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

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1   **Combined Sewer Overflows: A critical review on best practice and innovative solutions to**

2   **mitigate impacts on environment and human health**

3   **Alice Botturi[1], E. Gozde Ozbayram[2*], Katharina Tondera[3], Nathalie I. Gilbert[4], Pascale**

4   **Rouault [5], Nicolas Caradot[5], Oriol Gutierrez[6], Saba Daneshgar[1], Nicola Frison[1], Çağrı**

5   **Akyol[7], Alessia Foglia[7], Anna Laura Eusebi[7*], Francesco Fatone[7]**

6   [1] Department of Biotechnology, University of Verona, 37134, Verona, Italy

7   [2] Faculty of Aquatic Sciences, Istanbul University, 34134, Istanbul, Turkey

8   [3] IMT Atlantique, GEPEA, UBL, F-44307 Nantes, France

9   [4] Thames21, London, UK

10   [5] Kompetenzzentrum Wasser Berlin (KWB), Berlin, Germany

11   [6] Catalan Institute for Water Research, ICRA Scientific and Technological Park of the University

12   of Girona, Emili Grahit 101, 17003 Girona, Spain

13   [7] Department of Science and Engineering of Materials, Environment and Urban Planning-

14   SIMAU, Faculty of Engineering, Polytechnic University of Marche, 60121, Ancona, Italy

15   *** Corresponding author (A.L. EUSEBI)**

16   Department of Science and Engineering of Materials, Environment and Urban Planning-SIMAU,

17   Faculty of Engineering, Polytechnic University of Marche, 60121, Ancona, Italy

18   E-mail: a.l.eusebi@univpm.it, Phone: +39 071 2204911 Fax: +39 071 2204729

19   ***Corresponding author (E.G. OZBAYRAM)**

20   Faculty of Aquatic Sciences, Istanbul University, 34134, Istanbul, Turkey

E-mail: gozde.ozbayram@istanbul.edu.tr, Phone: +90554 734 6496

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

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64   minimally contaminated roof runoff, transport of storm water from low trafficked roads, streets

65   and pavements by open drains or the direct use for landscaping purposes is possible.

66   However, all sewer infrastructure is limited in its capacity for water intake and transport. Usually,

67   CSSs are unable to cope with the flows experienced during heavy rain events, so a relief

68   mechanism is inserted in the wastewater network which is a combined sewer overflow

69   infrastructure. This directs excess flows, comprising a mixture of untreated raw sewage and storm

70   water, to the receiving waterbodies. These structures are used to maintain the flowrates in the

71   network and protect properties from potential flooding (Bailey, Harris, Keedwell, Djordjevic, &

72   Kapelan, 2016).

73   Up to date, limited information has been published internationally concerning the extent and

74   occurrence of CSOs and discharge points. It is estimated that there are 2.2 million km of existing

75   sewerage systems in Europe, of which approx. 70% of the total network is combined sewers.

76   Moreover, there are approx. 650.000 CSOs and their impact on the receiving waterbody is an

77   increasing concern across Europe (EurEau, 2016). Some information can be obtained from

78   reports submitted to the European Union by member states. E.g. in 2012, Germany submitted a

79   request to extend the deadline of fulfilling the goals of the Water Framework Directive (reaching

80   a "good" ecological and chemical status of 80% of surface waterbodies by 2015) until 2027. In a

81   summary of the 2012 report to the European Commission (BMU, 2013), the authors describe that

82   10% of the key measures required reach the good status pertain to sewer systems and municipal

83   wastewater treatment plants. From the total number of these key measures mentioned in the

84   report, approximately 28% of them concern storm water in combined and separate sewer systems

85   and only 12% of them has a connection to the sewer system in general (UBA, 2012). Since this

86   report does not mention costs or the kind of measures taken to reach the EU targets, it still

87 remains unclear which role measures in the CSS play in relation to others.

