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Combined Sewer Overflows: A critical review on best practice and innovative solutions to mitigate impacts on environment and human health

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Abstract

Combined sewer overflows (CSOs) are of major environmental concern for impacted surface waterbodies. In the last decades, major storm events have become increasingly regular in some areas, and meteorological scenarios predict a further rise in their frequency. Consequently, control and treatment of CSOs with respect to best practice examples, innovative treatment solutions and management of sewer systems is an inevitable necessity. As a result, the number of publications concerning quality, quantity and type of treatments has recently increased. This review therefore aims to provide a critical overview on the effects, control and treatment of CSOs in terms of impact on the environment and public health, strict measures addressed by regulations, and the various treatment alternatives including natural and compact treatments. Drawing together the previous studies, an innovative treatment and control guideline is also proposed for the better management practices.

Keywords: Combined sewer overflows; nature based solutions; sewer system; urban water management; water quality

Abbreviations

BFU	Ballasted Flocculation Unit
BOD_5	Biochemical Oxygen Demand
BWD	Bathing Water Directive
COD	Chemical Oxygen Demand
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
CW	Constructed Wetland
EPA	United States Environmental Protection Agency
GAC	Granular Activated Carbon
NBS	Nature based solutions
NPDES	National Pollutant Discharge Elimination System
OCC	Optimum Coagulant Concentrations
PAA	Peracetic Acid
PFA	Performic Acid
RSF	Retention Soil Filter
SSO	Sanitary Sewer Overflow
SUDS	Sustainable Urban Drainage System
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solid
UVT	UV Transmittance
UWWTD	Urban Waste Water Treatment Directive
WFD	Water Framework Directive

WWTP	Wastewater Treatment Plant

1. Introduction

The European Water Framework Directive (WFD, 2000) is the key policy driver in the water sector focusing on management strategies for improving water quality and protection of the receiving bodies from wastewater effluent discharges. It emphasizes the control of diffuse pollution as a major factor in enabling good ecological status in all waterbodies of member states. Wastewater and storm water collection, as well as their management, are crucial services protecting public health and the environment, thus appropriate receiving systems facilitate urban development. Additionally, countries also develop national regulations to sustain environmental protection and to better manage the sewage systems.

In Europe, there are two major system types to collect and transport wastewater: the separate system and combined system and modified versions thereof. In the separate system, the waste water and storm water are transported in two separate pipelines (Figure 1a). The sewage from households and industry is carried to wastewater treatment plants (WWTPs) and the storm water is discharged into the nearest waterbody, usually only with physical pre-treatment. Although runoff from urban surfaces may collect contaminants along the way (such as pathogens, hydrocarbons, grit, sediment, chemicals and heavy metals), this discharge does not generally require an environmental permit and it is usually consented by environmental regulators (Jotte, Raspati, & Azrague, 2017).

In the combined sewer system (CSS), sewage and storm water are carried in one unified sewer network to the centralized WWTP. Under dry weather conditions, the CSS only collects municipal and industrial wastewater, but this is mixed with surface runoff under wet weather conditions.

In modified sewer systems, rainwater is treated according to its pollution: infiltration of minimally contaminated roof runoff, transport of storm water from low trafficked roads, streets and pavements by open drains or the direct use for landscaping purposes is possible.

However, all sewer infrastructure is limited in its capacity for water intake and transport. Usually, CSSs are unable to cope with the flows experienced during heavy rain events, so a relief mechanism is inserted in the wastewater network which is a combined sewer overflow infrastructure. This directs excess flows, comprising a mixture of untreated raw sewage and storm water, to the receiving waterbodies. These structures are used to maintain the flowrates in the network and protect properties from potential flooding (Bailey, Harris, Keedwell, Djordjevic, & Kapelan, 2016).

Up to date, limited information has been published internationally concerning the extent and occurrence of CSOs and discharge points. It is estimated that there are 2.2 million km of existing sewerage systems in Europe, of which approx. 70% of the total network is combined sewers. Moreover, there are approx. 650.000 CSOs and their impact on the receiving waterbody is an increasing concern across Europe (EurEau, 2016). Some information can be obtained from reports submitted to the European Union by member states. E.g. in 2012, Germany submitted a request to extend the deadline of fulfilling the goals of the Water Framework Directive (reaching a “good” ecological and chemical status of 80% of surface waterbodies by 2015) until 2027. In a summary of the 2012 report to the European Commission (BMU, 2013), the authors describe that 10% of the key measures required reach the good status pertain to sewer systems and municipal wastewater treatment plants. From the total number of these key measures mentioned in the report, approximately 28% of them concern storm water in combined and separate sewer systems and only 12% of them has a connection to the sewer system in general (UBA, 2012). Since this report does not mention costs or the kind of measures taken to reach the EU targets, it still remains unclear which role measures in the CSS play in relation to others.

The American Society of Civil Engineers estimated that the infrastructure for CSO control may cost around \$45 billion, which is the largest necessity in the water/wastewater sector for the country (Ruggaber & Talley, 2005). Today, in the USA there are 746 communities with CSSs containing a total of 9,348 CSO outfalls that are identified and regulated by 828 National Pollutant Discharge Elimination System (NPDES) permits. CSSs are found in 32 states and nine EPA (Environmental Protection Agency) Regions. CSO communities are regionally concentrated in older communities in the Northeast and Great Lakes regions. The EPA estimates that approx. $3.9 \cdot 10^9$ m^3 of untreated combined sewage is released as CSOs each year in the United States (US-EPA, 2004).

Since CSOs result from a mixture of raw sewage and storm water, they possess a serious threat of microbial pathogens (Al Aukidy & Verlicchi, 2017), micropollutants from personal care products (Heinz et al., 2009), hormones Phillips et al., 2012), pharmaceutical and illicit drugs (Munro et al., 2019), pesticides (Gasperi et al., 2012; Launay, Dittmer, & Steinmetz, 2016), suspended solids, heavy metals, nutrients and microplastics in surface waterbodies (Al Aukidy & Verlicchi, 2017; Kistemann, Schmidt, & Flemming, 2016; Madoux-Humery et al., 2015; Masi, Rizzo, Bresciani, & Conte, 2017; Munro et al., 2019; Suárez & Puertas, 2005; Tanaka & Takada, 2016; Tondera, Koenen, & Pinnekamp, 2013; Xu et al., 2018). Meteorological and climate change predictions indicate an expected rise in the frequency and intensity of storm events with the implication that sewer system capacity will be exceeded more regularly. Furthermore, increased base flow in sewers due to trends for increasing urbanization and population growth in many cities worldwide means sewers fill up faster, which increases the likelihood of overflows during smaller rain events. Expansion of urban areas also leads to an increase of impermeable surfaces within catchments and faster surface water runoff, which also influences the frequency of CSOs (Schertzinger et al. 2018).

Publications on treatment and control alternatives for CSOs are limited in number. More studies should focus on best practice and innovative solutions for treatment and management of sewer systems and recently there has been an increase in literature concerning the quality, quantity and type of treatments (Masi et al., 2017; Rizzo et al., 2018; Ruppelt, Tondera, Vorenhout, Van der Weken, & Pinnekamp, 2019; Tondera, 2017). Since sustainable city approach requires reducing impacts of wastewaters in aquatic environments, integrated strategies should be evaluated within this context. Additionally, smart network monitoring and smart data infrastructures (US EPA, 2018) are currently under development and application. These infrastructures are implemented in connection with a supervisory control and data acquisition (SCADA) system and are mainly focused on real-time monitoring of flow rates (physically or with alternative methods) and effluent levels in CSO’s with the aim of assessing potential flooding and pollution incidents and to support real-time or quasi real-time decision making about actions to be taken. Research and innovation play an important role in the implementation and improvement of new technologies and approaches in this field. Changes of frequency and intensity of rain events increase the pressure on meeting the requirements stated in the EU regulations (e.g. Water Framework Directive, Bathing Water Directive) and national legislations; thus, to integrate the reduction measures, several projects were founded within this scope. The EU 7th Framework Program for Research and Innovation funded more than 140 research and innovation projects related to this topic in the period 2007-2013, and other projects are being supported by Horizon 2020 Innovation funding. For example, one aim of the INTCATCH H2020 Project (http://intcatch.eu/), is technological innovation and integration in smart water monitoring in the treatment of CSOs before their discharge into a waterbody. A pilot plant was installed and operated for about two years on Lake Garda, Italy, to demonstrate the concept of technological innovation and public participation in the integrated and smart management of water infrastructures and basins.

