Environmental Science
Water Research & Technology

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Environ. Sci.: Water Res. Technol.*, 2023, **9**, 707

Combined sewer overflows: relating event duration monitoring data to wastewater systems' capacity in England†

T. Giakoumis and N. Voulvoulis *

Water pollution caused by the frequent use of combined sewer overflows (CSOs) has been attracting increased media and political coverage in England as in other places in the world. Considering that each of the country's 14 346 CSOs has been assessed for their environmental risk potential, as defined by the Environment Agency, and they have each been permitted to act as a storm overflow is indicative of a more systemic problem than currently perceived. While looking at the duration and frequency of discharges from individual CSOs not much can be said about their causes nor about what needs to be done to reduce them, here through an extensive investigation of event duration monitoring (EDM) data for 2021 and 2020, CSO spills are shown to be an issue across all sewerage companies related to how they operate their systems. By analysing EDM data considering the type and location of CSOs, and the sewerage networks they are connected to, our findings reveal the chronic under capacity of the English wastewater systems as a fundamental cause behind the increased frequency and duration of CSO spills. Other than pumping stations, 82% of the CSOs with the maximum spill duration per system were located at storm tanks and inlets of treatment works and had on average significantly higher spill durations in systems with insufficient hydraulic capacity both in 2020 and 2021, suggesting that CSOs are used to protect the works under peak dry weather flow conditions. Such frequent, and in some cases independent of rainfall, use of CSOs, could have detrimental effects for the receiving environment, as well as put thousands of water users at risk.

Received 17th August 2022,
Accepted 10th January 2023

DOI: 10.1039/d2ew00637e

rsc.li/es-water

Water impact

This is the first independent investigation of combined sewer overflow (CSO) event duration monitoring data in England for 2021 (and 2020), and the first time the capacity of their wastewater systems is uniformly estimated, allowing us to evaluate the extent to which the increased use of CSOs is down to the lack of capacity of wastewater systems in the country.

Introduction

The UK has a combined sewage system made up of hundreds of thousands of kilometres of sewers in many urban centres.[1] Combined sewer systems are normally designed to collect wastewater from domestic, commercial, and industrial activities and stormwater runoff from pervious, paved surfaces and roofs, and transport them to wastewater treatment works (WWTWs) for treatment.[2] However, in times of heavy rainfall when the flow can increase significantly, it has been generally accepted that it would be uneconomical to design sewerage systems to carry such flows to the WWTWs, and it is the usual practice to relieve the system of some of the excess flow at selected points by providing combined sewer overflows (CSOs). In the majority of cases, these take the form of a device (such as a weir) for discharging the excess flow to the nearest suitable watercourse. Small works are less likely to have CSOs, unless they collect wastewater from a larger area[3] (assuming they have enough capacity to treat diurnal variations in flow), while large systems requiring varying amounts of pumping to transfer wastewater to the works,[4] normally have multiple CSOs. CSOs can be located anywhere on the sewerage network: a branch sewer remote from the works; a pumping station; a storm tank or the inlet to a works. In addition to

Centre for Environmental Policy, Imperial College London, London SW7 2AZ, UK. E-mail: n.voulvoulis@imperial.ac.uk

† Electronic supplementary information (ESI) available. See DOI: **https://doi.org/10.1039/d2ew00637e**

CSOs, pumping stations often have an emergency overflow in case of complete pump failure,[5,6] but in those cases even though they may discharge through the same outfall pipe, they operate independent of rainfall, and can release raw sewage to the environment.[7]

The capacity of a wastewater system has normally been defined in terms of population equivalents (P.E.) or hydraulic load when it was built, based on the hydraulic capacity of the sewers and the treatment plant (flow or load, in millions m^3 d^{-1} designed to handle). Flow to full treatment (FFT) is the maximum flow a WWTWs can treat at any time and is often a requirement in their environmental permit.[8,9] FFT is normally calculated based on the work's dry weather flow (DWF),[10] the average daily flow to a treatment works during a period without rain,[4] a parameter used for forecasting future flows for design and strategic planning purposes.[1] In simple terms, the average WWTWs is designed as quasi-steady state and operated as near steady state as possible, so historically in the UK, flows entering WWTWs are limited to approximately six times the mean daily DWF through the use of CSOs in the system and an emergency overflow at the inlet of the works, which protects them from flooding.[11] This means that CSOs at the inlet of works operate when the flow exceeds the works' capacity, assuming that approximately three times the DWF passes to full treatment with the remainder discharged to storm tanks, which normally start discharging after two to six hours depending on their capacity (normally also 3DWF).[8,12–14] On the other hand, CSOs at pumping stations operate when the flows received exceed the capacity of the pumps and rising main. Lateral sewers are designed to handle short-term peak flow rates roughly four times the mean daily DWF, and trunk sewers, to handle peak flow rates two-and-a-half times the DWF.[15] In well-designed and maintained systems, CSOs therefore should only operate when, due to extreme rainfall, the combined flow to the works exceeds six times the DWF.[16,17]

All CSOs in England are regulated by the Environment Agency, which reviews their permits, to ensure they comply with the no deterioration objective, to avoid any increase in pollution to receiving water bodies from individual and aggregated discharges,[8] and are indeed expected to operate only in exceptional circumstances (such as unusually heavy rainfall).[18] However, following several reports[19,20] and media stories evidence has emerged that many CSOs in England discharge far more frequently. Frequent CSO spills, mean that untreated sewage enters the environment and can lead to the deterioration of the ecological and chemical status of the receiving water bodies, and affect tourism, bathing and recreational activities and pose a potential threat to human health,[21,22] particularly when CSOs discharge in the absence of rain.