88 The American Society of Civil Engineers estimated that the infrastructure for CSO control may

89 cost around $45 billion, which is the largest necessity in the water/wastewater sector for the

90 country (Ruggaber & Talley, 2005). Today, in the USA there are 746 communities with CSSs

91 containing a total of 9,348 CSO outfalls that are identified and regulated by 828 National

92 Pollutant Discharge Elimination System (NPDES) permits. CSSs are found in 32 states and nine

93 EPA (Environmental Protection Agency) Regions. CSO communities are regionally

94 concentrated in older communities in the Northeast and Great Lakes regions. The EPA estimates

95 that approx. $3.9 \cdot 10^9$ m^3 of untreated combined sewage is released as CSOs each year in the

96 United States (US-EPA, 2004).

97 Since CSOs result from a mixture of raw sewage and storm water, they possess a serious threat of

98 microbial pathogens (Al Aukidy & Verlicchi, 2017), micropollutants from personal care products

99 (Heinz et al., 2009), hormones Phillips et al., 2012), pharmaceutical and illicit drugs (Munro et

100 al., 2019), pesticides (Gasperi et al., 2012; Launay, Dittmer, & Steinmetz, 2016), suspended

101 solids, heavy metals, nutrients and microplastics in surface waterbodies (Al Aukidy & Verlicchi,

102 2017; Kistemann, Schmidt, & Flemming, 2016; Madoux-Humery et al., 2015; Masi, Rizzo,

103 Bresciani, & Conte, 2017; Munro et al., 2019; Suárez & Puertas, 2005; Tanaka & Takada, 2016;

104 Tondera, Koenen, & Pinnekamp, 2013; Xu et al., 2018). Meteorological and climate change

105 predictions indicate an expected rise in the frequency and intensity of storm events with the

106 implication that sewer system capacity will be exceeded more regularly. Furthermore, increased

107 base flow in sewers due to trends for increasing urbanization and population growth in many

108 cities worldwide means sewers fill up faster, which increases the likelihood of overflows during

109 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 (m³)	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)	-	-	-	7×10^6/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	3.2×10^6/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

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Table 2. The characteristics of combined sewer overflows

Study site	Monitoring strategy	TSS (mg/L)	BOD₅ (mg/L)	COD (mg/L)	TN (mg/L)	N-NH₄ (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

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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

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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,

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273 2018), they proposed a methodology which demonstrated the shortcomings of current long-term

274 classification as well as the potential for improvement by applying the proposed approach

275 regarding to the microbial safety. However, USEPA's BEACH Program conducted an annual

276 survey of the nation's swimming beaches. During the 2002 swimming season, CSOs and SSOs

277 were responsible for only 1 and 6 percent, respectively, of reported advisories and closings

278 (USEPA, 2004). Therefore, results are controversial and call for proper smart monitoring and

279 case-by-case analyses.

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

281 The necessity of controlling CSO pollution under the urban wastewater treatment directive

282 (UWWTD; OJEC 1991) and water framework directive (WFD; OJEC 2000) was stated by the

283 European Union. Discharges of CSOs may affect the achievement of "good status" of

284 waterbodies as required by the European Water Framework Directive. The scientific community

285 and the water sector operators are raising awareness of the environmental problems relating to

286 CSOs and are promoting initiatives for reduce their impact and improving the quality of surface

287 water (EurEau, 2016).

288 Since 1998, there have been significant changes in legislation with the implementation of the

289 water directives; and water quality and ecological standards have been revised. New issues have

290 arisen with an urgent need of adaptation and mitigation measures in the upgrading of urban

291 drainage systems. In the European legislation relating to CSOs, it is possible to distinguish

292 between Directives aimed at protecting receiving waters and Directives to control CSO

293 discharges (Morgan, Xiao, & McNabola, 2017). The Urban Waste Water Treatment Directive

294 91/271/EEC (UWWTD) highlights that the collecting systems shall be constructed and managed

295 in accordance with limiting the quantity of pollution entering receiving waters due to storm water

296 overflows. In addition, the UWWTD requires reporting of wastewater sewerage treatment

297 performance and a system of pre-authorization for all wastewater discharges, including CSOs.

298 The ongoing evaluation of the UWWTD has highlighted the importance of better managing

299 CSOs. The Bathing Water Directive 2006/7/EC (BWD) and the Habitats Directive 92/43/EEC are

300 limited to assess the bathing waters affected by CSOs as "subject to short-term pollution". In the

301 EU Regulation No. 166/2006 (2006)"concerning the establishment of a European Pollutant

302 Release and Transfer Register", EU member states are obligated to report pollutant loads,

303 specified in Annex II, to water. The threshold values are also specified in this regulation. Thus,

304 the pollutant loads from CSO discharges should also be estimated. However, this is very

305 challenging since CSO structures are not designed for monitoring purposes.

