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The role of open data in regulating combined sewer overflows

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ABSTRACT

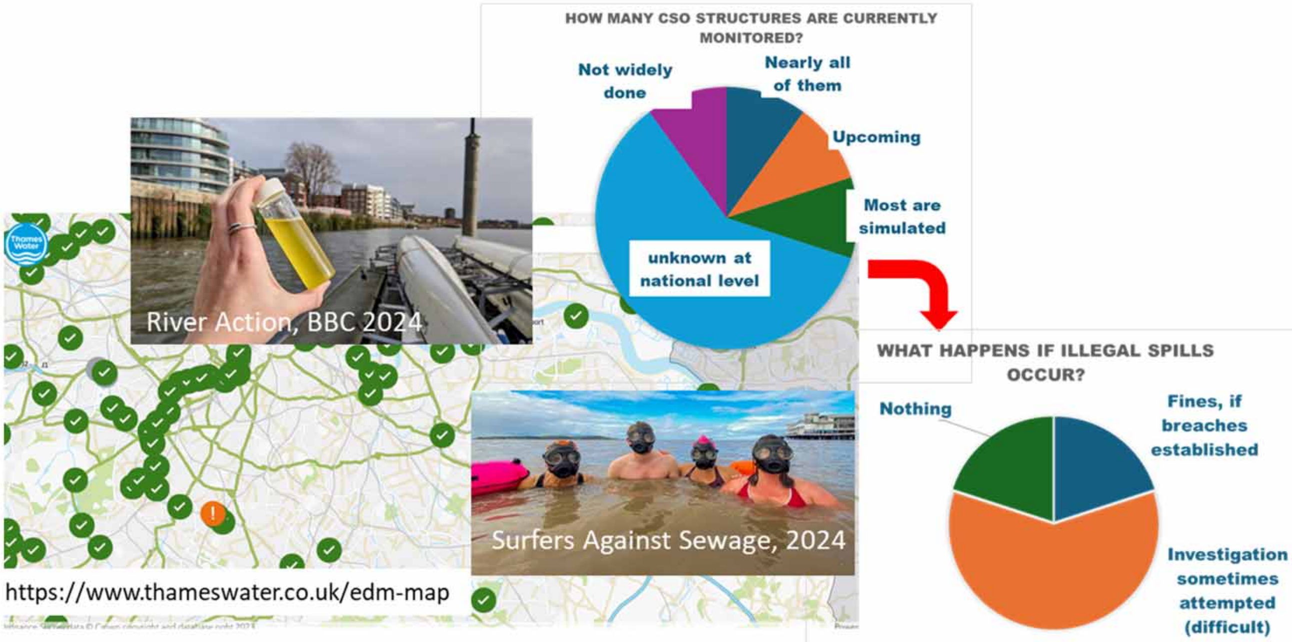
The aim of this work is to investigate how open data can play a beneficial role in the regulation of combined sewer overflows (CSOs). The investigation consists of a review and critical discussion of historic CSO design, alongside more recent developments of regulations and emerging experiences of monitoring CSOs and different levels of data openness. The study focuses on practice in 10 European countries/regions. The novelty of this work comes from its review of historical development of design guidelines and regulations, shifts in the aims of these regulations, practicalities around implementation and testing of compliance, alongside the openness and availability of data. The main conclusions are that increasingly complex regulation goes hand in hand with limited compliance checking and opaque decision-making, whereas opening up relatively simplistic performance data has generated public and political discussion about urban drainage systems and the potential costs of improvements in water quality of the impacted surface water bodies. Making CSO data open does, however, need to be done with due care. Collaboration with trusted citizen groups, ensuring the data are correct, easy to access, and understand, as well as avoiding a blame culture are all of key importance.

Key words: combined sewer overflows, compliance assessment, open data, policy, regulation

HIGHLIGHTS

- The comparison of combined sewer overflow (CSO)-related regulation and compliance assessment across several European countries.
- Exploration of the increasing complexity of CSO regulations and its challenges.
- Emerging experience with open CSO spill data and its potential to enhance transparency in regulation and foster public engagement.

GRAPHICAL ABSTRACT



INTRODUCTION

How a society deals with their wastewater collection and treatment system, its operation and regulation is a continuously evolving field. There is an ongoing shift towards a holistic view of the performance of the urban drainage system. However, this performance is complex to assess. There are increasing concerns related to both the cost of maintaining (let alone improving) deteriorating urban drainage systems, as well as the implementation of complex regulation.

In the European Union alone, the sewer infrastructure network has an estimated replacement value of 2.5 trillion € (IKT 2017). There is also a drive for more transparency in decision-making (EU 2024a) and public openness of information and data (e.g. Openaire 2024; Stream 2024).

Public concern is growing in several countries concerning combined sewer overflow (CSO) spills and their impacts on the environment and public health (e.g. City to Ocean 2024; Surfers Against Sewage 2024a; Surfrider Foundation 2024). However, assessment of the compliance of CSO spills with regulations can be based on monitoring data, models or a combination of these, and is a complex process containing uncertainty (Schellart *et al.* 2010). Assessing CSO spills compliance using measured data is currently state of the art in only a small number of regions (Rieckermann *et al.* 2020). In those regions where the practice of monitoring CSO spills is emerging, the data indicate that CSO structures spill far more than expected (Defra 2024), despite regulations being in place. If these underestimates of spill frequency were repeated across the majority of CSOs for which no data exists, the extent of the spill problem in Europe would be more severe than has been acknowledged to date, as corroborated by Botturi *et al.* (2021). CSOs now operate many times per year in most European countries, with many CSOs reported as spilling several 10 s times per year (Botturi *et al.* 2021; DEFRA 2024).

Hence, there is a need for a debate on improving urban drainage systems, and leveraging open data to improve management and regulation (e.g. by changing behaviour of public and water utilities, enabling public pressure on decision-makers, and facilitating better informed open debates on costs and willingness to pay).

To address the issues of appropriate CSO regulatory standards and the role of public scrutiny, we ask the questions: 'What type of monitoring data from CSOs would be most useful to collect and release to the public?' and 'what type of data would be best to support reducing the risk of environmental harm?' The paper will start to address these questions by reviewing the development of CSO design guidelines and CSO-related regulations, alongside experiences of monitoring CSOs and different levels of data openness. The study focuses on practice in European countries, where there is increasing political scrutiny of

CSOs through the recent revision process of the EU Urban Wastewater Treatment Directive (UWWTD; EU 2024b) and the new obligations in the UK Environment Act (UK Government 2021).

This research offers novelty through its synthesis of the historical regulatory development, evolving aims, and practical implementation challenges inherent in CSO management, with a particular focus on the implications of recent shifts towards more open data management.