Combined sewage systems are also found across Europe, with hundreds of thousands of kilometres of combined sewers and an estimated number of CSOs in excess of 650 000.[23] The European Urban Waste Water Treatment Directive (UWWTD) 91/271/EEC (EC 1991) indicates that member states will decide on measures to limit pollution from CSOs, which could be based on higher dilution rates, improvement of plant treatment capacity and regulation of the overflow (spill) frequency.[24] Article 3 of the directive requires the collection and treatment of wastewater in agglomerations above 2000 P.E. (European Commission, 2019), stating that "…*during situations such as unusually heavy rainfall, member states shall decide on measures to limit pollution from stormwater overflows. Such measures could be based on dilution rates or capacity in relation to dry weather flow or could specify a certain acceptable number of overflows per year*". What constitutes *unusually heavy rainfall* or an *acceptable number of overflows per year* is not defined, nor there is a requirement for monitoring of overflows. As a result, data gaps make the quantification of CSO events at each EU member state difficult,[25] with about 4% of the EU's surface waterbodies reported as failing to achieve good ecological status due to CSOs[26] and countries such as Belgium, Denmark, and parts of Germany and the Netherlands, using overflow frequency and partly also overflow duration as design criteria for CSOs.[24,27]

Similar is the situation in the United States (US), where about 46 million people in 32 states are served by municipally-owned combined sewers with 828 active CSO permits (issued to 746 communities) that regulate 9348 CSO discharge points.[28] CSOs therefore are a major water pollution concern for the approximately 772 cities in the US that have combined sewer systems.[29] For instance, more than 27 billion gallons of raw sewage and polluted stormwater are discharged out of 460 CSOs into the New York Harbour each year, with as little as one-twentieth of an inch of rain needed for the system to overload.[30] This is the reason, CSOs are currently attracting attention and are the focus of a global debate regarding the best techniques to manage growing volumes of sewage and stormwater runoff.[25,31–36]

In England, there are 5187 wastewater systems with 14 346 consented to discharge CSOs, owned by nine water companies (Fig. 1). While historically the cost of "*installation of event monitors or flow loggers or the provision of access facilities to install these monitors*", meant that the need for monitoring CSOs was minimal,[13] following a recent request by the government to install event duration monitoring (EDM),[37] water companies concluded a programme to install monitors on the vast majority of CSOs at the end of 2020, with the remaining to be installed by 2023. When combined with FFT monitoring EDM can provide a better picture of where flow is going when a works is at full capacity. An EDM device is usually situated immediately upstream of the FFT meter so if any excess flow goes into stream, it records it, and the data gets reported to the agency.

In 2021, a total of 12 393 CSOs (301 more than 2020) were monitored,[38] recording a total of 372 533 (from 403 375 in 2020) spill events of an aggregated duration of around 2.7 million hours (from 3.1 million in 2020) and an average aggregated duration of 7.4 hours (8.1 hours in 2020) and 29.4 incidents (32.6 in 2020) per CSO.[38] However, just knowing

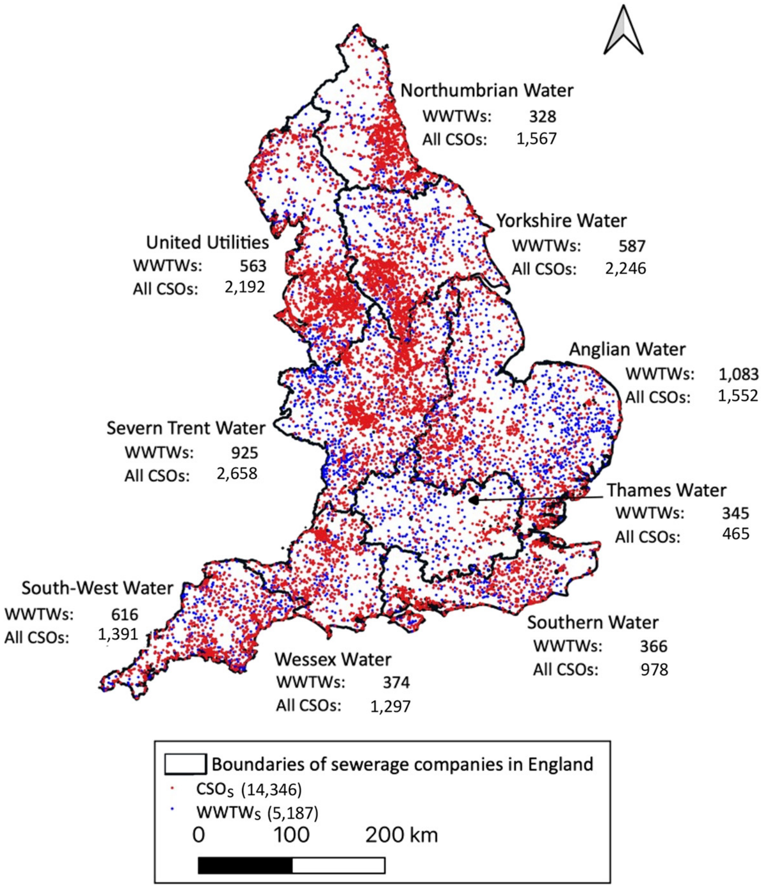

Fig. 1 Map of locations of wastewater treatment works (WWTWs) and CSOs consented to discharge, owned by water companies in England.

how often and for how long individual CSOs operate, not much can be said about the reasons of their increased frequency and duration, nor about their pollution load. Instead, the impacts from CSO discharges depend on the volume discharged, their pollutant load which varies from community to community depending on the size of the wastewater system and the relative amounts of domestic, commercial, and industrial wastewater components collected by the sewers for treatment,[39–41] as well as the dilution factor and other characteristics of the waterbody they discharge into (*i.e.*, sensitivity and value).[42,43]

While it may be obvious that CSOs discharge more frequently when the systems they are connected to have less capacity, in this work, by estimating the capacity of these systems uniformly for the first time, we are able to investigate the extent to which increases in the frequency and duration of CSO spills are down to the lack of capacity of wastewater systems in the country. Indeed, just looking at the duration and frequency of individual CSOs outside of the context of the wastewater systems they belong to, is not the right way to understand their causes nor the right approach for taking action to reduce them. Therefore, in this paper we examine potential links between the capacity, area and size of wastewater systems the types and location of CSOs, and their operation both in terms of their duration and frequency and pollution load; and make recommendations as to what needs to be done to reduce their occurrences.