306 CSO discharges have been identified as an important problem for European countries. Germany,

307 UK and other countries have started to establish CSO policies and actions before Water

308 Framework Directive (Malgat, 2013). Sixteen EU member states have national standards that

309 regulate storm water overflows, eleven of them have guidance documents that directly address

310 storm water overflows (EurEau, 2016). Common approaches in standards and guidance are:

311 -   Limit on the number of overflows (e.g. Belgium, Poland, Portugal);

312 -   Requirements for dilution (e.g. Bulgaria, Czech Republic, Estonia);

313 -   Other approaches seen: max total volume, or max number of days of overflows (e.g.

314 Germany).

315 The permitted number of overflows per year proposed by CSO regulation guidelines differs

316 according to each member country and ranges from 2-3 in Denmark and the Netherlands, 15-20

317 in the Galician region in Spain (Table 3, Montserrat et al., 2015) and 10 in Poland (Brzezińska et

318 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

320 In the UK the requirements for solids separation depend on the number of overflows per year.

321 The Urban Wastewater Treatment Regulation (6 (2), 1994), states that primary treatment must be

322 provided within CSO structures, in which the biological oxygen demand, determined over 5 days,

323 (BOD_5) of the incoming wastewater is reduced by at least 20% before discharge and the total

324 suspended solids reduced by at least 50% (Morris, 1999). The third periodic Asset Management

325 Plan review (AMP3: 2000–2005) specified a timetable for water companies to reduce the number

326 of unsatisfactory intermittent discharges caused by CSOs (McSweeney et al., 2009). In 2012, a

327 comprehensive framework for CSO improvement has been developed through the urban pollution

328 management program to assess the impact of CSO discharges on receiving water quality and to

329 develop water quality standards for the protection of aquatic life from intermittent pollution

330 caused by CSO discharges (Morgan et al., 2017). These criteria also form the basis of CSO

331 assessment in Ireland, as set out in the Procedures and Criteria in relation to Storm Water

332 Overflows. On the other hand, in Italy, a list of performance indicators to describe the technical

333 quality of the water utility management and operation were introduced in 2017 by the Italian

334   Regulatory Authority for Energy, Networks and Environment (Regulation Number 917/2017).

335   The section dedicated to the sewer system includes two restrictions; firstly, the adequacy of the

336   CSO stations and secondly, the number of overflows allowed in one year in each 100 km of

337   sewage system. Moreover, in Spain, the Royal Order RD 1290/2012 requires that all CSO

338   discharging points for places exceeding 2000 equivalent inhabitants be defined (Montserrat et al.,

339   2013). In France, it is just stated that CSOs spillages must not exceed 2% of the total average

340   annual volume for 5 years (Tabuchi, 2013) and according to the "Local Authorities General Code

341   2015 Order" monitoring must be ensured by the operator, municipality and the different water

342   policy services. However, in Germany, several guideline describe the design and construction of

343   CSO retention tanks at points with critical discharge (ATV-128, 1992; DWA, 2013b, 2013a).

344   Capacities depend on factors like the catchment area, population density, historical rainfall

345   patterns and the proportion of impervious surface areas. The percentage of wastewater in a

346   catchment that can be discharged via overflows is based on ten-year rainfall patterns and

347   determined by the sensitivity of the receiving waterbody. In 1994, the United States

348   Environmental Protection Agency issued the combined sewer overflow control policy in the

349   National Pollutant Discharge Elimination System program (NPDES). Within the scope of the

350   policy, site-specific permits were developed for all CSS considering cost/performance in relation

351   to the size of the individual systems. Additionally, a list of nine minimum measures were

352   determined for CSOs in order to develop and adopt long term control plans (U.S. EPA, 2001;

353   U.S.EPA, 2004). They include programs for control measures during installation and pollution

354   prevention, pre-treatment applications, maximization of the storage in collection system and flow

355   directed to the WWTP, monitoring, as well as public communication. In Canada, although there is

356   no federal legislation for CSOs control, some provinces, like Quebec, adopted specific rules to

357   restrict CSOs (MDDELCC, 2014). To be in accordance with the Strategy for the Management of

22

358 Municipal Wastewater Effluent, municipalities and developers have to demonstrate that new

359 developments will not result in an increase in the frequency of CSO (Mailhot, Talbot, &