In the European Union, the revised UWWTD requires establishing and implementing integrated urban wastewater management plans in all larger agglomerations (>100,000 Population Equivalents, PE, cf. Article 5) to reduce pollution from urban runoff and stormwater overflows. Annex V has been adapted (EU 2024b) to read 'an indicative *non-binding* objective is that storm water overflow represents *a small percentage that cannot be* more than *2%* of the annual collected urban wastewater load calculated in dry weather conditions'. It should be noted that the UWWTD uses the term 'storm water overflow' to specifically indicate a 'combined sewer overflow'. Outfalls from separated systems fall under the term 'polluted discharges of urban runoff'. New 'open data' obligations have also been proposed, 'Member States shall ensure that adequate and up-to-date information on urban wastewater collection and treatment is available to the public online, in a user-friendly and customised way, in each agglomeration' (Article 24). The required information is listed in Annex VI 4c and includes 'for agglomerations above 10,000 p.e. an estimate of the load of the discharges from combined sewer and storm water overflows for the parameters referred to in Tables 1 and 2 of Annex I'. In the UK, Section 82 of the Environment Act 2021 requires sewerage undertakers wholly or mainly in England to continuously monitor water quality upstream and downstream of assets that discharge into watercourses, such as CSOs and wastewater treatment works (WWTWs). Water quality is defined by the concentration of three pollutants, pH, and temperature. Sewerage undertakers are furthermore required to publish drainage and wastewater management plans (DWMPs), to 'provide the basis for effective engagement with customers and stakeholders on levels of service, environmental performance and resilience, now and for the future, and on the choices and costs to customers in providing that service' (UK Government 2024). The Environment Act, Section 79 states that the sewerage undertaker should annually review the DWMP and send a statement of the conclusions of its review to the Minister.

However, as far as the authors are aware, there is currently limited experience of what constitutes 'adequate' and 'user-friendly' open information, and/or how to create 'effective engagement with customers', although different experiences with open data are starting to emerge (City to Ocean 2024; CaSTCo 2025).

There is also increasing awareness about micropollutants, contaminants of emerging concern, and pathogens in CSO spills, both among professionals (e.g. Mutzner *et al.* 2022) and in the public domain (e.g. Usher 2023; Fluidion 2024; Surfrider Foundation 2024). Research by Büttner *et al.* (2022) found a severe impact of urban emissions on the ecological state of small- to medium-sized watercourses in Europe. The growing and ageing population, urbanisation, and climate change further exacerbate pressures on existing urban drainage systems. For example, Muelchi *et al.* (2021) projected a 40% decline in river flows in Switzerland due to changing runoff patterns, which would mean less dilution of any wastewater emitted through CSOs and increased pressure on aquatic ecosystems. These increasing concerns about the toxicity and microbial risks of CSO spills challenge current regulation.

The EU Water Framework Directive, Article 10 (EU 2000) requires the combined control of point and diffuse sources of pollution, with the establishment of emission control based on best available techniques or relevant emission limit values, and best environmental practices in the case of diffuse pollution. This has translated to different types of local regulation in relation to urban drainage, those based on emissions standards (e.g. limiting frequency or volume or pollutant loads of CSO spills themselves), or those based on impact on the state of the water body receiving the spills (e.g. duration and frequency of exceedance of certain pollutant concentrations in the receiving water; Blumensaat *et al.* 2012). Impact-based standards are held up as a more scientifically sound reflection of environmental harm such as acute toxicity to aquatic life. However, checking against impact-based standards is complex and uncertain due to the need for either a complex integrated sewer system and river impact modelling (e.g. Schellart *et al.* 2010) or continuous water quality data collection in the waters receiving the spills. Rigorous uncertainty analysis would be needed to get meaningful insights from integrated models, but this does not routinely happen (Tscheikner-Gratl *et al.* 2019). Unfortunately, screening studies do not find simple correlations between readily observable variables (such as rainfall volume, intensity, storage volume, and land use) and receiving water impacts (Engelhard *et al.* 2008; Meng *et al.* 2016). This is to be expected as, historically, urban drainage systems are designed to protect the urban area from flooding and protect human health, and not to protect the ecological status of the watercourse receiving the CSO spills.

Hence, a discussion on a more pragmatic way of regulating CSOs, and evidence-based compliance is needed to inform realistic future regulatory standards. This paper aims to aid the debate by critically reviewing the development of CSO design guidelines as well as regulatory guidelines, alongside emerging experience with open CSO performance data.

METHODS

This study involved a group of experienced researchers (the co-authors of this paper) comparing practice in their respective countries/regions. They reviewed local regulations and compliance checking, design guidance and available data, to answer and discuss the following questions:

- What is the number of CSO structures in your country/region? Who owns/operates and controls these CSO structures?
- What principle drove the historic design of CSO structures?
- What is the principle driving design of 'new' CSO structures/upgrades to existing CSO structures?
- How are existing CSO structures regulated? Is this spill frequency, spill volume, receiving water impacts, or a combination of these?
- How many CSO structures are monitored, using what parameters?
- Is CSO spill data used in regulation compliance assessment, and if so, what type of data is used for this?
- Does assessing compliance with data happen regularly or only in certain cases?
- What happens if illegal CSO spills occur? Who is responsible for follow-up investigation and preventing recurrence?
- Is CSO data made public? If so, what type of data is made public, and through what mechanism is this made public? Can the data be easily understood?
- Is river quality data collected regularly? If so, what data. Is this data country-wide and made open to the public?
- Are there any types of local citizen action groups concerned with river quality? Are they utilising and/or scrutinising data? Is there media impact from open data?

These questions were shared with all co-authors via email and the answers were collected in shared online documents for everyone to comment on and ask for clarifications where needed, sometimes via online meetings.

RESULTS

During the research, it became apparent that answers to, for example, the description of ownership, operation, and control of sewer systems could not always easily be summarised for a whole area, due to regional variations and complex layers of governance and regulation. For example, in Germany, CSOs are operated either by the public sewerage companies or municipalities, and regulations for self-control and reporting can vary a lot for each federal state. In the Netherlands, water boards also have different interpretations of national law. A summary of the responses to the questions is described in Table 1, with key findings illustrated in Figure 1. Findings that could not easily be tabulated are described in this section. Historical development regulations also inform the development of CSO design, more detail on the historical development CSO design is described in Supplementary Material, Part 2.

Hence, the results of this exercise are far from exhaustive, and to some degree anchored on the personal experience of the involved experts. However, the findings aim to demonstrate the intricacies of regulating wet weather emissions from urban areas, by considering incomplete information on wastewater generation, rain, non-linear rainfall-runoff responses, complex pollutant transport and transformation processes, and the role of public opinion. This serves as a starting point for a discussion on the regulation of CSO spills, and the role of open data, and citizens, may play in managing CSO spills.

Comparison of the number of CSO structures

A CSO structure has here been defined as a structure in the sewer system with the purpose of avoiding flooding and/or hydraulic overloading of WWTW due to 'heavy' rain. The numbers do not include the so-called emergency overflows, such as for example installed at a pumping station in case of pump failure. The report by Milieu (2016) gives an overview and for some regions a differentiation of types of overflow structures in the EU. Where possible, Table 1 contains more recent numbers, refer to Supplementary Material, Part 1 for details and references.