Methods

EDM data for 2021 and 2020 per CSO for the nine water and sewerage companies in England were acquired from the Environment Agency[38] and were matched to the public register for consented discharges to controlled waters with condition.[44] These data provide all permit details as required under the Environmental Permit Regulation. They contain three tiers of data for all active permits (site and general information, effluent details and determinant limits). The duration of spills per CSO was provided as annual aggregated spill duration recorded across several incidents. Although data on spill counts were also available in the EDM database, their utility was limited, as these were not monitored but calculated from the spill durations using the 12/24 spill counting method followed by the Environment Agency,[8] and therefore were not included in the analyses.

From the 12 272 CSOs with spill duration data in 2021 and the 11 976 CSOs with spill duration data in 2020, 11 424 (93%) and 10 610 (89%) passed quality control respectively (ESI† section 1) and were also investigated in relation to the location and type of each CSO (storm tank at WWTWs, inlet at WWTWs, sewer network, and pumping stations). Using data obtained from the Environment Agency's public register for consented discharges to controlled waters with condition,[44] we connected the CSOs to their wastewater systems (according to the unique permit number of their works) based on the methodology described in ESI† section 2. The accuracy of this approach was evaluated at 84%, by comparing our findings to a subset (7% of all EDM CSOs) for which data were available.

The hydraulic capacity of each WWTWs was estimated *via* the FFT/DWF ratio, with DWF and FFT obtained from the Environment Agency's public register for consented discharges to controlled waters with condition[44] (ESI† section 3). From the 5187 WWTWs, 4107 had data on DWFs and 2200 on FFT,[44] while for 151 additional WWTWs the FFT was obtained from the weir setting of the CSO at the inlet of the WWTWs. The 11 424 CSOs monitored in 2021 were found to be connected to 2724 of these WWTWs, while the 10 610 CSOs monitored in 2020 to be connected to 2546 WWTWs. We related event duration monitoring data to wastewater systems' capacity for 1974 wastewater systems with available data for both FFT and DWF, with CSOs (other than pumping stations) that spilled in 2021 (ESI† section 4) and again for 1837 systems with available FFT and DWF data, for the systems that had CSOs (other than pumping stations) that spilled in 2020.

The annual spill duration of each wastewater system (hereafter spill duration per system) was then calculated. In wastewater systems with more than one CSO, multiple CSOs can spill at the same time. Comparing the aggregate spill duration of all CSOs in a system to the maximum spill duration between the CSOs of each system, it was demonstrated that the latter provided a better estimate of the systems overall operation time per year (ESI† section 5). The maximum spill duration reported amongst the CSOs connected to each system, considering their type and location (excluding CSOs at pumping stations, which operate when the flows received exceed the capacity of the pumps and rising main) was therefore used to indicate the spill duration per system.

The systems were then classified according to their spill duration for 2021 (and 2020), into the following categories: those that did not spill (no spill); those that spilled up to a day (=/<1 d); those that spilled between a day and a week (1 d–1 w); those that spilled between a week and 1 month (1 w–1 m); those that spilled between 1 and 6 months (1 m–6 m); and those that spilled more than 6 months (>6 m).

Although the normal FFT requirement for CSOs at WWTWs is 3DWF, small wastewater systems are characterised by low DWFs and therefore a 3 DWF capacity is insufficient to accommodate flows from runoff due to rainfall, particularly in the absence of storm tanks.[3,8,9,12–14,45] Therefore, the role of WWTWs hydraulic capacity as a driver of CSO spills was investigated separately for large and small wastewater systems, categorised based on a DWF threshold of 286 m^3 d^{-1}, estimated assuming an agglomeration of population of 2000 water users[46] and a *per capita* consumption of 143 l d^{-1}.[47]

As for the reasons behind the increased frequency of CSOs spills provided in the EDM data by the sewerage companies as "*High Spill Frequency-Operational Review – Primary Reason*",[38] 1565 CSOs had data provided for 2021 but no data were made available for 2020.

Data on organic load entering and the organic load capacity of WWTWs in England were acquired *via* the European Commission[46] as it had been reported by the UK under the UWWTD (with 2018 as the most recent year with available data). This dataset covers all WWTWs serving population equivalent (P.E.) greater than 2000 if discharging to freshwaters or 10 000 if discharging to coastal/transitional waters, where a P.E. of 1 is equivalent to an organic biodegradable load having a 5-day BOD of 60 g per day.

Data analyses and management was carried out in R,[48] while spatial analyses and maps were generated using QGIS.[49]

Results

Out of the 11 424 CSOs with data of acceptable quality, 1744 and 810 CSOs from the 2021 EDM data were located at storm tanks and at the inlet of treatment works and spilled on average a total of 679 and 399 hours each respectively. A total of 2149 CSOs located at pumping stations spilled on average 177 hours and 6721 CSOs located on the sewer network spilled on average 106 hours each for the same year (Table 1). Around 18% of all the CSOs that spilled were at pumping stations, with 98% of them located at the network. Some 129 of these spilled for more than a month (2 of which more than 6 months) in 2021.

