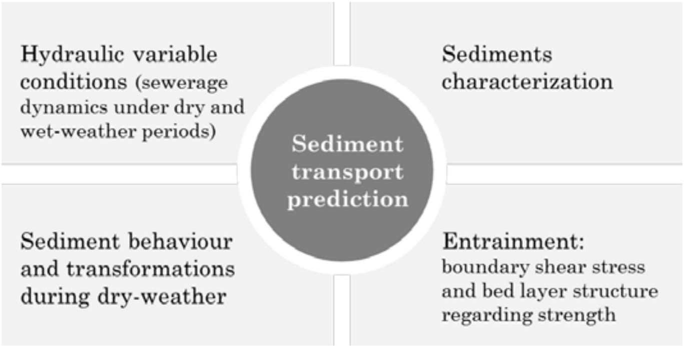


Figure 7-1 Broad outline of the key factors that affect the modelling prediction on sediment transport.

Despite all the work made and improvements in the field in this last two decades, when dealing with cohesive and organic sediments, there is still a clear lack in the knowledge and in the understanding of all the processes that control the sediment transformations that influence on the beds mobilization. Nowadays, the main problems in modelling are in representing the physical and biochemical processes involved in the stage of formation and storage of the sediment bed, which influence on the erosional resistance. The results of the experimental work in this research attempts to bring some clarity in that regard.

7.2 Comments on the sediment transport formulations

From the literature review, it was seen that several conceptual and mathematical models have been formulated intended to predict the in-pipe sediment erosion and transport. All of them have been probed / validated for a given data set and have a range of potential applicability. However, up to date the methods are still unable to a widespread application and are mainly sediment properties-dependents. The highly variable nature and distribution of the sediment in the system (spatially and temporally), increase the difficulties in a general applicability of the predictions.

As it was highlighted along this dissertation, in highly impervious and densely populated urbanized catchments like the analysed in the study site, the solids found were predominantly organics (with cohesive-like behaviour) product of the deposition of wastewater solids as main source. Nevertheless, coarse particles can be deposited in different sections of the same network. Coarse particles in urban sewerage are linked to the nearby existence of natural catchments (in the boundaries of the town), pervious areas or construction sites, this last as temporal source. Therefore, in the same system it could be found deposits with different sediment characteristics.

So then, which model / relationship is the best for predicting sediment transport in combined sewer systems? Might be the relationships for coarse sediment from rivers useful in sewerage? To answer these questions require focus on the characteristics of the sediments in the system. The best applicable formula will depend on the type of sediments found in the catchment.

In the selection of the method is indispensable a prior characterization of the sediment from the sewer system that is being analysed. Thus, an objectively selection of the more adequate formulation will be based on the range of the potential applicability given for each method.

7.3 Main conclusions

7.3.1 Field work

- The collected data in the catchment was sufficient for the verification of the model proposed in this study but still limited. More rain events (linked to flow rates and pollutant loads) are needed to be measured for improvements in modelling.
- The quantity and quality of the data acquisition is significant in the calibration of the predictive quality models. Measuring rainfall intensities, water levels / velocities, flow rates, pollutant loads as well as collecting sediment samples or measuring deposits depths in sewerage should be seen by operators as tools for enhance the knowledge and the management of the systems.

7.3.2 Laboratory studies on the sediment characteristics, behaviour and erosion resistance

- The physical properties and composition of the sediments collected from the sewer deposits was sufficiently characterized for the study purpose (density, size distribution, organic and gravimetric moisture content). Future field work might be needed to increase the number of samples to analyse possible temporal or spatial variations.
- Variations in the sediments properties suggest variations on the erosional resistance of the organic sediment deposits. Based on previous research findings compared against the results obtained in this research, the variation in the sediment properties (density and organic content) might also affect the resistance to erosion.
- The erodibility of organic sediments deposits is affected by the interaction of several transformation processes (physical, chemical and biological processes).
- The erodibility of organic sediments deposits is significant influenced by the environmental conditions at which sediments deposits were formed and storage in the pipes. It was suggested that environmental conditions might generate changes in the structure of the deposit (bonding forces between particles) and also in the nature of the sediments (biological changes).
- Tests were done to evaluate the influence of the oxygen availability. Significantly higher shear stress is needed to mobilize deposits subjected to environment with oxygen available compared with sediment beds analysed to erosion without oxygen supply.
- Results on the influence of the length of the dry-period suggested that increasing periods leads to increasing strengths of the deposits. Despite this, from around 24

hours of consolidation period, the increment in the resistance against erosion of the sediment bed is quite slow.