360 Lavallée, 2015). According to the Canada-wide Strategy for the Management of Municipal

361 Wastewater Effluent, CSO discharges are not entirely prohibited, but are allowed in exceptional

362 circumstances, such as during snow-melt in spring time (Jalliffier-Verne et al., 2016). Differently,

363 in Japan, in 2003, an amendment of "Enforcement Ordinance of Sewerage Law" related to CSO

364 discharges abatement was issued defining the BOD_5 concentration in the effluent overflow (< 40

365 mg/L), allowing a provisional limit of 70 mg/L applicable until structure standards start to be

366 applied. Small and midsize municipalities were obligated to implement improvements by 2013,

367 large municipalities by 2023. Environment Protection Authority of South Australia issued a code

368 of practice for wastewater overflow management giving a roadmap to the operators to comply

369 with their environmental obligations. The water utility is obligated to implement an overflow

370 abatement program, which encompasses an emergency response plan and short- and long-term

371 measures to prevent or reduce the re-occurrence of overflows. However, in South Africa the

372 policy related to runoff water disposal asserts that: "Urban stormwater discharged to the marine

373 environment should not have any negative impact on the Environmental Quality Objectives of the

374 receiving environment", it does not provide specification on treatment-at-source or land-based

375 treatment, which are considered specific to disposal of stormwater runoff.

376 Overall, different directives have been developed worldwide, which are mainly focused on the

377 affirmation of the negative effects of the CSO events and allowed a number of overflows per year.

378 Generally, the policymakers are revising and deriving the regulations to enforce authorities to take

379 pre-cautions and control CSO discharges. Although they pointed out the adverse impacts, in many

380 countries no specific limits for water parameters have not been set to limit pollution from CSO

23

381 discharges. This aspect is mainly related to the great variability in terms of quality and quantity of

382 CSO characterization in the different sewer systems, previously described in the Section 3.

383 Moreover, wide sampling campaigns and monitoring methods have to be implemented in order to

384 quantify the hydraulic and the characterization conditions to support the legislation improvements.

385 Finally, specific treatment technologies and control measures can be integrated into the regulations.

386 **5. Innovative methods for CSO determination**

387 Hydraulic conditions are the main factor to determine the proper method for monitoring CSOs.

388 Table 4 displays various methods used to estimate CSO volumes.

389 **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

390 Sensors and probes are also applied for monitoring purposes in most of the high income

391 countries, such as conductivity meters to detect occurrence and determine duration, level sensors

392 with moderate and/or higher cost, advanced sensors (eg UV-VIS) for also determining water

393 quality. Where budget is limited, level sensors can be coupled with overflow equations to

394 measure CSO volume. On the other hand, a level and a velocity sensor combined with

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395   flowmeters generate the most accurate/reliable data but require more investment cost and higher

396   maintenance (Montserrat et al., 2013).

397   The costs of data storage and high capacity computer systems are still an issue in CSO

398   monitoring. Moreover, in heavy rain events, huge quantities of data must be processed and

399   evaluated for every alarm situation in order to take immediate action (Bailey et al., 2016). The

400   other point is the location of the CSO control system. The characteristics of the land can make the

401   connection to the network difficult.

402   A low-cost method was introduced by Montserrat et al. (2013) to detect the occurrence and

403   duration of CSO events. The proposed method depends on the temperature changes between the

404   sewer gas phase and the overflowing mixture of wastewater and storm water. Using temperature

405   sensors for CSO detection has several advantages such as minimum capital cost, easy installation,

406   requirement of minimum technical knowledge for integration, tolerance to extreme

407   environmental conditions and minimum maintenance. The authors also validated their systems

408   and achieved detection greater than 80% of the total CSO occurrences, which showed that

409   temperature differentiation during seasonal changes does not have a negative impact on

410   effectiveness. However, physical features of the weir affect the detection performance. Later

411   research, published in 2018, increased the robustness of the method proposed in Montserrat et al.

412   (2013) by adding a second temperature sensor, improving the detection accuracy by

413   implementing an algorithm that accounted for the response time of the system and automatically

414   calculated the duration of CSO events (Hofer et al., 2018). As a result, in a 7-month test phase, all

415   20 CSO events were recognised without false detections.