Less than 13% of the CSOs monitored did not spill at all, the majority located on the sewer network (86% without considering pumping stations). The 2554 CSOs located at treatment works (storm tanks and inlets) had significantly higher average spill durations than those located on other parts of the sewer network (as revealed by one-way ANOVA ($F_{(3,11\,420)} = 781.5$, $p < 2 \times 10^{-16}$) and by Tukey's HSD test for multiple comparisons ($p < 1 \times 10^{-22}$)).

Fifteen out of the 8136 CSOs (other than pumping stations) that spilled, discharged for a total of more than six months each (73% located at storm tanks or inlet at WWTWs) (Table 2). Nine hundred and six CSOs spilled from one to six months (78% located at storm tanks or inlet of WWTWs) and 1794 CSOs (49% located at the network) for a total number of hours ranging from a week to a month each. The remaining 5421 CSOs spilled for less than a week each, with 86% of them located at the network (Table 2).

These 9275 CSOs are connected to 2531 wastewater systems, of which 126 systems (1.5%) with 132 CSOs monitored did not spill (Table 2, Fig. 2). Of the 2405 systems with CSOs that spilled, 57.2% (1375) had only one CSO, 17.6% (423) had 2 CSOs, 7.6% (182) had 3 CSOs and 17.7% (425) had more than 4 (on average 15) CSOs that spilled (ESI†

Table 1 Annual average spill duration per CSO type (storm tank at WWTWs, inlet at WWTWs, sewer network, pumping station) and classification of CSOs according to spill duration as follows: did not spill (no spill); spilled up to a day (=/<1d); spilled between a day and a week (1 d–1 w); spilled between a week and 1 month (1 w–1 m); spilled between 1 and 6 months (1 m–6 m); and spilled more than 6 months (>6 m), based on data provided for 2021 by the Environment Agency[39]

EDM CSO type	Mean spill duration (h)	No of CSOs (% of total)	No of CSOs that spilled (% per type)	No spill	=/<1 d	1 d–1 w	1 w–1 m	1 m–6 m	>6 m
Storm tank at WWTWs	679.11	1744 (15%)	1646 (94%)	98	146	286	623	582	9
Inlet at WWTWs	399.02	810 (7%)	748 (92%)	62	131	204	287	124	2
Sewer network	106.33	6721 (59%)	5742 (85%)	979	2870	1784	884	200	4
Pumping station	177.13	2149 (19%)	1820 (85%)	329	616	683	388	131	2
All		11 424 (100%)	9956 (87%)	1468	3763	2957	2182	1037	17

Table 2 Classification of CSOs (other than pumping stations) and wastewater systems according to spill duration in 2021, as follows: did not spill (no spill); spilled up to a day (=/<1 d); spilled between a day and a week (1 d–1 w); spilled between a week and 1 month (1 w–1 m); spilled between 1 and 6 months (1 m–6 m); and spilled more than 6 months (>6 m), and according to the type of CSO with the max spill duration per system (ST: storm tank at WWTWs; I: inlet at WWTWs and N: sewer network)

Spill duration	No of CSOs (other than pumping stations)	No of systems	Mean system spill duration (h)	CSO type[a]		
				ST	I	N
No spill	(1139)	(126)	0			
<1d	3147	273	8.67	104	71	98
1 d–1 w	2274	456	80.58	238	122	96
1 w–1 m	1794	903	370.68	557	203	143
1 m–6 m	906	758	1288.42	548	108	102
>6 m	15	15	2802.17	9	2	4
Total	**8136 (9275)**	**2405 (2531)**	**635.46**	**1456 (61%)**	**506 (21%)**	**443 (18%)**

[a] Based on the type of CSO with the max spill duration per system.

section 5). The classification of these systems is shown in Table 2 (and in ESI† section 5).

About 61% of CSOs with the maximum spill duration per system were those located at storm tanks, followed with 21% by those located at the inlet of works and with 18% by those located at the network (Table 2). These findings demonstrate a strong link between the CSOs that spill and the systems they belong to (*i.e.*, their size and/or capacity), with the CSOs discharging the most hours being distributed across the systems.

Those wastewater systems with insufficient treatment hydraulic capacity (*i.e.*, when FFT was less than 3DWF for large and 6DWF for small systems) had on average higher CSO spill durations, compared to systems with sufficient hydraulic capacity in both the last two years (Table 3) (for 2020 results see ESI† section 6). This difference in spill duration is significant for both large and small wastewater systems, $t_{(1,246)} = -5.5184$, $p = 4.158 \times 10^{-8}$ and $t_{(724)} = -3.2556$, $p = 0.001184$ respectively (after log transformation of the durations the p-values were $t_{(1,246)} = -7.7611$, $p = 1.745 \times 10^{-14}$ and $t_{(724)} = -3.1994$, $p = 0.001437$ respectively) and the trend is more evident in large compared to small wastewater systems (Fig. 3). This is also demonstrated in the data for 2020 (ESI† section 6).

Similarly, wastewater systems with FFT less than 3 DWFs, are larger systems with higher DWFs on average, compared to systems with FFT equal or above 3 DWFs, and therefore, their spills are also characterised by a higher pollution load. Indeed, 79% of the large and 82% of the small wastewater systems that spilled do not have sufficient hydraulic capacity (*i.e.*, hydraulic capacities less than 3 DWF and 6 DWF respectively) suggesting that they operate their CSOs to protect the works under peak dry weather flow conditions (Table 3). Moreover, when systems had the CSO with the maximum spill duration located at the network, these were large systems with many CSOs.