Taken together, the attempt of this review is to develop better understanding on CSOs by exploring the impact and mass load in terms of quantity and quality, treatments possibilities, both as conventional and more innovative options, guidelines to management and actual policy and future recommendations.

2. The characteristics of combined sewer overflows

Climatic factors such as quantity and intensity of precipitation are key factors determining the severity of CSO discharges. The characteristics of combined sewage are dependent on rainfall intensities and pollutant concentration and loads affected by wet and dry weather conditions (Sandoval, Torres, Pawlowsky-Reusing, Riechel, & Caradot, 2013). Moreover, during transportation in the sewer system, the physical, chemical and biological characteristics of wastewater changes (Nielsen, Raunkjær, Norsker, Jensen, & Hvitved-Jacobsen, 1992).

The relationship between rainfall, flood and overflow frequencies on water quality in CSO discharges are nonlinear (Willems, 2012). Climate change also has a major impact on CSO volumes for the regions where heavy rainfall events occur more frequently. As such, CSO discharges represent a great challenge to meeting required water quality standards in locations with CSSs. How CSOs impact the water quality of the receiving bodies should be evaluated in an integrated manner considering the flows, concentration and season in which the impact is more destructive – in Europe this is usually during low flow regimes during summer months (Willems, 2012). As this is also a period of increased recreational activities in surface waterbodies (Kistemann et al., 2016), severe health ramifications can be linked to CSO discharges (McBride, Stott, Miller, Bambic, & Wuertz, 2013). Monitoring studies indicate that the frequency of CSOs has increased in recent years. Whereas 9 CSO events were observed in 2012 in Lodz, the third largest city in Poland, the number increased to 23 in 2014 which exceed the number permitted by the legislation (10 times per year, Brzezińska et al., 2016) (Table 1). Similarly, CSO frequency and volume also increased by varying amounts in England (Willems, 2012). It is clear from the table that low number of events were analysed compared to the number of CSOs registered in the study area. In another study, Al Aukidy and Verlicchi, (2017) reported 20 CSO events within 3 months in the Po Valley, Italy. The total overflow volume ranged between 18-16.299 m^3, the volume increased over years. Heinz et al. (2009) indicated that 9–10 overflow events occur in Gallusquelle region in Germany annually with an average discharge of approximately 23,000 m^3. In the River Thames, London, approx. 39 million tons of untreated sewage enters the river annually from approx. 57 different CSO locations (Munro et al. 2019). Madoux-Humery et al. (2016) carried out their study in Québec (Canada) where the annual precipitation falling as rainfall is 625 mm/year and average cumulative precipitation falling as snow of approximately 2000 mm/year. They observed 2258 CSO events during the 2009-2011 period. Soriano and Rubió (2019) stated that there are 35 overflow points located along the Ebro river in which many of these overflow points have two to four discharge points, overall there are 72 overflow points in Ebro river.

An overview of pollutant ranges in combined sewage from CSO discharges is given in Table 2. The water quality varies according to factors such as location, rainfall duration, season etc.

Table 1. The combined sewer overflow monitoring

Area	**Monitoring Strategy**	**N° of events in the study area**	**N° of events analyzed**	**Period of study**	**Rain amount (mm)**	**Overflow discharged volume (m^3)**	**Reference**
Lodz, Poland	Sewer flowmeters located in the cathment	9 – 28/year	60	3 years		3.600- 49.822/year	Brzezińska, 2016
Po Valley, Italy	the CSO outfalls are located within the lifting pump stations	-	41	3 months (2014)	740/year	18-30383/event	Al Aukidy and Verlicchi, 2017
Gallusquelle, Germany	-	10/year	5	5 months (2005)	-	23.000 (5 events)	Heinz et al., 2009
Québec, Canada	Overflow markers, continuous data recorders and automatic data recorders	160/year (from 2009-2012)	-	-	-	-	Jalliffier-Verne et al., 2015
Stuttgart, Germany	Flowmeter	-	7	3 months (2014)	-	-	Launay et al., 2016
Québec, Canada	-	2258 (from 2009-2011)	5	-	625/year	92-19.530 (5 events)	Madoux-Humery et al., 2016
Vermont, USA	-	37 (from December 2007-November 2008)	-	1 year (2007-2008)	20-410/day	-	Phillips et al., 2012
Spain	-	-	46	-	-	2752-41.566/event	Suarez and Puertas, 2005
Berlin, Germany	179 CSO discharge points	37/year (from 2000-2007)	-	-	-	$7x10^6$/year	Weyrauch et al., 2010
La Garriga, Spain	14 CSO infrastructure with low-cost temperature sensors	36-49 (in 11 month)	-	1 year (2011-2012)	0.4-51.4/episode	-	Montserrat et al., 2015
Paris, France	Dry weather: daily	-	-	-	20.1/rainfall event	$3.2x10^6$/year	Gasperi et al.,

	samples for the 4 upstream sites. Wet weather: 4 of the 45 CSO sampled						2008
The Aire and Calder catchements, West Yorkshire, UK	Samples from WWTP, CSO and receiving water	-	5	-	-	-	Kay et al., 2017
City of Santiago de Compostela, Spain	-	-	925	4 years (1995-1999)	1600/year	-	Diaz-Fierros et al., 2002
Gorla Maggiore, Italy	69 CSO events	69 CSO events	69	1 year (2014-2015)	-	87-579/event	Masi et al., 2017

Table 2. The characteristics of combined sewer overflows

Study site	Monitoring strategy	TSS (mg/L)	BOD$_5$ (mg/L)	COD (mg/L)	TN (mg/L)	N-NH$_4$ (mg/L)	TP (mg/L)	Reference
Slovakia	8 CSO stations	430	175	445	16.8	6.21	2.63	Sztruhár et al., 2002
Gorla Maggiore, Italy	68 CSO events	-	-	176-612	-	3.8-28	-	Masi et al., 2017
Boudonville retention basin, Nancy, France	During rain events, CSO samples every 5-10 min	182.29-869.6	-	-	-	-	-	Samrani et al., 2008
Paris, France	Dry weather: daily samples for the 4 upstream sites. Wet weather: 4 of the 45 CSO sampled	150-700	-	-	-	-	-	Gasperi et al., 2008
Paris, France	4 CSO stations	135-353	36-180	136-446	-	3.3-9.3	1.2-5.4	Gasperi et al., 2012
General characteristics	-	270-550	60-220	260-480	-	-	-	Metcalf and Eddy, 1991
Harlem River, Bronx side, New York, The USA	50 CSO stations	-	-	-	-	1.3-2.7	0.5-3	Wang, 2014
North-Rhine Westphalia, Germany	>20 retention soil filters for CSO treatment	1-1123	-	15-918	-	-	0.1-16.1	Tondera, 2017
Shanghai, China (combined)	-	91-529	111-178	243-484	-	7.6-17.2	-	Li et al., 2010
Germany	-	174.5	60	141	12.6	1.94	1.25	Brombach et al., 2005
Two cities in Korea	from June 1995 to November 1997	99.0-215.7	33.7-81.5	118.5-223.5		-	-	Lee & Bang, 2000
	-	1-4420	3.9-696	-	-	-	0.1-20.8	EPA, 2004
The United States	-	237-635	43-95	120-560	2.9-4.8	-	-	Ellis and Jenkins, 2005
Canada	-	190	-	-	8.3	-	1.4	Ellis and Jenkins, 2005
United Kingdom	-	425	90	260-507	8.3	-	10	Ellis and Jenkins, 2005
Europe	-	105-721	39.9-200	148-530	2.1-14.4	-	2.4-4.0	Ellis and Jenkins, 2005