416   Another group from France, recently developed a system called the DSM-flux (Device for Storm

417   water and combined sewer flows Monitoring and the control of pollutant fluxes) to determine and

418   control both the quantity and quality of CSO discharges (Maté Marín et al., 2018). The validated

419   system can measure overflow volumes and pollutant concentration, decrease particulate

420   pollutants from sedimentation and the erosive potential of overflows to the receiving waters. The

421   advantages of installation of the DSM-flux system are: - direct measurement at the overflow

422   channel, - installation downstream from the existing CSO structure, -requirement of only one

423   level measurement for determination of discharge values, - not affected by inlet hydraulic

424   conditions, - reduced particulate pollutants and erosive potential of CSO discharges.

5.1. Smart CSO monitoring and control

426   Currently smart network monitoring and smart data infrastructures (US EPA, 2018) are under

427   development and application. These infrastructures are implemented in connection with a

428   supervisory control and data acquisition (SCADA) system and are mainly focused on real-time

429   monitoring of flow rates (physically or with alternative methods) and effluent levels of CSO's

430   with the aim of assessing potential flooding and pollution incidents. The final objective is to

431   support decisions in real-time or quasi real-time about actions to be taken. For instance, SPRINT

432   226 a European project focused on the implementation of real-time sewer system control for

433   eight European cities: Copenhagen (Denmark), Mantova (Italy), Verona (Italy), Genoa(Italy),

434   Berlin (Germany), Vitoria-Gasteiz (Spain), Bolton (United Kingdom), and Goteborg (Sweden)

435   (Entem, Lahoud, Yde, & Bendsen, 1998). The project showed decent real-time control

436   performance for overflow events of the sewer system in terms of prediction and generation of

437   strategies to be taken into consideration (Entem et al., 1998). Another study (Seggelke et al.,

438   2013) focused on real-time control of a CSS in a city in Germany with the aim of monitoring

439   frequency of overflow events and investigating how to reduce them. In addition, Carbone et al.,

440   2014 investigated a real-time control solution for an urban drainage network in Italy. It used an

441 innovative and smart series of gates that automatically adjusted themselves in order to optimize

442 the storage capacity of a sewer system during rainfall events. Moreover, in the INTCATCH

443 project, as an innovative approach to monitor water quality, autonomous and radio controlled

444 boats are developed and demonstrated in key catchments such as Lake Garda, Lake Yliki

445 (Warner, Nödler, Farinelli, Blum, & Licha, 2018). The results revealed that monitoring the

446 routine parameters can give an overview of the current status of the water body, as well as

447 contribute to reducing the monitoring cost. Moreover, real-time monitoring of site-specific

448 indicator allows determining the pollutant source which helps to derive proper catchment

449 management strategy (Warner et al., 2018). The applications of smart data infrastructure systems can be

450 optimized by two different methods. Whereas the system improvements refer to increasing weirs, optimizing the

451 efficiency curves or location of CSO control, the real-time control systems manage the operation of wastewater

452 networks and facilities in real time (US EPA, 2018Grey (such as large concrete tanks or tunnels)

453 and green strategies (such as bioretention facilities, green roofs, porous pavements, and

454 stormwater planters) can be applied to control CSOs (De Sousa, Montalto, & Spatari, 2012) and

455 hybrid system of grey and green methods more advantageous than grey method-only in terms of

456 economy, environment and society (Gong et al., 2019). The control strategies can be optimized

457 by hydrological model simulations supported with scenario analyses (Chen et al., 2019). In the

458 USA, different approaches are integrated in different states to control and manage CSOs. In

459 Philadelphia, the Water Department has a goal to reduce overflows (7.9 billion gallons of

460 overflow water) by 2036. For this purpose, smart data technology was integrated into existing

461 stormwater retention basins to monitor basin water level and precipitation, and maximize the

462 performance of the basin by real-time active control to selectively discharge from the basin

463 during optimal times. On the other hand, 10 high frequency cleanout sites with remote field

464 monitoring units were integrated in the San Antonio Water System (SAWS) in which day-to-day

465   level trend changes can be detected by an analytical software giving data for potentially

466   important changes in water levels. In the pilot locations, there were no sewer overflows in

467   May/June 2016 with when nearly 16 inches of rain overwhelmed the SAWS. The real-time

468   control system was adopted in Louisville in 1990s and actively used since 2006. The system

469   prevents more than 1 billion gallons of CSO volume annually. In Indiana, there are 152 sensors

470   located through the city of South Bend to maximize the capacity and performance of the city's

471   collection system, which helped to reduce total CSO volume by roughly 70 percent, or about 1

472   billion gallons per year during the period 2008-2014. Moreover, in Greater Cincinnati, there are

473   more than 200 CSO points, causing a discharge over 11 billion gallons of sewage into the Ohio

474   River and its tributaries annually. 164 overflow points were integrated within the frame of the

475   smart sewers network to date and sensors were installed through the watershed (USEPA, 2018).