CSO spills from large wastewater systems are characterised by larger volumes and higher pollution load compared to small systems as they receive higher volumes of wastewater (*i.e.*, the average DWFs is 10668 $m^3\ d^{-1}$ and 124 $m^3\ d^{-1}$ respectively). England's 1290 large WWTWs (above 2000 P.E.) receive around 13.7 million cubic meters of domestic, commercial and industrial wastewater, equivalent to 84% of the country's aggregate DWF, with the largest 66 works (150 000 P.E. and above) treating more than 8 million cubic meters of wastewater per day (51% of the country's aggregate DWF) corresponding to a total organic loading of over 43 million P.E. (Table 4, for aggregate DWF in England see ESI† section 3). In these very large wastewater systems, even CSOs with low spill durations can pose higher risks to receiving waterbodies than higher spill durations from CSOs that are connected to small works. Interestingly, a connection between the area served by the works and its system's spill duration was also observed (Table 5). Overall, the larger the area as indicated by the number of CSOs in a system, the longer the duration of the CSO (other than

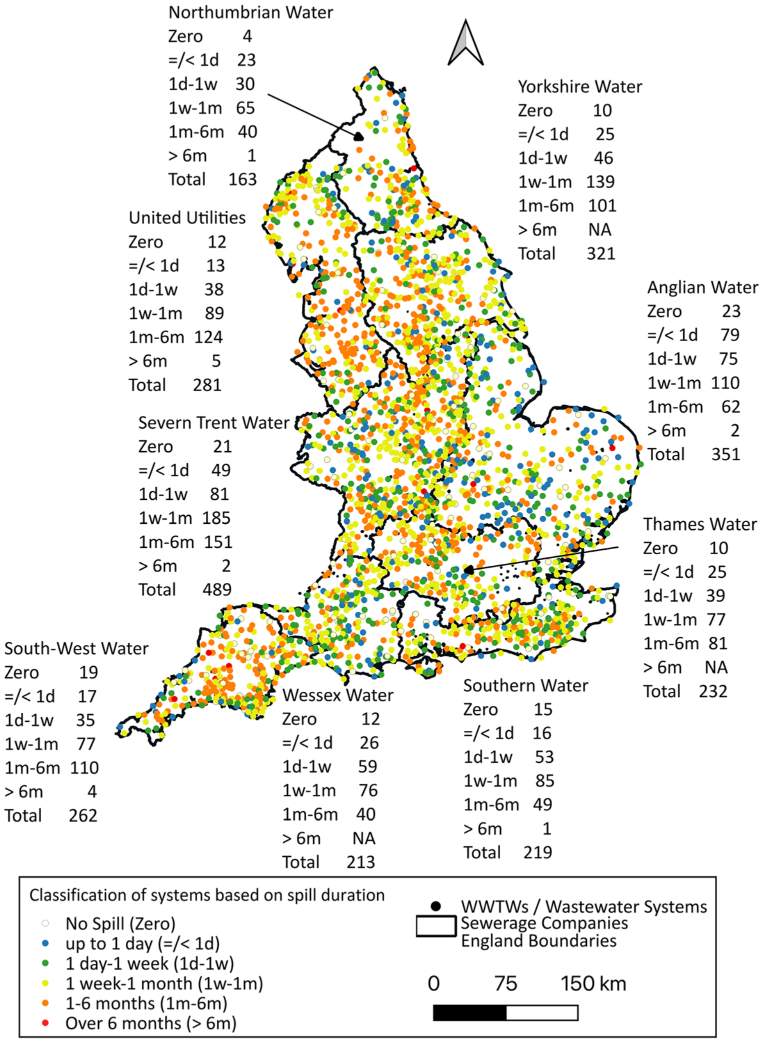

Fig. 2 Map of wastewater systems in England based on the location of their wastewater treatment works (WWTWs) showing their spill duration per water company for 2021.

pumping stations) with the maximum spill duration (Table 5). In the case of pumping stations, with most of the sites that spilled located at the network, 84% of those spilling for more than a month each belonged to large WWTWs, indicating issues related both to their maintenance and capacity that require further investigation.

Interestingly, out of the CSOs we studied and that the companies had provided reasons for the spills in the EDM data (1565 CSOs in total), the lack of hydraulic capacity was reported as the reason for 79.4% of those CSOs (ESI† section 8). Infiltration (including groundwater inundation) was the second most frequent reason for 8.2% (128 CSOs), and asset configuration for 5% (78 CSOs). Exceptional weather was reported as a reason for only 1.3% of the CSOs that spilled (20 in total) and blockages for less than 1% (12 CSOs).

Discussion

CSOs are part of the normal operation of combined sewer systems, designed with the intention of preventing spills and flooding at undesirable locations when the capacity of the system and/or of the treatment works is exceeded during extreme rainfall events,[23] or at least that was the case when the systems were designed and built. By design, CSOs are meant to operate intermittently and only in response to heavy rainfall events.[16,17] Today, the situation is quite different. Many CSOs operate frequently even under normal or no rainfall, discharging diluted or raw untreated sewage into water systems.