- The proposed structure of the sediment bed with increasing strength in the resistance to erosion with depth was experimentally verified.
- It was observed that high organic sediment deposits display lower shear strength against erosion with respect to the boundary shear stresses displayed by inorganic deposits.
- Despite the strength of the deposit increase in depth, the relative low values observed in the shear stress of organic sediment deposits suggest that the nature of these sediments may be one of the causes of the strong *first flush* of suspended sediments observed at the beginning of storm events.
- The organic nature of sediments is relevant, and the biological reactions should be considered in the analysis of the erodibility of sediment deposits since it clearly has influence on the erosional behaviour.
- The standardization of same of the laboratory techniques for the analysis of organic sediments from sewers is needed. Consistent definition of the temperature and time for drying the samples during *TSS* analysis is required in order to compare results with other tests conducted in different laboratories.
- Results obtained from the erosion tests performed allow for the assessment of erosion parameters that are later applied in the sediment transport methodology. Standardization of the erosion test methodology is also suggested as a way to evaluate sediment deposited in sewerage systems.

7.3.3 Quality modelling

7.3.3.1 Analogy of pipe-artificial sub-catchment in SWMM5

The conceptual model proposed does not give good results for the sediment transport loads when was applied in the study case. Several explanations may be suggested:

- The use of the formulations available in SWMM5 for wash-off in surfaces can be unsuitable for the mobilization of organic (and low dense) sediment deposits. The wash-off parameters have not a direct correlation with the real physical process. Therefore, because of the lack of physical meaning in the variables that govern the erosion process, the introduction of the effects of the cohesive and organic behaviour of the sediment on the erodibility is not possible with the current wash-off equations available.
- The analogy pipe – artificial sub-catchment need the prior individual calibration of the erosion evolution at each pipe. Information of the evolution of the sediment concentration loads eroded from the deposits is not actually available.
- Modifications in the methodology can be considered for further improvements in the prediction. The adaptation of the SWMM5 code to allow the inclusion of alternative sediment transport equations that perform better for cohesive sediments or of a user-defined function for wash-off process is suggested. Both possibilities are thought that can improve the better representation of the erosion process of organic sediments (low density and the influence of the organic behaviour).

7.3.3.2 Coupled model application (hydraulic and sediment deposit erosion-transport model)

- Results shown in general a good performance in the prediction capacity of the sediment transport model of Skipworth developed for cohesive-like sediment for sewerage. The assessment of the local transport parameters is indispensable for the good performance of the model.
- The sediment transport model performs well with the higher rain intensities. It was suggested a dependency between the performance of the model and the rain intensity nevertheless, more data is needed for verify the relation.
- The success in the results from the sediment release and transport applied in the study case are directly related with the use of local data, both for the sediment characterization (and parameters assessment), as well as for the hydraulic and quality evolution that was measured in the real studied combined sewer system. The analysis of local sediment characteristics as well as quantity and quality measures in the analysed catchment is essential in any water quality study.
- With the presented model it is possible to predict the sediment mass evolution (and concentration) at any pipe outlet of the network despite that the results in this dissertation were solely showed at the outlet (where measured data was collected).
- Once the model adequately predicts the sediment transport from in-pipe deposits, it is feasible to model the evolution of solid-attached pollutants by the use of correlation factors experimentally assessed.
- The hydraulic variability on the mobilization of the sediments has a relevant influence. Therefore, the linking between the hydrodynamic results from SWMM5 and the sediment transport model shows a clear advantage in the final results.
- The hydrodynamic results from SWMM5 (one-dimensional model), do not considers the local influence on the flow caused by the singular structures, changes in diameter or slopes that produce 2D or even 3D flow patterns. These might produce additional turbulences in the water flow. The effect of these turbulences might cause locally higher erosion rates or even sedimentation of the particles, which the transport model does not consider.
- The variation on the structure strength of the deposited bed is calculated independently the initial deposit depth conditions, based on a depth-of-erosion concept. Therefore, the transport model performance can be considered independent on the initial conditions of the sediment deposit.
- A current limitation in the applicability of the methodology is related with the calibration of the method made using the data collected in one specific catchment. There may be a local dependence of the assessed values for the erosion / transport parameters. Then, transferability of the applicability of the method into catchment with similar urban and climate patterns is not feasible without a previous verification in a different site.
- Non sedimentation process is considered during the performance of the model during rainfall runoff inside pipes.