Santiago de Compostela, Spain	Monitoring over a 40-month period	160-411	70.5-171	134-540	-	5.2-12.8	0.5-4.6	Diaz-Fierros et al., 2002
Louisville, Atlanta	-	14-227	-	40-107	-	-	-	Arnone and Walling, 2006

3. Water quality impacts of CSO discharges

The pollutants released with CSO discharges can have detrimental impacts on aquatic environments and public health. The pollutants in the untreated wastewater can increase the organic content of receiving water bodies and oxygen depletion occurs with biodegradation, promoting eutrophication. In a comprehensive study carried out by Viviano et al. (2017), it was reported that more than 50% of the total phosphorous loads in the Lambro River resulted from CSO discharges during heavy rain events. Thermal pollution may also occur where the temperature of the CSO is different to the receiving water. Moreover, as a consequence of increased turbidity, photosynthesis is inhibited/reduced (Riechel et al., 2016). In warm seasons, low flows can limit dilution effects and, therefore, increase the problem (Montserrat, Gutierrez, Poch, & Corominas, 2013). On the other hand, the concentrations of wastewater contaminants such as total solids, COD, TKN, and P_{tot} can decrease due to the dilution caused by high precipitation. The study carried out by Gasperi, et al. (2012) showed that the parameters can be decreased almost one-third of the dry season (Table 2). On the other hand, a high variation between maximum and minimum values for the parameters were determined in various studies (El Samrani, Lartiges, & Villiéras, 2008; Li, Tan, & Zhu, 2010; Tondera, 2017; U.S.EPA, 2004) and the highest values were reported by EPA (2004) in which TSS, BOD_{5}, and TP were determined as 4420 mg/L, 696 mg/L, and 20.8 mg/L. The variation could be attributed to the precipitation volume, duration, location, etc. and confirmed the high stochastic nature of CSO events Masi et al. (2017).

Emerging contaminants, such as pharmaceuticals, hormones and substances from personal care products, can be introduced into aquatic environments via CSO discharges (Del Río et al., 2013; Montserrat et al., 2013; Passerat et al., 2011)). These contaminants may also be mobilized from sediments during storm events and end up in the water (Del Río et al., 2013). The runoff from urban surfaces transports additional loads of heavy metals, polycyclic aromatic hydrocarbons and a variety of other micropollutants such as pesticides Gasperi et al., 2014; Phillips & Chalmers, 2009). Metals contamination is another important issue in CSO discharges, which can accumulate in the sediment and affect the aquatic ecosystem, for example by inhibiting reproduction in sensitive macroinvertebrates (Schertzinger, Ruchter, & Sures, 2018). A correlation between metals concentration in the sediment and the number of CSOs were determined by Hnaťuková (2011).

Recent studies revealed that, even though CSO discharges represent only a small proportion of the total annual wastewater discharge, these overflows contribute to 30-95% of the annual load for different pollutants including caffeine, ibuprofen, polycyclic aromatic hydrocarbons (PAHs), phenolic xenoestrogens, hormones, and urban pesticides (Launay et al., 2016; J. P. Phillips et al., 2012). Furthermore, Phillips et al. (2012) stated that micropollutant concentrations could be up to 10 times higher in CSO discharges than that of the treated wastewater. Despite the short duration of CSO discharges, they introduce, high loads of micropollutants into waterbodies (Musolff et al., 2009). Moreover, the concentrations of PAHs in CSO discharges were found 2000 times greater than Environmental Quality Standards (Birch, Mikkelsen, Jensen, & Holten Lützhøft, 2011). Gasperi, et al. (2012) evaluated the concentrations of priority pollutants as well as wastewater quality parameters for CSO discharges, wastewater, and storm runoff. Whereas runoff is the major source for pesticides and dissolved metals (e.g. Zn) in CSO discharges, wastewater is the main contributor to volatile organic compounds. On the other hand, hydrophobic organic pollutants (e.g. PAHs, APnEOs) and particulate-bound metals (e.g. Pb and Cu) are mostly caused by in-sewer deposit erosion in the CSO discharges. Although wastewater effluents and CSO discharges are the main contributors for endocrine-disrupting compounds and personal care products in receiving water bodies, the concentrations depend on the removal rates in wastewater treatment plants, stormwater dilution factor, and the quantity of wastewater bypassed the treatment plant (Ryu, Oh, Snyder, & Yoon, 2014). Studies suggest some substances suitable as markers for CSOs, especially those which are biologically degraded in WWTPs or are specific to stormwater runoff. In combined sewer networks, caffeine can be proposed as a tracer for CSO discharges (Buerge et al., (2006). Similarly, Fono and Sedlak (2005) introduced propranolol, a pharmaceutical component, as a tracer for anthropogenic discharges.

CSO discharges introduce infectious pathogens originating from human faces and organic waste in the sewage, as well as from animal feces in run-off originating from wildlife (e.g. birds) or domestic animals (especially dogs) (Schares et al., 2005). They can contain antibiotic resistant bacteria (Young, Juhl, & O'Mullan, 2013).

Monitoring programs usually focus on indicator organisms, such as *E. coli* and intestinal enterococci, which are e.g. relevant for the EU Bathing Water Directive, or thermo-tolerant coliforms (WHO, 2008). They are chosen to indicate specific pollution, e.g. by fecal contamination. Ideally, this should enable one to conclude that a health risk is present. Some studies have investigated and detected further bacterial pathogens such as *Campylobacter, Salmonella, Aeromonas spp., P. aeruginosa;* enteric viruses such as Adenovirus and Norovirus, and human polyomavirus as well as protozoan parasites such as *Giardia lamblia* and *Cryptosporidium* (Christoffels, Mertens, Kistemann, & Schreiber, 2014; McGinnis et al., 2018; Tondera et al., 2015).

Direct measurements in CSO discharges regarding *E. coli* concentrations are rare; more often, polluted river water after overflow events is sampled instead. In the few published investigations with direct measurements, the median concentrations of *E. coli* at the outlet of overflow or CSO retention tanks range from 10^4 to 10^6 MPN or CFU/100 mL (Stott, Tondera, Blecken, & Schreiber, 2018).

If surface waters are used for recreational purposes, these microbial contamination result in risks of infections with gastrointestinal illnesses, pneumonia, bronchitis, and respiratory infections (U.S.EPA, 2004). McBride et al. (2013) revealed that the highest risks for swimmers derive from noro- and rotaviruses in such contaminated waters. Pond (2005) gives a detailed overview on infections and sequelae caused by these pathogens, some of which are chronic. The author associates the discharge of CSOs with these diseases and recommends closing recreational areas after heavy storm events and sewage treatment in general as a management strategy against possible infections. Accordingly, Tondera et al. (2016b) modelled the overall impact of CSO discharges on microbial contaminations in the Ruhr River relative to other sources, e.g. from WWTP effluent or diffuse pollution. The authors showed that in the river, which passes through a densely populated area in Germany, CSO discharges had the highest impact on elevated microbial concentrations up to two days after rainfall events. Moreover, Jalliffier-Verne et al. (2016) stated that high E.coli concentrations at raw water collection points for drinking water production correlate with the discharged concentrations from CSOs, the location of overflows, dispersion processes in the surface waterbody, and the season. In a study carried out by Riechel et al. (2019), the authors used a tracer approach using wastewater volume as a proxy for pathogen emissions to assess the relationship between different CSO outlets and bathing water quality for Berlin, Germany. According to their results, wastewater including only 5% of the CSO volume contributes >99% of the pathogen loadings to the receiving environment. Wastewater volume was also of relevance for determination of point sources for the hygienic impairment of the receiving environment. In another study by the same group (Seis, Zamzow, Caradot, & Rouault, 2018), they proposed a methodology which demonstrated the shortcomings of current long-term classification as well as the potential for improvement by applying the proposed approach regarding to the microbial safety. However, USEPA's BEACH Program conducted an annual survey of the nation's swimming beaches. During the 2002 swimming season, CSOs and SSOs were responsible for only 1 and 6 percent, respectively, of reported advisories and closings (USEPA, 2004). Therefore, results are controversial and call for proper smart monitoring and case-by-case analyses.