To explore any regional differences, the average number of inhabitants per CSO structure was calculated. The number of inhabitants per country was taken from different statistics offices; refer to Supplementary Material, Part 1 for references.

Table 1 | Comparison of CSO monitoring, regulation, and compliance assessment in several European countries

Questions	England/Wales	France	Switzerland	Belgium	Denmark	Spain	Netherlands	Germany	Austria	Norway
Number of CSO structures	14,530	9,468	est. 5,000 (no official statistics)	**Flanders**: est. 8,000 **Brussels:** est. 100	4,257	7,995 for 80% of territories	est. >15,000	20,880 without storage 27,992 with tanks	Estimated 10,300	3,928
Ratio of nr. inhabitants/ nr. CSO structures	4,108	7,200	1,748 (est.)	990 (Flanders and Brussels combined)	1,394	n/a	1,187	1,824 (all types CSOs combined)	884	1,418
How are existing CSO structures regulated?	**Emission based** (Pass-forward flow). Occasionally **Moving to Emission + river impact based**	**Emission based.** (Municipality decides): spill frequency, **or** spill volume, **or** spill pollutant load	**Receiving water impact based.** Some cantons are different (e.g. spill duration in Basel)	**Flanders: Emission based** (Spill frequency)	**Emission based.** Nr. of CSO events, yearly volume, max discharge (l/s/ha)	**Emission based** (spill volume) and **receiving water impact based** in some cases	**Emission and sensitivity of the receiving water based**	**Emission based** Permits based on COD load. In some federal states, additional criteria may apply	**Emission based.** Legally binding regulation planned since 1996, but adoption failed	**Emission based.** (Rules vary based on p.e. thresholds. spill duration and pollutant load in overflow for larger systems)
How many CSOs are monitored, using what attributes?	**13,323 CSO structures** (2022), start and end time of spill monitored	**Not publicly known at the national level.** Data could be obtained at the municipal level or from Water Agencies	**Unknown at the national level**. Data could be obtained at utilities. Reporting not obligatory	**Brussels:** 50% of CSO structures (Frequency and duration, simulation of the volume via level and velocity data). **Flanders:** 30% CSOs monitored (VMM)	**Most are simulated.** 0.6% has monitoring of spill quality, 7% monitoring of hydraulic parameters	**Upcoming:** all sewer systems >50,000 p.e. will be monitored (spill duration, volume, and some cases pollution)	**In some areas, monitoring is obligatory**, the monitoring network is growing	**Not widely done** (only for certain types of CSOs, i.e. with tanks); monitoring of CSOs with tanks compulsory in two federal states	**Unknown at the national level**	**Unknown at the national level**
Is **monitored** or **simulated** CSO spill data used in regulation compliance assessment?	**Yes**, **monitored** spill duration data	**Depends, monitored, or simulated** (largest CSO structures must be monitored)	**Not yet.** Permits based on **simulated emissions** Some cantons ask for CSO attributes	**Brussels:** A reporting of **monitored** CSO spills happens on at yearly basis by 'Brussels Environment'	Each municipality **has to report** the (**mostly simulated**) yearly discharges	**Upcoming**: river basin authorities will be informed on **monitored and simulated** CSO data	**No,** just to get an indication of the evolution of spills	**No monitored data is used.** Permits are based on **simulated emissions**	**No.** Only very limited data is available. Where available, mostly measured voluntarily and not made public	**Depends, monitored or simulated.** Limited data on permits are to be reported annually. Nr and duration, m^3 and kg tot-P are asked 'if available'
Does assessing compliance with data happen regularly or only in certain cases?	**Spill frequency is regularly assessed. Receiving water impact only rarely**	Municipalities **must report** CSO compliance. Evaluated yearly from data collected in previous 5 years	**No**, currently no legal requirements for CSO monitoring and reporting	**Brussels:** Follow-up on a yearly basis	Compliance checked by the Environmental Agency, but controls are not sufficient	**Just in few cases** and depending on the river basin authority	**No**	**Not regularly**. Only if data are far out of the expected, water authority might interfere	**No**, currently no legal requirement for CSO monitoring and reporting existing	**In theory, yes.** Control visits to check if compliant with permits, but the frequency of visits is not regulated

(*Continued.*)

Table 1 | Continued

Questions	England/Wales	France	Switzerland	Belgium	Denmark	Spain	Netherlands	Germany	Austria	Norway
What happens if illegal spills occur? Who is responsible for follow-up and preventing recurrence?	Fines for breaches of EA spill permits. Water utilities negotiate with EA and OFWAT on investment in 'solutions'	Municipalities are responsible. If illegal spills are detected, the source is investigated (but difficult to find)	Legal action is only for spills by private entities. If a municipality contaminates environment: nothing happens	**Brussels:** In case of illegal spill detection, 'Brussels Environment' tries to track its source, but often very difficult	Theoretically the responsible entity can receive a fine. In practice, this only very seldomly occurs	**Fines for illegal spills**. CSO compliance has been applied in just a few cases till now, as regulation since 08/23	Theoretically, the responsible organisation/ person can receive a fine. In practice, this very seldomly occurs	No standard procedure. **Difficult to categorise a spill during wet weather as illegal**	**Nothing.** There are currently no legal requirements for CSO monitoring and CSO reporting exists	Private persons or companies get fines. If a permit is violated by a municipality, procedure is followed that may end in a fine, but mostly in a discussion on solutions
Is CSO data made public, if so, what data, through what mechanism?	**Yes.** Event frequency and duration by EA, through big .csv files. Visualisations by NGOs	**No**	**Mostly No**. Yearly performance report of utility (authors only know of 1 utility that does it regularly)	**In some regions. Brussels:** data collected via FLOWBRU is Open Data	**Yes, public homepage.** NGO and journalists provide visualizations	**No**. Only some Aggregated data, not easy to understand	**In some regions**. In most areas, **only via a formal request**	**No.** Citizens have a legal right to information, they **only get monthly/ annually aggregated via formal request to water authorities**	**No**	**No**. All permits, control protocols and data are public, but mainly focused on WWTWs. CSO data not public
Is river quality data collected, regularly, if so, what data; is it country-wide and made open to public?	**Yes**. 160 stations for continuous monitoring plus infrequent grab samples and invertebrate surveys. Data public through EA	**Yes.** These data are made publicly available, e.g. on websites of Water Agencies	**Yes**, but not always continuously. Grab samples in selected rivers. Data public and country-wide	**Yes Brussels:** Continuous measurements of the main two CSO-receiving water bodies	**Yes.** River data available online, the number of monitored rivers is small, so several data are outdated	**Yes.** River data at selected gauging stations used for river basin management plans. Data are openly available	**Yes.** Monitoring, water quality, and warnings are issued (e.g. risk to swimmers)	**Yes.** Monitoring according to requirements of the EU WFD. Not specifically related to CSO events	**Yes,** monitoring according to the requirements of the EU WFD. Not specifically related to CSO events	**Yes.** How regular depends on the waterbody
Are citizen groups or NGOs concerned with river quality? How are they utilising data? Media impacts?	**Yes**. NGOs and river-custodian groups using data. **Costs of sewer upgrades in policies of all major parties and discussed in media**	**Yes**. NGOs with concerns about river quality. Not frequently concerned with CSOs	**Yes**, and also national action groups. Not actively scrutinising, but occasional media coverage	**Brussels: Yes.** 'City to Ocean' uses the CSO data to raise awareness of the impacts of CSO spills	CSO data in newspapers every year. **Big focus on CSO from farmers association**	**Not yet**. Some action groups debated separate vs. combined sewer and SuDS implementation	**Yes**, e.g. the NGO 'Natuur & Milieu' incidentally reports results of monitoring campaigns	River quality is only in the media related to spectacular events causing large-scale fish kill	**Currently no**, since no CSO data is currently publicly available	**Yes**. Mainly by fishery groups. No big public debate/media impact is visible. Growing public concern about water quality Oslofjorden