Not a new issue

This is an issue that the water industry has been called to resolve before. In 2012, for example, the European Commission took infringement action against the UK in relation to discharges from CSO systems in London (Beckton, Crossness and Mogden WWTWs, the largest agglomerations in England), and Whitburn in Tyneside for breaching the UWWTD. On average, 39 million tonnes of untreated wastewater containing raw sewage had overflowed from CSOs around 50 to 60 times a

Table 3 Classification of wastewater systems' spill duration in 2021 across five categories:; spilled up to a day (=/<1 d); spilled between a day and a week (1 d–1 w); spilled between a week and 1 month (1 w–1 m); spilled between 1 and 6 months (1 m–6 m); and spilled more than 6 months (>6 m), and based on the type of their CSO (other than pumping stations) with the max spill duration in 2021 (ST: storm tank at WWTWs; I: inlet at WWTWs and N: sewer network) related to the hydraulic capacity of each WWTWs as flow to full treatment (FFT) expressed as multiples of dry weather flow (DWF)

		DWF (m^3 d^{-1})					No of WWTWs				=/<1 d			1 d–1 w			1 w–1 m			1 m–6 m			>6 m		
Size	FFT	Min	Median	Mean	Max	CV	Percentage (in brackets)		CSOs	Mean duration per system (h)	I	N	ST	I	N	ST	I	N	ST	I	N	ST	I	N	ST
Large	<1 DWF	1070.00	8400.00	29 731.85	171 140.00	175%	13 (1%)	982	94	700.02	0	0	0	0	0	1	1	2	4	0	3	2	0	0	0
=/>2000 PE	2-1 DWF	290.00	3127.50	30 157.83	1 344 000.00	394%	184 (19%)	(79%)	1477	971.52	0	3	3	1	4	16	9	13	43	7	11	72	1	0	1
	3-2 DWF	288.00	1900.00	7489.94	340 000.00	275%	785 (80%)		3629	784.36	7	18	31	9	22	86	25	46	229	20	51	236	0	3	2
	3-6 DWF	290.00	1200.00	5843.14	225 000.00	322%	238 (89%)	266	982	506.37	7	16	10	12	12	26	15	13	75	2	9	40	0	0	1
	>6 DWF	286.00	487.50	1747.83	28 129.00	291%	28 (11%)	(21%)	76	441.18	1	2	3	4	2	6	1	1	3	0	1	3	0	0	1
	All	**286.00**	**1800.00**	**10 556.88**	**1 344 000.00**	**471%**	**1248**[a]		**6258**	**750.36**	**15**	**39**	**47**	**26**	**40**	**135**	**51**	**75**	**354**	**29**	**75**	**353**	**1**	**3**	**5**
Small	<1 DWF	72.00	140.50	124.25	144.00	28%	4 (1%)	597	4	2123.19	0	0	0	1	0	0	0	0	0	0	0	3	0	0	0
<2000 PE	2-1 DWF	18.00	139.00	151.51	280.00	50%	38 (6%)	(82%)	49	1063.23	1	1	1	0	0	3	4	0	14	2	0	10	0	1	1
	3-2 DWF	7.00	130.00	135.74	285.00	59%	258 (43%)		325	726.28	7	3	17	18	2	32	25	4	56	17	1	75	1	0	0
	3-6 DWF	5.80	117.00	124.92	285.00	61%	297 (50%)		371	597.47	21	3	13	31	5	24	62	5	55	41	0	37	0	0	0
	>6 DWF	4.00	72.50	87.48	275.00	77%	129 (18%)		147	429.09	13	4	2	26	3	10	39	2	13	10	1	4	0	0	2
	All	**4.00**	**115.00**	**123.28**	**285.00**	**63%**	**726**[a]		**896**	**646.11**	**42**	**11**	**33**	**76**	**10**	**69**	**130**	**11**	**138**	**70**	**2**	**129**	**1**	**1**	**3**

[a] No of systems with available both FFT and DWF data.

year into the river Thames spilling even under light rainfall.[18,50] Similarly, in Whitburn, during 2002 to 2004 the number of CSO spills ranged from 56 to 91 while between 2006 and 2008 CSO spills had ranged from 25 to 47 (case C-301/10). The European Court of Justice ruled that the UK had failed to fulfil its obligations under the UWWTD, as the CSOs were operating in "normal and common" climatic conditions, with their discharges breaching the directive (case C-301/10). Despite given five years to sort it out, spills are still occurring in Whitburn under moderate rainfall[51] even after some upgrade works (*i.e.*, a combination of storage tanks and sustainable urban drainage systems-SUDS) completed at the end of 2017, and as a result that judgment has not yet been satisfied.[52,53] During 2021, Whitburn steel pumping station (permit number: 245/1207) spilled 31 times to a total of 118.95 hours and 23 times to a total of 67.92 hours in 2020. As for the three works in London, a £4.13bn super-sewer, the "Thames Tideway Tunnel" was commissioned in 2016 and expected to be completed by early 2025,[54] constructed underneath the Thames, to capture more than 95% of the CSO spills that enter the river,[18,50,55] as a way of dealing with their lack of capacity. All three works (Becton, Crossness and Mogden) still have a hydraulic capacity of less than 2 DWFs (ESI† section 7).

A cause of concern?