4. Policy, legislation, governance and regulation to address the challenges

The necessity of controlling CSO pollution under the urban wastewater treatment directive (UWWTD; OJEC 1991) and water framework directive (WFD; OJEC 2000) was stated by the European Union. Discharges of CSOs may affect the achievement of "good status" of waterbodies as required by the European Water Framework Directive. The scientific community and the water sector operators are raising awareness of the environmental problems relating to CSOs and are promoting initiatives for reduce their impact and improving the quality of surface water (EurEau, 2016).

Since 1998, there have been significant changes in legislation with the implementation of the water directives; and water quality and ecological standards have been revised. New issues have arisen with an urgent need of adaptation and mitigation measures in the upgrading of urban drainage systems. In the European legislation relating to CSOs, it is possible to distinguish between Directives aimed at protecting receiving waters and Directives to control CSO discharges (Morgan, Xiao, & McNabola, 2017). The Urban Waste Water Treatment Directive 91/271/EEC (UWWTD) highlights that the collecting systems shall be constructed and managed in accordance with limiting the quantity of pollution entering receiving waters due to storm water overflows. In addition, the UWWTD requires reporting of wastewater sewerage treatment performance and a system of pre-authorization for all wastewater discharges, including CSOs. The ongoing evaluation of the UWWTD has highlighted the importance of better managing CSOs. The Bathing Water Directive 2006/7/EC (BWD) and the Habitats Directive 92/43/EEC are limited to assess the bathing waters affected by CSOs as “subject to short-term pollution”. In the EU Regulation No. 166/2006 (2006)“concerning the establishment of a European Pollutant Release and Transfer Register”, EU member states are obligated to report pollutant loads, specified in Annex II, to water. The threshold values are also specified in this regulation. Thus, the pollutant loads from CSO discharges should also be estimated. However, this is very challenging since CSO structures are not designed for monitoring purposes.

CSO discharges have been identified as an important problem for European countries. Germany, UK and other countries have started to establish CSO policies and actions before Water Framework Directive (Malgat, 2013). Sixteen EU member states have national standards that regulate storm water overflows, eleven of them have guidance documents that directly address storm water overflows (EurEau, 2016). Common approaches in standards and guidance are:

- Limit on the number of overflows (e.g. Belgium, Poland, Portugal);
- Requirements for dilution (e.g. Bulgaria, Czech Republic, Estonia);
- Other approaches seen: max total volume, or max number of days of overflows (e.g. Germany).

The permitted number of overflows per year proposed by CSO regulation guidelines differs according to each member country and ranges from 2-3 in Denmark and the Netherlands, 15-20 in the Galician region in Spain (Table 3, Montserrat et al., 2015) and 10 in Poland (Brzezińska et al., 2016).

Table 3. Regulations issued CSOs

Country	Regulation/Legislation/Guideline	Issue
Italy	Regulation Number 917/2017	Number of overflows per year
Denmark	Danish Nature Agency, 2011:55	Number of overflows per year (2-3)
Netherlands		Number of overflows per year (2-3)
Spain	Royal Order RD 1290/2012	Number of overflows per year (15-20)
UK	The Urban Wastewater Treatment Regulations 1994, Regulation 6 (2)	Number of overflows per year (15-20)
Canada	MDDELCC, 2014	New developments will not result increase in the frequency of overflows
Japan	Enforcement Ordinance of Sewerage Law (2003)	BOD_5 parameter
Australia	Environment Protection Authority, a Code of practice	Implementation of overflow abatement program
France	Local Authorities General Code 2015 Order	Monitoring must be ensured by the operator, municipality and the different water policy services

In the UK the requirements for solids separation depend on the number of overflows per year. The Urban Wastewater Treatment Regulation (6 (2), 1994), states that primary treatment must be provided within CSO structures, in which the biological oxygen demand, determined over 5 days, (BOD_5) of the incoming wastewater is reduced by at least 20% before discharge and the total suspended solids reduced by at least 50% (Morris, 1999). The third periodic Asset Management Plan review (AMP3: 2000–2005) specified a timetable for water companies to reduce the number of unsatisfactory intermittent discharges caused by CSOs (McSweeney et al., 2009). In 2012, a comprehensive framework for CSO improvement has been developed through the urban pollution management program to assess the impact of CSO discharges on receiving water quality and to develop water quality standards for the protection of aquatic life from intermittent pollution caused by CSO discharges (Morgan et al., 2017). These criteria also form the basis of CSO assessment in Ireland, as set out in the Procedures and Criteria in relation to Storm Water Overflows. On the other hand, in Italy, a list of performance indicators to describe the technical quality of the water utility management and operation were introduced in 2017 by the Italian

Regulatory Authority for Energy, Networks and Environment (Regulation Number 917/2017). The section dedicated to the sewer system includes two restrictions; firstly, the adequacy of the CSO stations and secondly, the number of overflows allowed in one year in each 100 km of sewage system. Moreover, in Spain, the Royal Order RD 1290/2012 requires that all CSO discharging points for places exceeding 2000 equivalent inhabitants be defined (Montserrat et al., 2013). In France, it is just stated that CSOs spillages must not exceed 2% of the total average annual volume for 5 years (Tabuchi, 2013) and according to the "Local Authorities General Code 2015 Order" monitoring must be ensured by the operator, municipality and the different water policy services. However, in Germany, several guideline describe the design and construction of CSO retention tanks at points with critical discharge (ATV-128, 1992; DWA, 2013b, 2013a). Capacities depend on factors like the catchment area, population density, historical rainfall patterns and the proportion of impervious surface areas. The percentage of wastewater in a catchment that can be discharged via overflows is based on ten-year rainfall patterns and determined by the sensitivity of the receiving waterbody. In 1994, the United States Environmental Protection Agency issued the combined sewer overflow control policy in the National Pollutant Discharge Elimination System program (NPDES). Within the scope of the policy, site-specific permits were developed for all CSS considering cost/performance in relation to the size of the individual systems. Additionally, a list of nine minimum measures were determined for CSOs in order to develop and adopt long term control plans (U.S. EPA, 2001; U.S.EPA, 2004). They include programs for control measures during installation and pollution prevention, pre-treatment applications, maximization of the storage in collection system and flow directed to the WWTP, monitoring, as well as public communication. In Canada, although there is no federal legislation for CSOs control, some provinces, like Quebec, adopted specific rules to restrict CSOs (MDDELCC, 2014). To be in accordance with the Strategy for the Management of

Municipal Wastewater Effluent, municipalities and developers have to demonstrate that new developments will not result in an increase in the frequency of CSO (Mailhot, Talbot, & Lavallée, 2015). According to the Canada-wide Strategy for the Management of Municipal Wastewater Effluent, CSO discharges are not entirely prohibited, but are allowed in exceptional circumstances, such as during snow-melt in spring time (Jalliffier-Verne et al., 2016). Differently, in Japan, in 2003, an amendment of "Enforcement Ordinance of Sewerage Law" related to CSO discharges abatement was issued defining the BOD_5 concentration in the effluent overflow (< 40 mg/L), allowing a provisional limit of 70 mg/L applicable until structure standards start to be applied. Small and midsize municipalities were obligated to implement improvements by 2013, large municipalities by 2023. Environment Protection Authority of South Australia issued a code of practice for wastewater overflow management giving a roadmap to the operators to comply with their environmental obligations. The water utility is obligated to implement an overflow abatement program, which encompasses an emergency response plan and short- and long-term measures to prevent or reduce the re-occurrence of overflows. However, in South Africa the policy related to runoff water disposal asserts that: "Urban stormwater discharged to the marine environment should not have any negative impact on the Environmental Quality Objectives of the receiving environment", it does not provide specification on treatment-at-source or land-based treatment, which are considered specific to disposal of stormwater runoff.