476   The monitoring technology should be pursued in the catchment base, and economical analysis

477   should be carefully proceed to decide to integrate the best smart strategy.

5.2. Innovative treatment alternatives

479   Different strategies are developed to reduce the impacts of CSOs, such as increasing storage

480   capacity, detention/retention facilities, as well as sewer separation to fulfill the requirements of

481   the related regulations (Figure 2). However, converting CSS into a separated system can be

482   prohibitive due to cost and it does not always guarantee pollution reduction (Li et al., 2010). One

483   of the many goals of this review is to gather the latest information on treatment technologies,

484   grouped as natural and technological treatment, and their performances in treating CSOs.

485   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)

	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)
Technological treatment	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)

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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

535 efficient performance in terms of organic carbon and TSS removal under dry weather conditions.

536 As expected, during the storm events there were a prompt increase in carbon and TSS load for a

537 short period followed by a dilution effect.

538 *5.2.2. Technological compact treatment*

539 Minimizing the negative impact of CSOs in the receiving waters can be achieved by in-line

540 treatment methods such as settling without additives, which is the most commonly applied

541 method, and chemical coagulation before discharge. Coagulation and flocculation are an effective

542 method to remove organic materials with organic/inorganic polymers as coagulants and

543 flocculants to get better sedimentation. In a study carried out by El Samrani et al. (2008), effects

544 of different commercial coagulants - namely, ferric chloride solution (CLARFER) and aluminum

545 salts (WAC HB) - were evaluated on turbidity and heavy metal removal from samples collected

546 during rainy weather at the inlet of Boudonville retention basin. The results showed that both

547 coagulants provided excellent removal of heavy metals; indeed; the concentrations of Cu, Zn and

548 Pb in the treated water complied with the water legislation.

549 Regarding flocculation treating CSOs, Gasperi et al. (2012) examined the performance of a full-

550 scale ballasted flocculation unit (BFU) implemented at the bypass of the wastewater treatment

551 plant located downstream of Paris on the Seine River. Ferric chloride ($FeCl_3$) and anomic

552 polymer were respectively used as coagulant and flocculant according to the turbidity levels

553 entering BFU, and high surface area was achieved by microsand to enhance flocculation, assist

554 flock formation and act as ballast, which aids rapid settlement. The performance of the system

555 was evaluated during the wet period, in which the bypassed combined sewage was treated only

556 with BFU and bio-filtration in order to remove nitrogen, before discharge. Significant removal

557 rates (>80%) were achieved for the compounds with a strong hydrophobic character (log Kow >

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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 $84 \pm 9\%$ 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

605 the configuration according to the treatment requirements.

606 To sustain the safety of the water quality of receiving water bodies used for recreational

607 purposes, microbial loads from CSOs should be reduced. Since quality and quantity of CSOs are

608 very variable, it a challenge to find suitable disinfection technologies which can be operated

609 spontaneously for a short period at full capacity. The most commonly applied disinfection

610 methods for the treatment of WWTP effluent are using chlorine compounds, ozone and ultra-

611 violet (UV). However, these are not ideal for CSO treatment due to the high concentrations of

612 solids and dissolved organic compounds: using chlorine compounds can lead to the formation of

613 toxic, mutagenic and carcinogenic chlorinate by-products (Bayo, Angosto, & Gómez-López,

614 2009; Nurizzo, Antonelli, Profaizer, & Romele, 2005).

615 Undesirable by-products can also be the result when using ozone. Tondera et al. (2015) evaluated

616 the effects of ozonation on diluted wastewater in a pilot scale application. Although the reduction

617 of pathogenic bacteria, viruses, and protozoan parasites were promising and more effective than

618 UV irradiation for the tested conditions, the operation of an ozone generator under these

619 conditions is difficult to manage and both installation and operation is costly.