Increased frequency of CSO spills independent of rainfall could result in detrimental effects for the receiving waterbodies. Discharges of untreated wastewater from CSOs can lead to hydraulic stress, oxygen depletion or a temporary increase of pollutant concentrations in receiving waters.[24] Municipal wastewater contains microbial pathogens, total suspended solids (TSS), nutrients, and fats, oils and greases (FOGs) from households and additional pollutants such inhibiting chemicals (acids, toxins, bactericides), persistent organic pollutants (POPs) and heavy metals[4,56] from industrial and commercial activities,[4,57,58] and as a result when wastewater is discharged untreated, these can enter the environment, potentially having dire consequences. For example, Yorkshire Water was fined £233 000 and ordered to pay £18 766.06 costs and £170 victim surcharge in 2022 after it admitted to being responsible for a sewage leak from a pumping station in Tong Beck, near Bradford that led to the deaths of hundreds of adult and juvenile brown trout and caused significant damage to the ecology of the beck in 2017.[59] It was outside the scope of this work to investigate the impacts of individual CSO discharges, as these depend not only on the pollution load of what is discharged but also the sensitivity (*i.e.*, waterbody type, size, ecological status, designations) and value (uses and richness in ecosystem services) of the receiving environment. However, there is mounting unease about environmental and human health risks from exposure to pollutants from these discharges. Such pollutants can be persistent and bioaccumulate in wildlife, with trace concentrations building up over time and polluting the food chain, as well as potentially contaminating

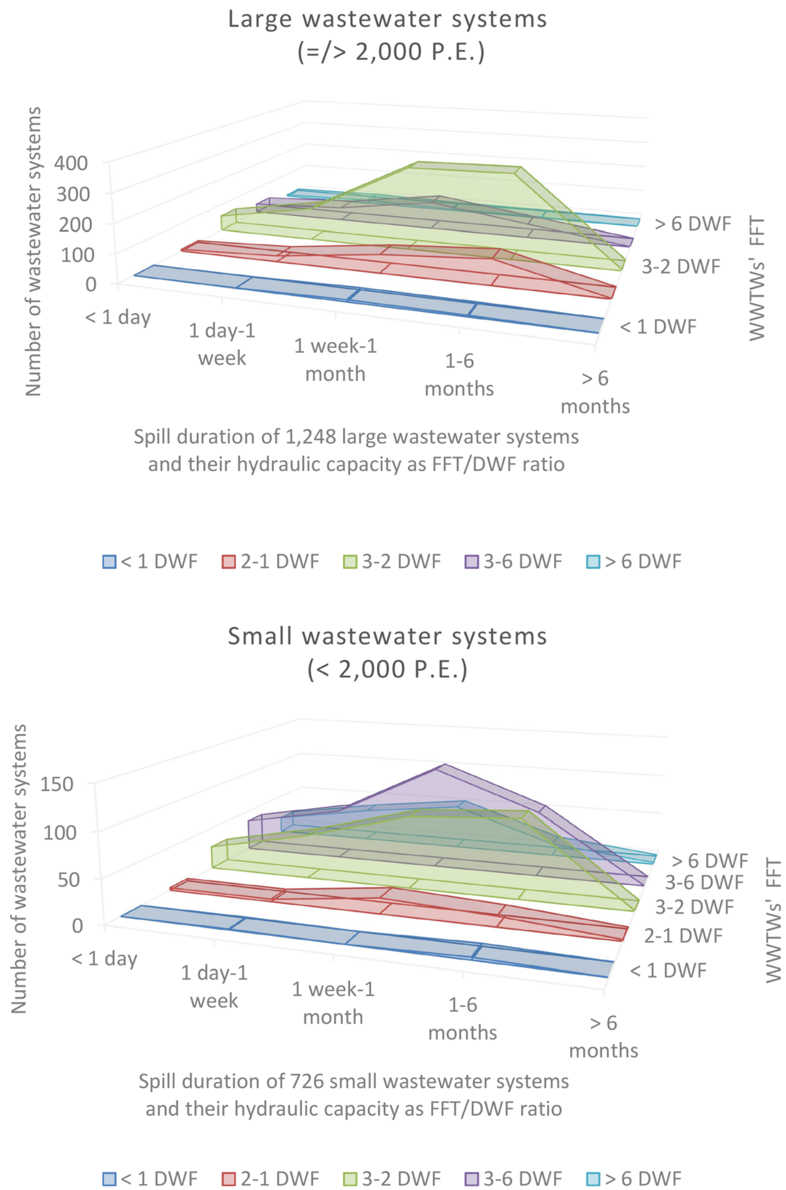

Fig. 3 Spill duration of wastewater systems during 2021 and the flow to full treatment (FFT) of their wastewater treatment works (WWTWs) expressed as multiples of dry weather flow (DWF) in five categories: spilled up to a day (=/<1 d); spilled between a day and a week (1 d–1 w); spilled between a week and 1 month (1 w–1 m); spilled between 1 and 6 months (1 m–6 m); and spilled more than 6 months (>6 m).

Table 4 England's 857[a] small and 1290[b] large wastewater treatment works (WWTWs) grouped based on their agglomeration size expressed as population equivalent (P.E.) and the mean and aggregate (sum) dry weather flow (DWF) per group

WWTWs size	P.E.	WWTWs	Aggregated capacity (P.E.)	DWF (m^3 d^{-1})	
				Mean	Sum
Small	<2 K	857	NA	120.38	103 162.50
Large	2–10 K	693	2 637 761.55	960.27	665 470.44
	10–15 K	120	1 454 210.85	2917.37	350 084.60
	15–150 K	411	19 139 572.59	10 826.65	4 449 752.64
	>150 K	66	43 104 388.68	124 928.02	8 245 249.00

[a] These WWTWs had CSOs (other than pumping stations) that spilled and have DWF data. [b] These WWTWs had CSOs (other than pumping stations) that spilled and have both DWF and P.E. data.