Overall, different directives have been developed worldwide, which are mainly focused on the affirmation of the negative effects of the CSO events and allowed a number of overflows per year. Generally, the policymakers are revising and deriving the regulations to enforce authorities to take pre-cautions and control CSO discharges. Although they pointed out the adverse impacts, in many countries no specific limits for water parameters have not been set to limit pollution from CSO discharges. This aspect is mainly related to the great variability in terms of quality and quantity of CSO characterization in the different sewer systems, previously described in the Section 3. Moreover, wide sampling campaigns and monitoring methods have to be implemented in order to quantify the hydraulic and the characterization conditions to support the legislation improvements. Finally, specific treatment technologies and control measures can be integrated into the regulations.

5. Innovative methods for CSO determination

Hydraulic conditions are the main factor to determine the proper method for monitoring CSOs. Table 4 displays various methods used to estimate CSO volumes.

Table 4. CSOs measurement methods (adopted from Maté Marín et al., 2018).

Position	Technique	Features	Main drawbacks
Overflow channel	Stage-discharge relation methods	Pre-designed device	Need for specific hydraulic conditions
	Stage-discharge relation methods	On-site calibration	Site-dependent
	Velocity based methods	-	Representativeness
Main channel (upstream & downstream from the CSO)	Stage-discharge relation methods	Pre-designed device	Need for specific hydraulic conditions
	Stage-discharge relation methods	On-site calibration	Site-dependent
	Velocity based methods	-	Representativeness
	-	-	Double equipment
	-	-	Indirect measurement
CSO chamber	Stage-discharge relation methods	Classical geometry	Need for specific hydraulic conditions
	Stage-discharge relation methods	On-site calibration	Site-dependent

Sensors and probes are also applied for monitoring purposes in most of the high income countries, such as conductivity meters to detect occurrence and determine duration, level sensors with moderate and/or higher cost, advanced sensors (eg UV-VIS) for also determining water quality. Where budget is limited, level sensors can be coupled with overflow equations to measure CSO volume. On the other hand, a level and a velocity sensor combined with flowmeters generate the most accurate/reliable data but require more investment cost and higher maintenance (Montserrat et al., 2013).

The costs of data storage and high capacity computer systems are still an issue in CSO monitoring. Moreover, in heavy rain events, huge quantities of data must be processed and evaluated for every alarm situation in order to take immediate action (Bailey et al., 2016). The other point is the location of the CSO control system. The characteristics of the land can make the connection to the network difficult.

A low-cost method was introduced by Montserrat et al. (2013) to detect the occurrence and duration of CSO events. The proposed method depends on the temperature changes between the sewer gas phase and the overflowing mixture of wastewater and storm water. Using temperature sensors for CSO detection has several advantages such as minimum capital cost, easy installation, requirement of minimum technical knowledge for integration, tolerance to extreme environmental conditions and minimum maintenance. The authors also validated their systems and achieved detection greater than 80% of the total CSO occurrences, which showed that temperature differentiation during seasonal changes does not have a negative impact on effectiveness. However, physical features of the weir affect the detection performance. Later research, published in 2018, increased the robustness of the method proposed in Montserrat et al. (2013) by adding a second temperature sensor, improving the detection accuracy by implementing an algorithm that accounted for the response time of the system and automatically calculated the duration of CSO events (Hofer et al., 2018). As a result, in a 7-month test phase, all 20 CSO events were recognised without false detections.

Another group from France, recently developed a system called the DSM-flux (Device for Storm water and combined sewer flows Monitoring and the control of pollutant fluxes) to determine and control both the quantity and quality of CSO discharges (Maté Marín et al., 2018). The validated system can measure overflow volumes and pollutant concentration, decrease particulate pollutants from sedimentation and the erosive potential of overflows to the receiving waters. The advantages of installation of the DSM-flux system are: - direct measurement at the overflow channel, - installation downstream from the existing CSO structure, -requirement of only one level measurement for determination of discharge values, - not affected by inlet hydraulic conditions, - reduced particulate pollutants and erosive potential of CSO discharges.

5.1. Smart CSO monitoring and control

Currently smart network monitoring and smart data infrastructures (US EPA, 2018) are under development and application. These infrastructures are implemented in connection with a supervisory control and data acquisition (SCADA) system and are mainly focused on real-time monitoring of flow rates (physically or with alternative methods) and effluent levels of CSO's with the aim of assessing potential flooding and pollution incidents. The final objective is to support decisions in real-time or quasi real-time about actions to be taken. For instance, SPRINT 226 a European project focused on the implementation of real-time sewer system control for eight European cities: Copenhagen (Denmark), Mantova (Italy), Verona (Italy), Genoa(Italy), Berlin (Germany), Vitoria-Gasteiz (Spain), Bolton (United Kingdom), and Goteborg (Sweden) (Entem, Lahoud, Yde, & Bendsen, 1998). The project showed decent real-time control performance for overflow events of the sewer system in terms of prediction and generation of strategies to be taken into consideration (Entem et al., 1998). Another study (Seggelke et al., 2013) focused on real-time control of a CSS in a city in Germany with the aim of monitoring frequency of overflow events and investigating how to reduce them. In addition, Carbone et al., 2014 investigated a real-time control solution for an urban drainage network in Italy. It used an innovative and smart series of gates that automatically adjusted themselves in order to optimize the storage capacity of a sewer system during rainfall events. Moreover, in the INTCATCH project, as an innovative approach to monitor water quality, autonomous and radio controlled boats are developed and demonstrated in key catchments such as Lake Garda, Lake Yliki (Warner, Nödler, Farinelli, Blum, & Licha, 2018). The results revealed that monitoring the routine parameters can give an overview of the current status of the water body, as well as contribute to reducing the monitoring cost. Moreover, real-time monitoring of site-specific indicator allows determining the pollutant source which helps to derive proper catchment management strategy (Warner et al., 2018). The applications of smart data infrastructure systems can be optimized by two different methods. Whereas the system improvements refer to increasing weirs, optimizing the efficiency curves or location of CSO control, the real-time control systems manage the operation of wastewater networks and facilities in real time (US EPA, 2018Grey (such as large concrete tanks or tunnels) and green strategies (such as bioretention facilities, green roofs, porous pavements, and stormwater planters) can be applied to control CSOs (De Sousa, Montalto, & Spatari, 2012) and hybrid system of grey and green methods more advantageous than grey method-only in terms of economy, environment and society (Gong et al., 2019). The control strategies can be optimized by hydrological model simulations supported with scenario analyses (Chen et al., 2019). In the USA, different approaches are integrated in different states to control and manage CSOs. In Philadelphia, the Water Department has a goal to reduce overflows (7.9 billion gallons of overflow water) by 2036. For this purpose, smart data technology was integrated into existing stormwater retention basins to monitor basin water level and precipitation, and maximize the performance of the basin by real-time active control to selectively discharge from the basin during optimal times. On the other hand, 10 high frequency cleanout sites with remote field monitoring units were integrated in the San Antonio Water System (SAWS) in which day-to-day level trend changes can be detected by an analytical software giving data for potentially important changes in water levels. In the pilot locations, there were no sewer overflows in May/June 2016 with when nearly 16 inches of rain overwhelmed the SAWS. The real-time control system was adopted in Louisville in 1990s and actively used since 2006. The system prevents more than 1 billion gallons of CSO volume annually. In Indiana, there are 152 sensors located through the city of South Bend to maximize the capacity and performance of the city's collection system, which helped to reduce total CSO volume by roughly 70 percent, or about 1 billion gallons per year during the period 2008-2014. Moreover, in Greater Cincinnati, there are more than 200 CSO points, causing a discharge over 11 billion gallons of sewage into the Ohio River and its tributaries annually. 164 overflow points were integrated within the frame of the smart sewers network to date and sensors were installed through the watershed (USEPA, 2018). The monitoring technology should be pursued in the catchment base, and economical analysis should be carefully proceed to decide to integrate the best smart strategy.

5.2. Innovative treatment alternatives

Different strategies are developed to reduce the impacts of CSOs, such as increasing storage capacity, detention/retention facilities, as well as sewer separation to fulfill the requirements of the related regulations (Figure 2). However, converting CSS into a separated system can be prohibitive due to cost and it does not always guarantee pollution reduction (Li et al., 2010). One of the many goals of this review is to gather the latest information on treatment technologies, grouped as natural and technological treatment, and their performances in treating CSOs. Treatment alternatives are summarized in Table 5.