620 Suspended solids and turbidity in CSOs are also limiting parameters on the disinfecting effects of

621 UV radiation (Tondera et al., 2015). In another study, Gibson et al. (2016) evaluated the effects

622 of chemical pre-treatment of CSOs for subsequent UV disinfection. When applying 20 mg/L

623 alum, the UV light transmission of the raw CSO increased from 30 to 60% after settling. The

624 high charge density cationic polymer improved the removal of turbidity but did not affect UV

625 transmittance (UVT) and TSS. The use of alum (metal coagulants) can achieve a UVT of 78%,

626 while the use of cationic polymers reached a value of 60%. Pre-treatment to remove particles via

627 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.

38

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

674   data-driven decision support towards water infrastructure upgrading. Although, the negative

675   impacts of CSO discharges on aquatic environments are defined extensively, strict limitations are

676   still needed to be set in the national regulations to force water managers taking necessary actions.

677   To date, several cost-efficiency real-time monitoring systems are available and innovation

678   projects are even using cloud and IoT platforms to better engage stakeholders and citizens and

679   raise awareness about the CSO management importance. A combination of NBS and compact

680   treatment system coupling smart monitoring with green and gray eco-innovative solutions should

681   be planned at catchment scale, depending on the best technical, environmental and economic

682   sustainability. Modular structures of these systems enable to set up different configurations

683   according to the treatment requirements and field features. Moreover, extensive research is

684   needed to validate actual integrated actions at catchment scale, integrating novel low-cost

685   sensors, innovative treatment technologies, digital platforms and eco-efficiency assessment.

686   Further researches and monitoring experiences will support the development of future concrete

687   guidelines and strategies to manage the CSOs and to mitigate their impacts on the environment.

688   **Conflict of interest**

689   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).

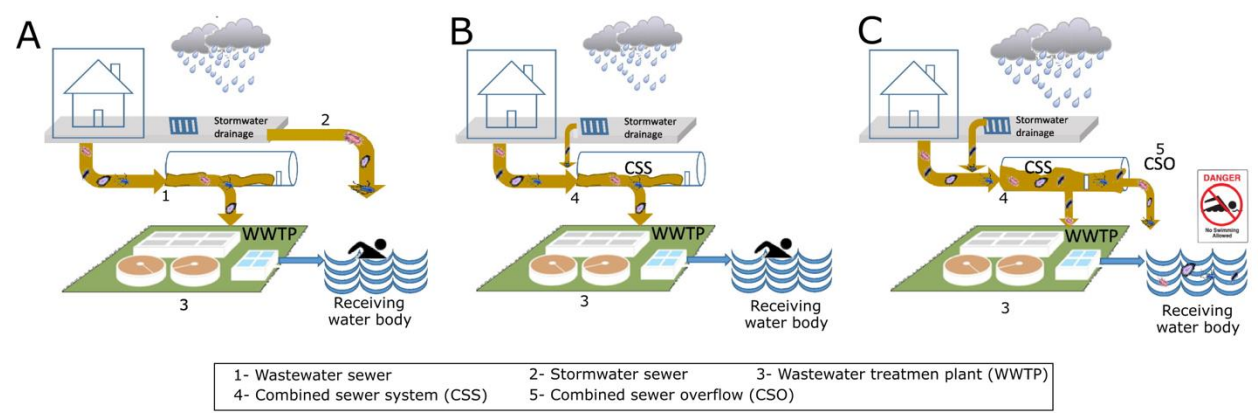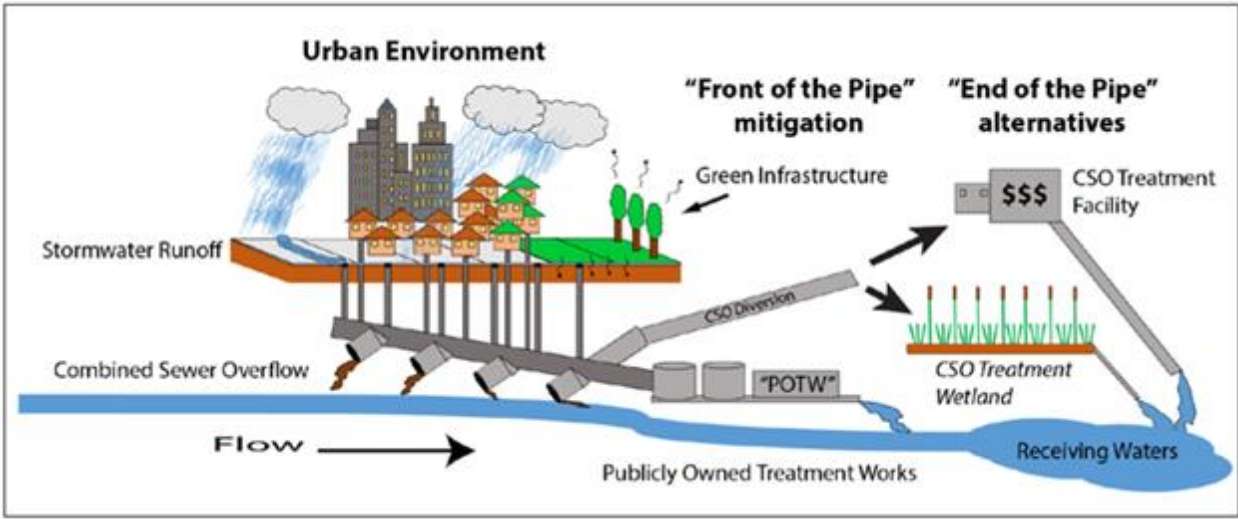| 1- Wastewater sewer | 2- Stormwater sewer | 3- Wastewater treatmen plant (WWTP) |
| 4- Combined sewer system (CSS) | 5- Combined sewer overflow (CSO) | |