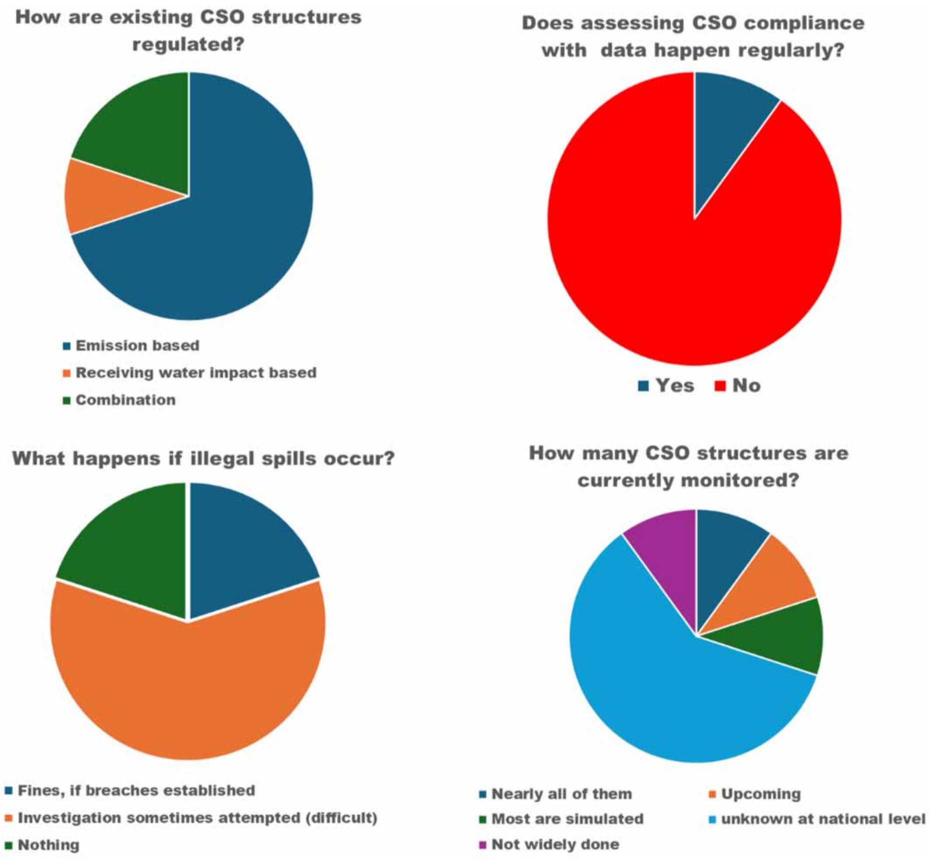


Figure 1 | Overview of CSO structure monitoring, regulation, and compliance checking in the 10 countries and regions studied.

This indicated a number of between approximately 900 and 1,800 inhabitants per CSO structure in most regions, except for France (7,200), and England and Wales (4,108).

Historic developments of CSO design

Historic urban drainage design standards varied regionally but were aimed mainly at keeping people safe from wastewater through separation and removing stormwater from roads and pavements to prevent flooding. When WWTWs were introduced, CSO structures were designed to limit the flow into the WWTW, so as not to overload it hydraulically, but there were regional variations. Supplementary Material, Part 2 provides more detail and references to original local design guidelines. Figure 2 illustrates evolving CSO design practice and design guidance development from a European perspective, alongside other developments.

Late 19th century to 1970s: slow process of formalising CSO design

CSO design evolved from two main 'rules of thumb' establishing the allowable flows going to the WWTW. The *first method* is creating an 'overflow setting', n. The amount of flow retained in the system to be treated at the WWTW was calculated as follows:

$$Q_{\text{retained flow}} = n \cdot Q_{\text{DWF, average}}$$

where $Q_{\text{DWF, average}}$ is the average dry weather flow, and n is a number between 3 and 10 (e.g. *England and Wales, France, Spain, Netherlands, Norway*). The *second method* is making an estimate of the amount of paved area and allowing a certain amount of runoff to be passed to the WWTW (e.g. *Austria, Germany, and Switzerland*). In the first method, the assumption is that after the overflow setting is reached, the wastewater is highly diluted, resulting in reduced environmental impact on the