Table 5. Studies with different treatment alternatives for CSOs

Treatment	Location	System	Purpose	Target	Reference
Natural Treatment	Gorla Maggiore, Italy	Vertical flow subsurface beds (VF) as first stage and a free water surface bed (FWS) as second stage	Flow reduction	Flow reduction: 86.2%	Rizzo et al. (2018)
	Germany	Retention soil filters (RSFs)	CPOD, TSS and P	COD removal: 49% TSS removal: 38% Phosphorous removal: 34%	Tondera et al. (2017)
	Gorla Maggiore, Italy	Vertical flow subsurface beds (VF) as first stage and a free water surface bed (FWS) as second stage	COD and NH_4^+	COD removal: 87% NH_4^+ removal: 94%	Masi et al. (2017)
	Tettnang, Germany	RSFs	Micropollutants and pathogenic/antibiotic resistant bacteria	COD removal: 80 ± 10% E. coli removal: 2.7 log-units Enterococci removal: 2.2 log-units	Scheurer et al. (2015)
	Carrión de los Céspedes, Spain	Vertical flow CW + horizontal flow CW + Free water surface CW	TSS and disinfection	TSS removal: 90 ± 8% disinfection efficiency :4.7 logarithmic units CFU/100 mL for E. coli	Ávila et al. (2013)
	Pilot –scale experiment	Activated soil filter	Biocides and biocide metabolites removal	Dry weather conditions: Removal rates: 80-100% High flow conditions: Triazines: 50-70% Phebylureas: 16-100% DCOIT: 99-100% BIT: 72-96% IPBC: 43%	(Bester et al., 2011)
	Pilot–scale experiment	Activated soil filter	Organic micro-pollutant removal	Lipophilic compounds removal: 64-99% Persistent hydrophilic compounds removal: 0-95% depending on the	(Bester & Schäfer, 2009)

				operation period	
Technological treatment	Boudonville, France	Coagulation with ferric chloride solution (CLARFER), aluminum salts (WAC HB)	TSS and heavy metals	Turbidity removal: >86%	El Samrani et al. (2008)
	Seine Aval plant, France	Ballasted flocculation unit	TSS, POC, COD, P	TSS removal: 86.7% -80.2% POC removal: 84.8% -77.5% COD removal: 75.2% -76.8% P_{tot} removal: 86.4% - 88.4% Hydrophilic compound removal: 20% - 50%	Gasperi et al. (2012)
	Germany	Adsorption: Biochar	Specific pollutants	Acetaminophen removal: 94.1% Naproxen removal: 97.7 %	Jung et al. (2015)
	Simulated CSO with real wastewater	Activated soil filter (Bio filter)	TOC and micro pollutants	Hydrophilic markers: 81-98% Lipophilic markers: 30-99% TCPP: 64% TOC removal: >50%	Bester and Schäfer (2009)
	Kærby, Denmark	PAX dosing point before the HydroSeparator followed by a dosing point for PAA + CW	TSS, P, disinfection	Turbidity removal: 89.8% Phosphate removal: 26.6% Enterococcus removal: 1.3-3.5 log	Chhetri et al. (2016)
	Synthetic CSO	The adsorption and photo-reduction-a composite catalyst of TiO_2 and Graphene	Zn^{2+}	Zn^{2+} removal: 20.3 ± 0.04% increase	Kumordzi et al. (2016)
	North Rhine-Westphalia, Germany	Performic acid	Disinfection	*Aeromonas* spp. reduction: 1.8 log *E. coli.* reduction: 3.1 log Somatic coliphages reduction: 2.7 log	Tondera et al. (2016)
	Synthetic sanitary sewer overflow	Biofilter	BOD_5 and TSS	BOD_5 removal: 84 ± 9% TSS removal: >90%	Tao et al. (2010)
	Synthetic CSO	Disinfection by PFA and acid PAA	Disinfection	*E.coli* reduction: ~3 log units *Enterococcus* reduction: ~3 log	Chhetri et al. (2014)
	Synthetic CSO	Disinfection by PAA	Disinfection	Full disinfection at pH 8.5	McFadden et al.

	and hypochlorite			(2017)
Ruhr, Germany, simulated CSO	UV disinfection and ozonation	Disinfection	*E.coli* reduction: 2.2-3.5 log Coliform bacteria reduction: 1.7-3.3 log	Tondera et al. (2015)
	UV disinfection with coagulation	UV transmission	Increase on UVT: 78%	Gibson et al. (2016)
Lake Garda, Italy	A dynamic rotating belt filter, adsorption on granular activated carbon and UV disinfection	TSS, COD and *E. coli* removal	TSS removal: >90% COD removal: >69% E. coli removal: >99%	Botturi et al. (2020)

5.2.1. Natural extensive treatment

Green infrastructure and nature-based solutions (NBS) use natural processes to contribute to the improved, sustainable management of water as well as enhancing natural capital and biodiversity. Green infrastructure is recognized to deliver multiple benefits by combining continuous treatment of CSOs with additional services in terms of flood protection, increased biodiversity, climate change resilience and recreational activities.

There is growing recognition that green infrastructure are flexible, multi-purpose alternatives to traditional, often costlier treatment solutions that can be applied in diverse wastewaters (Vymazal, 2011) including treatment of residential, municipal and agricultural storm water and wastewater and urban run-off. They are incorporated into and promoted in Europe by the European Commission Strategy on Green Infrastructure (EC, 2013) and in the UK; an example is the London Environment Strategy (GLA, 2018). Green infrastructure is therefore an increasingly important possible solution for pollution mitigation. As well as being an environmentally friendly alternative, green infrastructure are flexible in terms of size, cost-effective and have a discrete layout (Fu, Goddard, Wang, & Hopton, 2019). Of the green infrastructure techniques, constructed wetlands (CW) have a long history of wastewater treatment and have many applications for CSO treatment (Levy, Smardon, Bays, & Meyer, 2014; Masi et al., 2017; Pálfy et al., 2018, 2016; Rouff, Eaton, & Lanzirotti, 2013; Tondera, 2017). The largest number of constructed wetlands for combined sewer overflow treatment (CSO-CW) exist in Germany, where the first large-scale treatment plants were implemented in the early 1990. In North-Rhine Westphalia alone, a state with approx. 18 million inhabitants, more than 150 facilities exist with a treatment capacity of 100 to 36,000 m^3 (site currently under construction) per rainfall event. The newly released national guideline (DWA, 2019) describes design, construction and maintenance of the system. In principal, pre-settled combined sewage is distributed on a vegetated filter body with a sand layer of 0.75 cm. A ponding zone allows temporary storage of up to 2 m^3 per m^2 water and the outflow is throttled and ideally does not open before full saturation of the filter body has been reached. The filter material consists of engineered media ('technical sand', 0/2 mm). The required capacity is based on ten-year rainfall simulations and the sensitivity of the surface waterbody.

Investigations of these systems, especially in the last 15 years, show a total suspended solid (TSS) removal of >90%, chemical oxygen demand (COD) removal of >80%, a high nitrification potential (ammonium removal of >60% depending on inflow concentrations and preceding dry period), bacterial removal of 1 to 3 $\log_{10}$, but also removal of certain micropollutants (Christoffels et al., 2014; Scheurer et al., 2015; Tondera, 2017; Tondera et al., 2013; Tondera, Ruppelt, Pinnekamp, Kistemann, & Schreiber, 2019). Phosphate and heavy metals can be reduced until the overall sorption capacity of the filter body has been reached; an increase is possible by adding adsorptive materials or implementing post-filter steps.

The layout has been adapted in research projects in France and Italy (Meyer et al., 2013). Masi et al. (2017) describes the Italian approach implemented at Gorla Maggiore (Table 5). The system was designed to treat the first flush of the overflow via vertical-flow wetlands, whereas the later occurring, higher diluted overflow is bypassed into a free water surface wetland. During the study period, 69 CSO events happened and the system successfully reduced the COD concentration by 87% and NH_4 concentration by 93%. As additional benefit, the construction mitigates flood risk. Rizzo et al. (2018) describes the Italian approach and shows that the system reduced the effects of CSOs in the river by smoothing peak loads and contributing to improved water quality.