Fig. 2. Management strategies for combined sewer overflow (adopted from Levy et al., 2014).
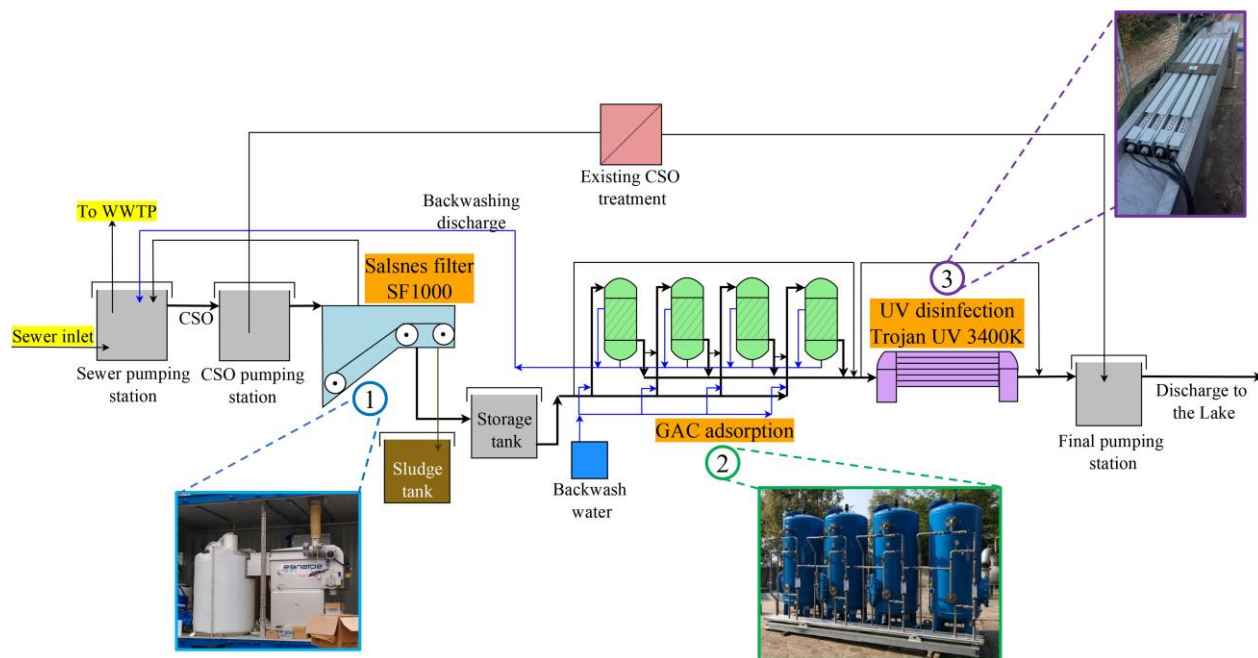
1033   **Fig. 3.** Location of the INTCATCH pilot plant in Lazise, Villa Bagatta

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