7.4 Recommendations

The necessary improvements in the methodology for monitoring and data collection were brought to light during the application of the transport model in the study case. Here below are listed some of the suggested improvements in the performing of measurements for future works in combined sewer systems needed to better adjustments of the sediment transport model results:

- To reduce the sampling frequency during the beginning of the rain event, when the highest variability of *TSS* loads was observed. Sample collection with two minutes interval during the first 30 minutes from the beginning of the runoff is suggested. Turbidity monitoring linked to *TSS* can be implemented instead with a previous field and laboratory works to adequate relate both parameters.
- To improve the rain data and runoff evolution correlation, the raingauge must be located in a closer location to the flow rate control section, preferably inside the borders of the analysed catchment. One minute interval time for both measurements is desirable for small catchments.
- To periodically collect sediment deposits samples. To determine, if exists, temporal patterns of the sediment deposited characteristics.
- To monitor the sediment deposits depth. The knowledge of the sediment depth in—pipes gives the initial conditions for modelling the erosion and transport. Monitoring is desirable in different sections of the network previous to the expected rain events.

Additional recommendations are suggested:

- If feasible, an extra monitoring station in the same analysed catchment would be useful in the adjustment of the performance of both, the hydrodynamic and the quality model.
- The standardization of the laboratory method for the assessment of the erosion of sediments from sewer will allow an easier implementation and will provide the tools for an adequate comparison between results tested in different studies.

7.5 Future research

After the research performed for this dissertation many questions remain open. There are several lines of research arising from this work that can be pursued.

- There is clearly further work to be done on analysing the variability of the sewer sediment properties and on transformation processes inside the network.
- Regarding analysis of the influence of the antecedent conditions on the resistance to erosion, it is suggested:
    - The verifications of the influence of the temperature during consolidation period
    - The performance of tests varying the organic content of the samples and other sediment properties is suggested for the identification of quantifiable relations between the transport parameters and the sediment characteristics.
    - The performance of erosion tests with intermediate dry-period between 16 and 27 hours might allow to confirm the increasing resistance of the bed with time.

  - The use of a closed reactor during the erosion tests (with no renewal of water) might have effect on the biological reactions occurring in the sediment surface of the deposits. Experiments with flushing flows might be tested.
  - The improvement in the knowledge of the influence of the biological transformations.

- Enhancement of the modelling approach:
  - To include mechanisms that takes into account the biological transformation processes in erosion predictive equations.
  - To include of the possible deposition of sediment during runoff should be considered in future improvements of the transport model.
  - To test other sediment transport formulas and extend the methodology to adapt the work to the use of different algorithms.

- On-line modelling for simultaneous calculation of the sediment transport prediction based on the hydraulic changes in the system. The coding of the proposed coupled methodology in SWMM5 will allow an easier application of the method. Exploiting the advantages of the open source for the introduction of the erosion and transport model in SWMM5 will improve the current capacities of the software packages.
- The transferability of the resultants transport coefficients should be tested in other different catchments with similar pattern regarding both the sediment characteristics and the climate conditions (dry-period length and storm intensity).
- The adequacy of the methodology for the application with different sediment characteristics (organic sediment and fine sand mixtures) should be also verified.