Similarly, Ávila et al. (2013) demonstrated the function of a pilot-scale treatment system consisting of a vertical subsurface flow, a horizontal subsurface flow and a free water surface constructed wetland for the treatment of effluent from a combined sewer and results showed efficient performance in terms of organic carbon and TSS removal under dry weather conditions. As expected, during the storm events there were a prompt increase in carbon and TSS load for a short period followed by a dilution effect.

5.2.2. Technological compact treatment

Minimizing the negative impact of CSOs in the receiving waters can be achieved by in-line treatment methods such as settling without additives, which is the most commonly applied method, and chemical coagulation before discharge. Coagulation and flocculation are an effective method to remove organic materials with organic/inorganic polymers as coagulants and flocculants to get better sedimentation. In a study carried out by El Samrani et al. (2008), effects of different commercial coagulants - namely, ferric chloride solution (CLARFER) and aluminum salts (WAC HB) - were evaluated on turbidity and heavy metal removal from samples collected during rainy weather at the inlet of Boudonville retention basin. The results showed that both coagulants provided excellent removal of heavy metals; indeed; the concentrations of Cu, Zn and Pb in the treated water complied with the water legislation.

Regarding flocculation treating CSOs, Gasperi et al. (2012) examined the performance of a full-scale ballasted flocculation unit (BFU) implemented at the bypass of the wastewater treatment plant located downstream of Paris on the Seine River. Ferric chloride ($FeCl_3$) and anomic polymer were respectively used as coagulant and flocculant according to the turbidity levels entering BFU, and high surface area was achieved by microsand to enhance flocculation, assist flock formation and act as ballast, which aids rapid settlement. The performance of the system was evaluated during the wet period, in which the bypassed combined sewage was treated only with BFU and bio-filtration in order to remove nitrogen, before discharge. Significant removal rates (>80%) were achieved for the compounds with a strong hydrophobic character (log Kow >

5.5) and removal rates of 50-80% were achieved for intermediate hydrophobic compounds ($4 < \log Kow < 5.5$). On the other hand, low hydrophobic compounds ($\log Kow < 4$) were poorly (<20%) to weakly removed (<50%). The authors concluded that it is a promising process to treat CSO waters in order to remove various compounds.

Another possibility to remove very small particles or dissolved substances especially is by adsorption. Although (Jung et al., 2015) investigated positive removal of micropollutants such as acetaminophen and naproxen (94.1 and 97.7 %, respectively) from artificial combined sewage with biochar in a lab scale study, there is no application on a large scale yet, since removing the adsorbent from the wastewater matrix is difficult. Easier is the combination of a sand filter or vertical-flow constructed wetland containing an activated layer; such as investigated by Bester & Schäfer (2009). They evaluated the performance of an activated soil filter (bio filter) in order to eliminate diverse xenobiotics from combined sewage, storm water and wastewater. The results indicated that the removal efficiency of organic micropollutants depends on the application of an organic layer in the filter, enabling higher removal efficiency. In a comprehensive study of sanitary sewer overflow treatment with fixed media biofilters, results showed that, all bioreactors can remove TSS, ammonia and phosphorous effectively (Tao, Mancl, & Tuovinen, 2010). Moreover, BOD_5 reduction efficiency of 84 ± 9% can be reached with sand bioreactors. In another study Kumordzi et al. (2016) focused on to remove the most abundant heavy metal, namely Zn^{2+}, in simulated CSOs by a composite catalyst of TiO_2 and Graphene under various process conditions such as pH, light intensity, catalyst loading and light source in a lab-scale system. The adsorption and photo-reduction of Zn^{2+} enhanced with TiO_2-G under the solar spectrum. On the other hand, adsorption is not the best solution in case of high clogging risk and water volume.

Rotating belt filter is another option for CSO treatment in terms of their minimal footprint and also easier implementation. (Gutierrez, 2015).

Within the scope of INTCATCH Horizon2020 Innovation funded European project, a demo plant, with the aim of treating CSOs before their discharge into Garda Lake, was installed at Villa Bagatta. Additional aims considered the concept of technological innovation and public participation in integrated and smart management of water infrastructure and basins (Figure 3).

The pilot plant has a compact modular design, composed of three main sections; rotating belt filtration (RBF), filtration on granular activated carbon (GAC) and disinfection by UV treatment (Figure 4). Despite the fact that the processes used in this project used for decades for wastewater treatment, they have not been applied specifically for the treatment of CSO discharges.

The plant can treat 54 m^3/h. The Rotating Dynamic Filter (Salsnes Filter, SF1000) accomplished the sieving of the CSOs through a mesh size of 350 µm and the retained solids are thickened using an embedded screw-press unit, achieving a total solid concentration of 20-35%. The outlet CSOs is stored in an existing concrete open tank where it may be pumped up to 3.6 m^3/h to the GAC filtration system. Following the GAC system, is an ultraviolet disinfection unit with 4 modules (Trojan Technologies, UV3400K) installed in the open channel. Electrical conductivity, pH, and multiple parameters simultaneously derived by UV/Vis optical spectrometry (Intelligent Spectral Analyser (ISA)) are installed to monitor the system. Data are gathered and transmitted to cloud computing which is also integrating sustainability evaluation and assessment tools in order to provide eco-efficiency indicators of the treatment and management system. The plant reached satisfactory removal efficiencies for TSS (90%), COD (69%) and *E. coli* (%99). However, further treatment is required for efficient nutrient removal in which TN and TP removal of around 41% and 19%, respectively (Botturi et al., 2020). The innovations of this project are its modular structure, compactness, rapid treatment and resilience of the system which enables to re-shape of the configuration according to the treatment requirements.

To sustain the safety of the water quality of receiving water bodies used for recreational purposes, microbial loads from CSOs should be reduced. Since quality and quantity of CSOs are very variable, it a challenge to find suitable disinfection technologies which can be operated spontaneously for a short period at full capacity. The most commonly applied disinfection methods for the treatment of WWTP effluent are using chlorine compounds, ozone and ultra-violet (UV). However, these are not ideal for CSO treatment due to the high concentrations of solids and dissolved organic compounds: using chlorine compounds can lead to the formation of toxic, mutagenic and carcinogenic chlorinate by-products (Bayo, Angosto, & Gómez-López, 2009; Nurizzo, Antonelli, Profaizer, & Romele, 2005).

Undesirable by-products can also be the result when using ozone. Tondera et al. (2015) evaluated the effects of ozonation on diluted wastewater in a pilot scale application. Although the reduction of pathogenic bacteria, viruses, and protozoan parasites were promising and more effective than UV irradiation for the tested conditions, the operation of an ozone generator under these conditions is difficult to manage and both installation and operation is costly.

Suspended solids and turbidity in CSOs are also limiting parameters on the disinfecting effects of UV radiation (Tondera et al., 2015). In another study, Gibson et al. (2016) evaluated the effects of chemical pre-treatment of CSOs for subsequent UV disinfection. When applying 20 mg/L alum, the UV light transmission of the raw CSO increased from 30 to 60% after settling. The high charge density cationic polymer improved the removal of turbidity but did not affect UV transmittance (UVT) and TSS. The use of alum (metal coagulants) can achieve a UVT of 78%, while the use of cationic polymers reached a value of 60%. Pre-treatment to remove particles via CSO–CWs, as described above, not only increases the removal of microbial loads, but also allows reduction of dissolved parameters. In addition, no chemical addition is required, but space availability and installation costs are critical.

Alternative treatment with peroxy acids was investigated in several recent studies. Peracetic acid (PAA) requires a reaction time of several hours (Chhetri et al., 2014). The influence of particles on the removal efficiency gave controversial results: While Chhetri et al. (2016) found that bacterial reduction was more mostly efficient with a pre-treatment by particle separator and an additional coagulation with poly-aluminum-chloride, McFadden et al. (2017) could not find an effect of particle removal on the efficiency of CSO treatment with PAA.