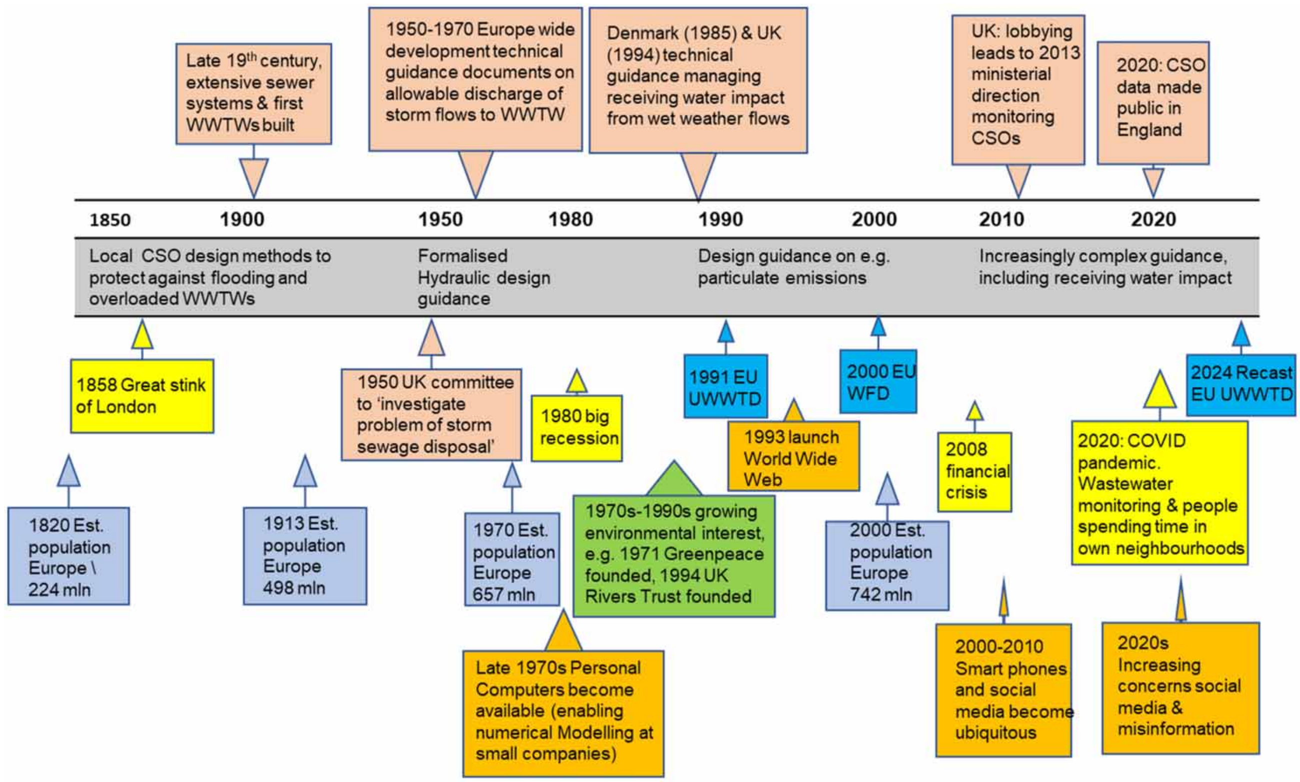


Figure 2 | Timeline of historical development of CSO design guidance and related regulations in Europe, alongside other historical developments (population in millions, computing developments, environmental awareness, and external disruptive events).

water receiving the spill. In the second method, the thought is also that the initial runoff from urban areas is polluted and should be treated at the WWTW.

1980s and 1990s: moving to more complex CSO structure design

There is a growing consideration of flows of pollutants escaping through CSOs during this era. For example, in *England and Wales*, CSO structures were retrofitted with screens to retain solids. In Germany, since 1992, the underlying concept is that the long-term average of the annual chemical oxygen demand (COD) load emitted from the combined system (i.e. WWTP and CSO) is not higher than the COD load that would have been emitted from a (virtual) separate system established in an identical catchment (ATV-A 128 1992). More complex design calculations were made possible with increasing computer power that enabled numerical hydraulic network models and computational fluid dynamic models.

Both *Denmark and the UK* developed specific modelling guidance, where the CSO emissions should be defined depending on water quality targets and their impact on specific water bodies (Spildavandskomiteen 1985; FWR 1994a).

From the 2000s, a move towards more integrated water quality regulation

Following the publication of the EU Water Framework Directive (EU 2000), more countries moved towards integrated approaches to assess the impact of emissions on receiving waters. Importantly, however, the implementation of this receiving water impact guidance is far from common practice (Table 1 and Figure 1). There is now in some areas a move to prescribe the monitoring of receiving water impact of existing CSO structures, whereby 'monitoring' can mean either actual measurements or estimates made by numerical models. There is often not a clear distinction between these terms. In France, a clarification on this has been added to the regulation (Ministère de l'Environnement de l'Energie et de la Mer 2015).

When is a CSO spill 'illegal'? How is compliance with regulation checked, and does this involve monitored data?

The previous sections considered mainly the *design* of new CSO structures, not the *regulation* of existing structures. CSOs were originally designed using the guidance valid at the time and the (predicted) amount of population and impermeable area. CSOs were only redesigned or upgraded when they were deemed 'unsatisfactory' or 'illegal'. Such upgrades are rare, however, either because there is no legal description of what constitutes an illegal spill, or because the legal description is open to different interpretations, and/or because investigation and tracking the source of the illegal spill is found to be very difficult (Figure 1 and Table 1). CSO monitoring for compliance assessment is not widely done, although the number of CSO structures in Europe being monitored is increasing.

In several localities, there is no definition of what constitutes an 'illegal' CSO spill. In *Austria*, since 1996, there has been a legally defined intention to limit emissions from CSOs with a separate wastewater emissions regulation for CSOs. There was an initial draft for this in Bundesministers für Land- und Forstwirtschaft Umwelt und Wasserwirtschaft (2001), but it failed to be adopted due to resistance from cities and municipalities.

In *Germany*, only in the state of North-Rhine Westphalia, comprehensive monitoring of specific types of CSO structures has been required since 2013. Operators must summarise spilling frequency, duration, and volume in quarterly reports that are to be presented to water authorities upon request. From 2024, similar regulations apply in Baden-Wuerttemberg, but are limited to CSO structures with storage. Most other states have self-control regulations that require monitoring only of selected CSO tanks that are considered particularly relevant. In the cases where monitoring is required, it is rarely enforced by water authorities.

There is no formal procedure to assess if a particular spill or the performance of a specific CSO structure, in general, is due to failures in operation or design. In *Switzerland*, there are self-checks by sewer operators at emission points based on visual appearance. There are no formal comparisons of modelled and measured overflow behaviour (e.g. days with overflow per year/hours with overflow per year). There is no mandatory check of correctly functioning flow limiters.

In *Spain*, a CSO spill must not occur during dry weather by law (Royal Decree 2023). However, the legal framework around CSO spills occurring during wet weather is unclear. It is generally understood that rainfalls accounting for less than 80% of annual daily precipitation have to be controlled, and that CSO spills during extreme events are allowed. Although there is no clear definition of what constitutes an extreme event, it is generally accepted to mean a flooding event.

In *Denmark* and *Norway*, discharge permits are granted by local authorities (municipalities) based on the expected discharges and the sensitivity of the water body receiving the spills while the national environmental authority is responsible for compliance monitoring. Compliance checking is rarely happening, and the current set-up has been criticised by an independent parliamentary committee in 2023 (Rigsrevisionen 2023).

In *Belgium*, the 1970/80s 'environmental governance' became a responsibility of the regions. In Brussels, large-scale WWTWs were non-existent until after the UWWTD (EU 1991) and WFD (EU 2000). Only in 2007, the whole Brussels Capital Region was covered. To date, regulation on CSO design is lacking, although the Flemish Code of good practice for sewers 20/08/2012 (Coördinatiecommissie Integraal Waterbeleid 2012) is used as a guideline, targeting a maximum CSO occurrence of seven spills a year. Currently, most Brussels CSO structures are spilling far more frequently.