As an alternative to PAA, performic acid (PFA) requires only a short contact time Under real scale conditions, Chhetri et al. (2015) showed a reduction of 2.0 $\log_{10}$ of *Escherichia coli* and 1.3 $\log_{10}$ of intestinal enterococci (contact time of 20 min, 8 mg l-1 min-1 reduced approximately), and Tondera et al. (2016) proved additional reduction of coliform bacteria, *Aeromonas spp*. and *P. aeruginosa* with a $\log_{10}$ reduction between 1.8 and 2.9 (contact time of max. 30 min, 12 to 24 mg l^{-1} min^{-1}). Additionally, a reduction of somatic coliphages with 2.7 ± 1.7 $\log_{10}$ could be shown. Another advantage of using PFA is that the commercially available reaction chamber providing PFA seems to be tolerant to long standstills, which can occur during dry seasons without CSOs.

6. Economics

Municipalities should invest in infrastructures to monitor, control and treat CSOs to meet regulatory obligations of the receiving water bodies. It should be noted that the private companies can also involve in the controlling of sewerage systems besides the government. Since legislations are encouraged to apply better management strategies for CSO discharges, there are no strict regulations. Thus, CSO discharge management is still an issue.

Real time control systems seem a cost effective alternative since they only require additional implementations to the existing systems. The design step is crucial to select the right equipment with the proper communication system and software, which may lead to significant capital investment costs. In real time control systems, cleaning equipment needs to be integrated into the instrumentation to prevent, fouling of the sensors. While, these integrations increase the capital costs, they have an advantage in the long term of reduced maintenance costs (Campisano, Cabot Ple, Muschalla, Pleau, & Vanrolleghem, 2013). Colas et al., (2004) summarized the benefits of real time controlling on CSOs for different locations. In Paris, the capital cost of CSO controlling was reduced by almost 25% by application of real-time control to the system. In Louisville, the municipality has reduced the cost of CSO long-term control program by $150 million by integrating a real-time controlling system. In another application in Quebec, $90 million was saved in the capital cost to the Quebec City CSO Control Program in terms of reducing the number and the size of some facilities. In Berlin €90 million was invested to reduce CSO's, in which the cheapest measures are real time controlling inside the CS. On the other hand, construction of retention basins cost 1000€/m^3. An external basin has been tested in Berlin's River Spree since 2011 but at the end costs were not lower than for underground structures. In Ancona and Falconara Marittima (Italy) € 22 million have been planned to be invested for CSO management.

Different technologies and approaches can be integrated and/or applied for CSO controlling. During the decision, the optimum method should be evaluated based on the physical properties of the interface, applicability of the technology, operational & maintenance costs, cost-benefit ratio.

7. Conclusions and further research needs

CSO discharge is still a major environmental threat that need to be better monitored to provide data-driven decision support towards water infrastructure upgrading. Although, the negative impacts of CSO discharges on aquatic environments are defined extensively, strict limitations are still needed to be set in the national regulations to force water managers taking necessary actions. To date, several cost-efficiency real-time monitoring systems are available and innovation projects are even using cloud and IoT platforms to better engage stakeholders and citizens and raise awareness about the CSO management importance. A combination of NBS and compact treatment system coupling smart monitoring with green and gray eco-innovative solutions should be planned at catchment scale, depending on the best technical, environmental and economic sustainability. Modular structures of these systems enable to set up different configurations according to the treatment requirements and field features. Moreover, extensive research is needed to validate actual integrated actions at catchment scale, integrating novel low-cost sensors, innovative treatment technologies, digital platforms and eco-efficiency assessment. Further researches and monitoring experiences will support the development of future concrete guidelines and strategies to manage the CSOs and to mitigate their impacts on the environment.

Conflict of interest

The authors have declared no conflict of interest.

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Figure captions

Fig. 1. A) Separate sewer system, B) Combined sewer system, C) Combined sewer overflow (adopted from Al Aukidy et al., 2017).

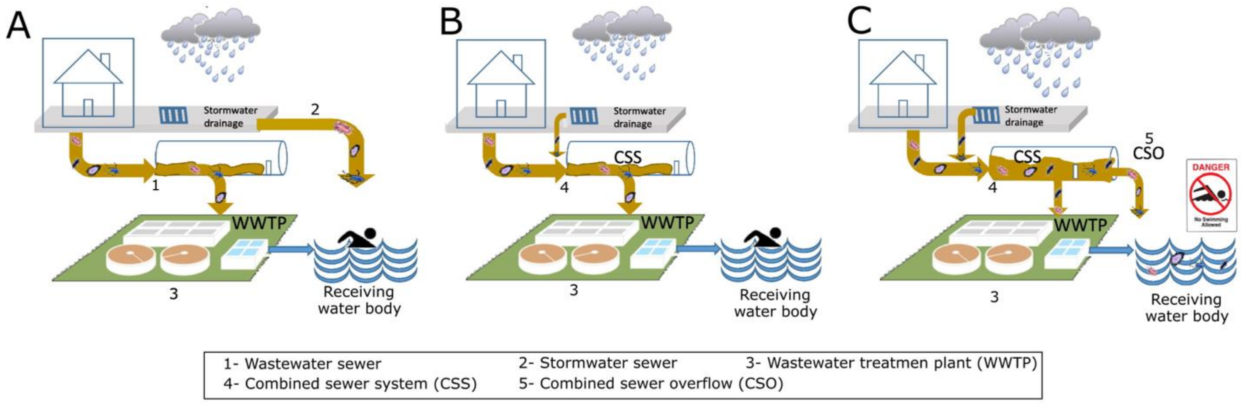

Fig. 2. Management strategies for combined sewer overflow (adopted from Levy et al., 2014).

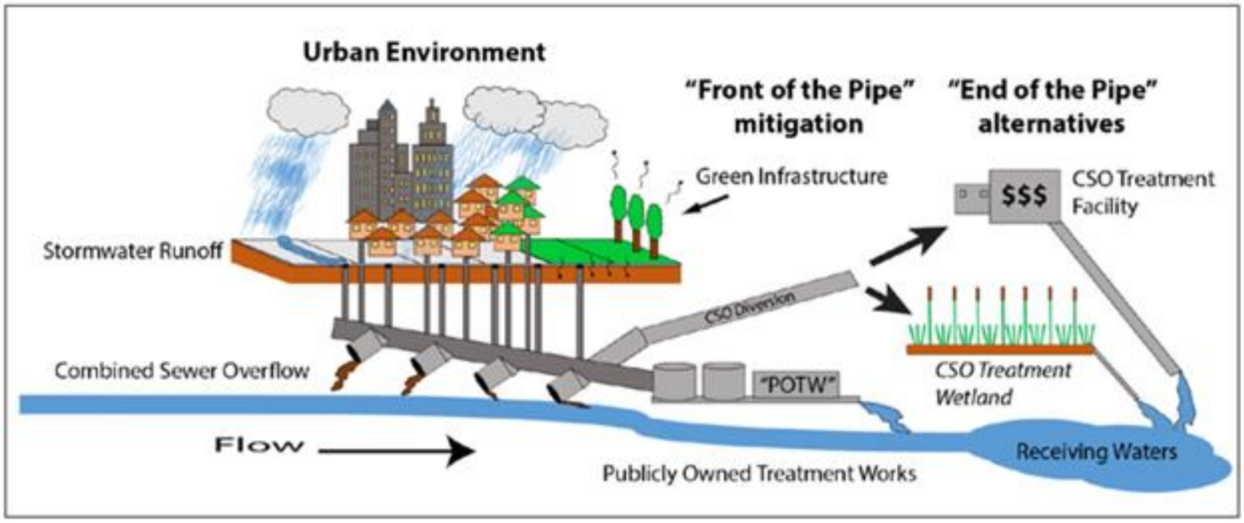

Fig. 3. Location of the INTCATCH pilot plant in Lazise, Villa Bagatta

Fig. 4. Flow diagram of pilot plant in Villa Bagatta – INTCATCH (Botturi et al., 2020)