Here, it is worth noting most of the current definitions of what is considered 'illegal'. CSO spills are not formulated in the same way as the proposed objective in the recast UWWTD, e.g. 'non-binding objective that storm water overflow represents a small percentage that cannot be more than 2% of the annual collected urban wastewater load calculated in dry weather conditions'. However, in France (Decree of 21 July 2015, article 22.III: see Supplementary Material, Part 2), two of the three possible criteria to evaluate CSO compliance are similar to the recast UWWTD criterion. Nevertheless, if values are higher than these thresholds, this is not, *sensu stricto*, 'illegal spill', but a non-compliant CSO performance requiring corrective actions checked by the water police.

Formal compliance assessment with CSO-related regulation involving monitored CSO data currently takes place only in *England*, where monitored annual spill frequency and duration is required since the Environment Act (UK Government 2021). Water companies have been fined for illegal spills, for example between the start of 2015 and July 2023, there were 59 prosecutions, with fines handed down by the courts of over £150 mn (House of Lords 2024). The Environment Act mandates the use of receiving water impact standards as laid out in FWR (2018).

Availability of public CSO data and river quality impact data, citizens groups

There are only limited examples of publicly available monitored CSO spill data (DEFRA 2024; Hydria 2024). River water quality data (not related to intermittent spills) tends to be made publicly available in most localities. However, CSO-related regulation does not usually lead to associated river quality data being released.

In *England and Wales*, the requirement for CSO monitoring followed from a 'ministerial direction', a legal instruction from (the former Minister for Natural Environment and Fisheries to English and Welsh water companies (Benyon 2013). This was a very unusual action, made outside the normal consultation processes. Consequently, from 2021, an openly available database of annual summaries of event frequency and duration for practically all CSOs in England and Wales was made accessible (DEFRA 2024). Since 2021, this data has been mapped on a publicly accessible website by the River Trust NGO (Rivers Trust 2024). This revealed the spatial extent, and annual frequency and duration of CSO emissions. For example, in 2023, there were 14,530 CSO structures listed in the annual return, of which 20.3% spilled >60 times per year and 40.5% spilled <10 times per year (DEFRA 2024). Some water companies publish CSO spill stop and start times, in near real-time (Thames Water 2024).

In *Brussels (Belgium)*, detailed CSO structure-related data (relative and absolute water levels of the sewer and receiving water, spill weir height, flow and velocity in the sewer and rainfall, basic water quality of the receiving water) are made public in near real-time via graphs on the Flowbru website (Hydria 2024). In *Denmark*, CSO data are published on a yearly basis on the Danish Environmental Portal (Miljoeportal 2024), and data are routinely scrutinised by the public press and specialised media. These data include yearly overflow volume and pollutant loads for each structure, and they are based primarily on simulations from detailed hydrodynamic models (about 60% of CSO structures), or on the combination of hydraulic measurements and tabular concentration values (9% of CSOs). In areas where bathing water quality is threatened by CSOs (as in the Copenhagen harbour), there is a public warning app, which informs citizens about CSO discharges.

In *Switzerland*, cantonal regulatory authorities are tracking fish-kills and publishing statistics on this (Fischereistatistik 2024), where 'domestic wastewater' causes ca. 10–30 fish kill events per year (10–15% of all causes); however, it is unclear whether this is related to malfunctioning WWTPs or CSOs.

In *France*, monitored data targeting the Olympic swimming events in the Seine in Paris have also attracted public attention to CSO impact on swimmers' health, and scrutiny of the costs of solutions (e.g. actuParis 2024). A citizens' organisation has collected samples from the Seine for water quality analysis (Surfrider Foundation 2024) and found that samples frequently did not meet bathing water standards (Fluidion 2024).

Most regions studied in Table 1 do have some form of citizen groups or NGOs concerned about river water quality, but their interests and actions vary widely. They can arise from water sports communities and be concerned about human health, or from fishing and river-custodian groups that have an environmental protection emphasis.

DISCUSSION

The discussion is grouped around the main topics highlighted in this paper: challenges around checking compliance with increasingly complex CSO-related regulations, challenges and opportunities around the drive for openness, and an outlook on the future management of urban drainage systems.

Current challenges in compliance checking and lack of transparency

While studying the impact of CSOs on surface water quality, ecology, and public health is important, using impact-based standards may not be the most suitable way to regulate CSOs. This is due to the complexity of establishing the source of negative impacts. In areas where there are legal definitions of what constitutes an 'illegal spill', the complexity and time involved in proving a causal link between a spill from a CSO structure and the surface water quality failing the required standard, means there are very limited follow-up actions. Although it is theoretically possible to hold the responsible organisation accountable for the illegal spill and mandate preventive measures, in practice this is difficult, costly, and time-consuming.

For example, in England, there are very different assumptions of what constitutes 'exception conditions' in the text from the EA permitting system, 'CSOs should only spill in exceptional conditions' (e.g. House of Lords 2024). This is not surprising when the regulations do not contain clear definitions of what constitutes exceptional rainfall intensity, duration, and frequency.

When CSO spill frequencies are stipulated, this seems clearer, as it can be measured directly. However, there are still assumptions involved, for example deciding whether two short periods of water level recorded above a weir counts as one or two spills. In England, the CSO-EDM database employs a 12–24-h spill counting method (UK Government 2018) to work out the number of spills per year based on monitored data. Spill frequency can also be worked out using various hydrological and hydraulic models, but then there is a larger set of model assumptions and uncertainty involved (for example, the type of rainfall data used as input, e.g. Schellart *et al.* 2012). Then, the setting of a specific spill frequency can feel arbitrary. For example in Spain, an indicative value of 20 per year is used, regardless of differences between wetter northern regions and the drier parts of the country where conditions in surface waters are different (Hernáez *et al.* 2011).

A CSO spill pollutant load volume (as in the revised UWWTD) is thought to be scientifically more meaningful than just a spill frequency, although the frequency is also important. However, in practice, spill volumes can only be estimated using models, as monitoring would be complex and costly (although the costs of some monitoring equipment may come down, the cost involved in employing people to install and maintain equipment in a hazardous environment does not). The model simulations involve accompanying assumptions/uncertainties, with the estimation of pollutant load being particularly difficult, and sometimes biased and wrong as shown by Bertrand-Krajewski & Maruéjouls (2019).

Regulating for environmental impact and/or impact on human health (as per the UK Environment Act, the EU Water Framework Directive, and the EU Bathing Water Directive) further increases the number of uncertain assumptions to be made when checking compliance. Environmental and human health impacts all involve an element of exposure to a harmful contaminant and/or low dissolved oxygen. Consequently, these impacts are reflected in standards that specify acceptable concentration, duration, and frequency. This involves a long-term (typically 10 years) simulation of CSO spill volumes and pollutant loads, river flows and the background pollutant levels in the river and the dilution of pollutants and oxygen depletion in the river (e.g. Schellart *et al.* 2010). For example, in England, the initial decision of whether or not a stretch of river will be investigated includes subjectivity. It is based upon older guidance and results from a combination of public complaints, pollution incidents, and inspections (FWR 1994b). As receiving water impact investigations are costly and time-consuming, they thus do not happen frequently. Subjective reasons are usually found not to do so. It is worth noting that the FWR (2018) standards are design standards, however, in the Environment Act (UK Government 2021), they have been transformed into regulatory standards. As explained in Mohan (2024), the original design standards sometimes have a high factor of safety built in, which is suitable for the design of structures with decades of design life, but arguably less suitable when deciding whether actual harm to the surface water has occurred in the current situation.

All regulatory standards involve assumptions and are open to different interpretations. However, complex standards make compliance checking more opaque, making it harder to attribute specific environment harms to specific CSOs.

Although there are calls for stricter national regulations from some areas of 'the public', e.g. Surfers Against Sewage (2024b), and researchers (Botturi *et al.* 2021), this alone is unlikely to improve water quality. Evidence from other sectors suggests that strict regulations can generate unwanted side-effects (Gunningham & Sinclair 2017). For example, if proving compliance with regulation becomes excessively complex, model simulations are needed as well as monitoring, which considerably increases the scope for opaque decision-making (Schellart *et al.* 2010; Tscheikner-Gratl *et al.* 2019). Furthermore, very descriptive regulation can stifle innovation, which is a concern with the UK Environment Act (UK Government 2021), which requires compulsory water quality monitoring upstream and downstream of nearly all CSO structures. The regulations derived from the act very specifically describe how and where NH_4 should be monitored, and that it should be monitored in a fixed location. However, the quantified impact at fixed measurement points will be strongly affected by in-stream advection and diffusion processes, which are highly influenced by river flow rate and are thus highly variable from event to event (Rutherford 1994). The new regulation does not consider or support the use of more innovative, potentially more cost-effective sensing techniques based on different principles which may improve on current practice.

Drive for openness, challenges, and opportunities

Opening up CSO data comes with multiple technical and non-technical challenges and opportunities. Where CSO data have been made publicly available, different experiences with open CSO data are emerging, which will be discussed here.

In Brussels, the Belgium civil association City to Ocean (formerly known as Canal It Up) started making use of the open data (City to Ocean 2024). To ensure correct use and interpretation of the data, a positive collaboration between City to Ocean and the Flowbru team from HYDRIA, the regional sewer operator operating the monitoring network (Hydria 2024) has been established. The interaction between both actors enabled Flowbru's CSO data to be presented in a way that could be more easily understood while remaining correct from the perspective of HYDRIA. The City to Ocean (2024) webpages explain what a CSO is, and why the legacy of CSOs is there. The data are presented together with the overall precipitation in that year. The action group sends out clear and positive messages on how citizens can be 'part of the solution', by taking more ownership of the urban water cycle via positive action such as installing a water butt.

The messages from City to Ocean stand in contrast with messages from several citizen organisations and NGOs from England and Wales. The sewage map from the Rivers Trust (2024) is an easy-to-understand visualisation of the yearly frequency and duration of CSO spills; however, it does not inform residents on contextual factors like rainfall amount and intensity, nor does it explain that CSOs are a legacy infrastructure existing long before water companies were created. The website of Surfers Against Sewers (2024a) asks the public to report water pollution. However, most of their recommendations focus on structural political factors, for example 'to end pollution for profit', or 'mainstream use of nature-based solutions' without also encouraging citizens' own action, for example, avoiding disposal of plastic wipes through the drainage system.

Following extensive negative press related to sewage spill and water utilities in England, evidence about the abuse of water utility workers has emerged. In a survey by the workers' union, 52% said that they believed that reports about sewage pollution had contributed to an increase in abuse (GMB 2024). This current negativity and lack of trust around water utilities is also likely to hamper attracting people to work in the sector, which is already facing a people and skills shortage (Cave 2025).

While several English nature conservation websites prioritise measures to hold water back in homes and gardens as a way of addressing flooding, the link to reducing sewage pollution is not usually discussed (e.g. Wildlife Trust 2024). Advice linking public behaviour and sewer overflows was mainly found on websites of water utilities, e.g. Yorkshire Water (2022) 'bin it don't flush it' campaign against flushing wet wipes that block sewers and thereby cause premature CSO spills. However, in England, the water utilities are now no longer trusted by many. According to Usher (2023), in England, the marketised structure of water and sewerage provision sets up an opposition between the public, regulators, and companies. The debate could progress better with more nuanced and less incendiary language, a non-sensationalist explanation of what CSOS are and how they evolved, and some discussion about how everyone can take action to help reduce the risk of sewer overflows.

There is also some experience with open CSO data outside Europe. Referring to open CSO data in Massachusetts, USA, Sanders (2019) describes how achieving policy agreement between policymakers, voluntary organisations, and the public begins with a shared understanding of the facts. The latter, in turn, depends on the existence of robust data, but also everyone having access to that data. Sanders' analysis of this open CSO data showed that areas with more people who are poor, non-white, and/or linguistically challenged, face higher CSO discharges, which is concerning.

Finally, when opening CSO data, gaining citizens' trust is important. This makes checking and reporting measurement errors and hardware failures very important. For example, in Germany, Dittmer *et al.* (2015) investigated the data quality of a CSO monitoring database at a regional regulator. They found that, for 2013, less than 40% of the reported spill data passed a basic plausibility check. Hence, standardised data validation practices are required, such as those suggested for data related to wastewater treatment (Zidaoui *et al.* 2023).

Looking to the future

Looking to the future, the cost aspect of improving urban drainage systems is likely to be of major concern throughout Europe (IKT 2017). Water UK commissioned a report, which concluded that substantial investment is required to reduce environmental harm from overflows. For example, a policy limiting CSO spills to 40 spills/year in non-sensitive locations, and 10 spills/year in sensitive locations is estimated to cost between £18 (€ 36) billion and £110 (€ 132) billion (based on different possible mixtures of SuDS and storage tanks), which would increase annual household water bills between £30 (€ 36) and £208 (€ 238) per year, according to Gill *et al.* (2021). The report by Gill *et al.* (2021) furthermore concluded that SuDS have higher carbon emissions than storage tanks. It should be noted here that Gill *et al.* (2021) assumed that the distributed nature of SuDS requires them to be connected and joined up, and the approach considered source control, conveyance as well as storage, which explained the relatively large carbon estimation. However, for SuDS to make a noticeable impact on spills, they will need to be installed in large numbers and would need to be coordinated.

It would be expected that the cost of SuDS-based solutions may be reduced through collaboration from the public, however, in England, with the current public anger about CSOs, a call by water utilities for the public to assist by the installation of e.g. permeable paving or water butts, may not go down well.

Usher (2023) described that it is already a long-standing problem to maintain an expensive, resource-intensive, dilapidating infrastructural system, which predates the privatisation of UK water utilities. The UK water authorities were privatised in 1989 in the first place to gain more funds to improve dilapidated water infrastructure without recourse to additional taxation.

A wider public discussion on how to improve surface water quality and how much people would be willing to 'pay' to achieve this is therefore very welcome. The word 'pay' is used here in a wider sense, not just water bills but also changes in behaviour, such as not using wet wipes, or different car-parking arrangements to allow for SuDS. This discussion should also involve industrial and agricultural discharges, which are another considerable contributor to poor surface water quality, e.g. Büttner *et al.* (2022). Widespread open data is expected to help inform the public during this discussion. However, there is still a long way to go before the widespread availability of urban drainage performance data and surface water quality data. The barriers that hinder digital transformation and data evaluation as described for Switzerland in Manny *et al.* (2021) are likely to be encountered in other locations. These barriers were found to be a lack of resources, a lack of vision, lack of digitalisation culture, and administrative fragmentation. Digitalisation culture tends to be more advanced in larger municipalities or utilities (see e.g. Gutiérrez *et al.* 2022). Although the Thames Water (2024) CSO data is reasonably FAIR (Findable, Accessible, Interoperable, and Re-usable), Smalley *et al.* (2025) still encountered several interoperability issues when trying to use data directly to train a data-driven model.

It is thought that rather than evolving stricter and/or complex regulations, increasing openness using relatively simple CSO data may be more beneficial to receiving water quality. For example, binary near real-time CSO overflow data (currently overflowing yes/no, such as City to Ocean 2024; Thames Water 2024) at least allows anyone living in the local area to notice whether a CSO is operating during dry weather or very low rainfall, which means a CSO is not operating as designed. It also allows the water operators to find out about 'dry weather spills' and fix these sooner, e.g. Dirckx *et al.* (2022). The data also enables further innovation via the use of CSO data in other environmental forecasting models (e.g. Smalley *et al.* 2025). Relatively simple open data also encourages honest discussion with the public on why CSO spills happen, and what it would cost to reduce these. A lively positive discussion on this may help to bring this area of work to attention and attract more people to work in this field.

CONCLUSIONS

The conclusions concern two main areas, first, the CSO design and regulatory standards, and second, the role of (open) measured performance data and the public.

Design standards and regulation

CSOs were originally designed using simple and reasonably unambiguous design rules. However, as expectations and understanding of water quality impact changed, these design rules have gradually become more complex, and some have evolved into specific regulatory requirements. When holding ageing infrastructure against new more stringent rules, it is not surprising that the infrastructure fails the new regulatory standards. Moreover, the complexity and cost related to checking CSO compliance with surface water quality impact standards means we lack oversight data concerning CSO compliance and impacts.

Those regulating CSOs are faced with a tension between designing meaningful regulatory standards that are attentive to the impact on surface water quality and those that are simple to understand and enforce, but less meaningful. All the standards are open to interpretations to some extent, however, with more complex standards the room for different interpretations increases considerably. Evidence-based regulation using relatively 'simple' measured (not estimated) data is good as it is less open to different interpretations and can help capture real abuses of the regulations as it did for some regions in England. Standards should, however, remain open to some interpretation, as too strict descriptions of standards can stifle valuable innovations being implemented.

The revised European UWWTD and the UK Environment Act both advocate the publishing of water management plans and making more data open to the public. Although criticism can be given to the actual objectives proposed, e.g. the '2% pollutant load…' from the UWWTD, it provides a direction to work towards.

The UK's Environment Act clearly stipulates monitoring of CSO spill event frequency and duration at all CSO structures, as well as monitoring several surface water quality parameters upstream and downstream of every CSO structure. The recast UWWTD is more nuanced, and Article 21.1 and Annex V1b stipulated that either monitoring or modelling may be used, based on what is 'appropriate'.

However, what is needed is a combination of both monitoring and modelling data around CSO spills and their impact on surface water. Generating either type of data is not straightforward. Detailed understanding and analysis of uncertainties and limitations of both the monitored data as well as the models in relation to compliance checking would be needed. This is what would deserve a separate study. Information about the data collection, as well as the modelling assumptions, and limitations of either technique, should be made accessible and transparent to ensure good practice.

To advocate trust, more openness should include providing robust measurable indicators, which the public would be able to check for themselves, such as CSO overflow duration and frequency.

Role of open data and the public

The public's interests and discussions vary with time as well as location. Depending on the local situation, there is currently a different degree of pressure for stricter oversight and control of CSOs. In some areas, the response to this has been the provision of relatively 'simple' open data, for example, concerning whether a CSO is flowing or not. The paper has shown that even if it is simplistic when data are openly available, it can help to stimulate debate. There are many positive effects of this. It is always hard to stimulate investment in infrastructure systems, particularly those systems that are largely invisible, like the sewage system, so if open data can lead to debate and investment, this seems to be a positive outcome.

For all these positive consequences, there are also problems with the prominence given to simplistic data. In England in particular, one problem is that at a time when new and thoughtful water engineers are desperately needed, recruitment of new personnel is difficult and likely not helped by water utilities being portrayed as untrustworthy polluting organisations. Equally seriously, if regulation is only focusing on simplistic data, it may require action based on arbitrary measures. This means that while investment is happening, it may not be happening in the places that have the biggest impact on the environment. This is likely to lead to disappointment in the long run, as enormous amounts of money may be spent with limited impacts on the final water quality. While the public concern may be directed at CSOs, these have become an emblematic issue for a general concern with the health of rivers, which really deserve better and more thoughtful regulation.

In some areas, CSO data has already helped to highlight challenges in managing urban drainage systems and started discussions around the costs of improvements, leading to somewhat more transparent governance. However, the data needs to be of good quality, and FAIR. As demonstrated in England and Wales, the availability of (reasonably) FAIR data allows for e.g. mapping of CSO spills by an NGO, aggregation by authorities, and producing national overviews. Licensing is also important; data should be in the public domain (CC0 license).

Opening up data is especially challenging given the inherent spatial and temporal variability and complexity of the processes involved (e.g. rainfall, rainfall-runoff, solute, and particulate transport and transformation). Closer and further collaboration between urban drainage engineers, social scientists, governance specialists, communication specialists, and citizen science groups is urgently needed. This may help people's understanding of why and how investments are made, as well as encourage better management of their own contributions to urban runoff and wastewater.

'Good practice', from the limited evidence of public engagement with open CSO data

The evidence on open access CSO data from only a limited number of locations has already taught some valuable lessons. It is imperative that data should be made open with due care and collaboration with 'independent'/'trusted' local citizen organisations. Any data on the frequency and/or duration of CSO spills should be easy to interpret and always be provided together with appropriate summary rainfall data. It is helpful to ensure that a clear, brief, and non-sensationalist or polemic-oriented explanation is provided of what CSOs are, and why they are there. Positive messaging, and avoiding a 'blame culture' is important, bearing in mind the already worrying shortage of skilled workers in this area.

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AUTHOR CONTRIBUTIONS

A.S., L.S., J.-L.B.K., and J.R. conceptualised the study. The other authors all provided input on design and compliance practice in their locality. A.S. and L.S. wrote and edited the article. All critically reviewed the text.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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