Table 5 England's wastewater treatment works (WWTWs) with CSOs that spilled in 2021, categorised in terms of size according to their consented dry weather flow (DWF) and the corresponding average spill duration of their systems as calculated from EDM data

WWTWs size	DWF (m^3 d^{-1})	WWTWs (n)	Average system spill duration (h)
Small	<286	857	606.20
Large	286–1489	636	714.46
	1489–4546	368	638.78
	4546–11 539	227	656.14
	11 539–74 900	196	858.83
	>74 900	32	1077.07
	Total	2316	

groundwater intended for potable use. CSO discharges can also lead to the deterioration of the ecological and chemical status of the receiving waterbodies,[25,60,61] alter their physical characteristics,[62,63] cause significant visual or aesthetic impacts,[13,64] lead to shellfish harvesting and beach closures,[65–67] threat drinking water supplies and instigate public health concerns from risks to recreational uses.[68] Most recently, microplastics and nanoparticles in untreated wastewater have been a source of concern,[69] being recognised as a threat, both directly and as vectors for persistent organic pollutants adsorbed onto their surfaces.[70–72] Cosmetics from human use and pharmaceuticals such as antibiotics can also be found in sewage and can have both ecological effects based on their mode of action and in the case of antibiotics even contribute to the proliferation of antimicrobial resistance (AMR)[73–75] indirectly on top of more direct routes through any resistant strains in sewage. CSO discharges have been found to increase concentrations and loads of pathogens in waters downstream from CSOs with contamination levels above acceptable risks for recreational use.[76,77] Users in contact with waterbodies polluted by CSOs face significant health risks such as gastrointestinal illness among swimmers.[78,79]

What is being done

Most research, government initiatives and industry proposals tend to put forward solutions that aim to reduce the impacts of CSO discharges instead of targeting the causes of their occurrences. Proposals about separating combined sewers into separate foul and surface water drains,[80] re-engineering existing infrastructure and landscapes,[81,82] reducing the amount of surface water entering combined sewer networks,[83] and preventing blockages from unflushable products such as wet wipes[84,85] and fats,[86,87] can potentially help but do not address what is causing the increases in CSO spills frequency and duration, while other solutions such as building additional storage tank capacity[88] and treating discharges from overflows in wetlands[89] end up treating the symptoms and not preventing the use of CSOs.

For example, installations of vertical-flow constructed wetlands (known also as bioretention filters) to treat first flushes from CSOs have been in operation for more than 20 years in some European countries with evidence of TSS removal and chemical oxygen demand (COD) reduction efficiency,[90–92] however these schemes cannot be effective when the CSOs consist of undiluted wastewater (not rainfall induced spillages). SUDS can reduce surface water runoff, but is not a panacea for addressing CSOs overspilling, particularly in cases these operate in the absence of rainfall, where water companies need to invest in sewerage infrastructure to provide sufficient capacity for existing and future water services.[93] For example, combining SUDS (*i.e.*, bioretention basins) with conventional "grey" infrastructure solutions (*i.e.*, storage tanks at the CSO outlets) can be effective in reducing stormwater inflow but are not always enough to substitute for the lack of capacity, as was the case with the £10 million Whitburn spill reduction project.[51,53]

Similarly, while sewer blockages can indeed increase frequency of CSO events, they are a mere contributing factor that of course needs to be addressed but which by no means will prevent most of the CSO occurrences. Wet wipes that are flushed into sewers instead of being disposed of with household waste, can account for up to 90% of material causing sewer pipe blockages,[33] while FOGs from kitchens that are disposed of down drains can also accumulate in sewers and increase the probability of blockages within the system,[94] but there is no evidence that taking action on these (other than what the industry is already doing) will result in a significant reduction of CSO spills.

On the other hand, while there is no question that climate change significantly impacting the hydraulic operation of the wastewater systems beyond their historic functional design requirements,[95,96] it is an operational risk that wastewater engineering needs to adapt to. The most recent decade (2010–2019) has been on average 1% wetter than 1981–2010 and 5% wetter than 1961–1990 for the UK overall.[97] For the years we studied, 2020 was the UK's fifth wettest year in a series from 1862, with 116% of the 1981–2010 average and 122% of the 1961–1990 average rainfall.[98,99] In 2021, the UK as a whole was slightly drier than average,[100] which also explains the relative reduction in spill duration of a number of CSOs compared to the previous year. The inherently variable nature of the UK's climate means that extreme weather events are to be expected in any given year.

Increases in frequency and intensity of precipitation events, mean that more rain inflows enter combined sewer systems and faster,[101,102] but their capacity is significantly reduced by the volume of wastewater they now collect, causing their frequent overloading and therefore increasing the frequency and duration of CSO events.[103,104] This is also confirmed by the EDM water company returns which rarely report extreme weather as the primary reason for the increased frequency of CSO spills. Still, the recurrence interval of unusual rainfall could be another important parameter that affect CSO operation. Unusual rainfall shortly after a first rainfall event will result in longer spill durations since the storage capacity is still being depleted from the first rainfall event.[25] All these are important factors, but could they be diverting attention from "the elephant in the room"?

The UWWTD aims to protect the environment from the adverse effects of wastewater discharges and compliance with the directive and regulations requires that urban wastewater (domestic, industrial and rainwater run-off) is collected and conveyed to secondary treatment. The relevant specific requirements for collecting systems (sewers) are set out in article 3 and annex 1A and footnote 1 of the directive, and for treatment works in articles 4 and 10, and annex 1B. So, for combined sewers, there is a clear expectation that storm water is also collected and treated. It is that capacity of collecting and treating stormwater that has been used to address increases in the volumes of wastewater produced over time, that has resulted in the increased frequency of CSOs spills way and above their intermittent use due to extreme weather conditions.

Lack of capacity of wastewater systems

Most cities have experienced population growth and wastewater system expansion, at rates that have not been matched by water infrastructure growth.[68] Just over the past decade England's population has increased by 6% (between 2011 and 2019) – by 6.2% in urban areas, where the greatest rate of population increase was in urban major conurbations (6.9%).[105] In 2019, 56.3 million people lived in urban areas (82.9% of England's population).[105] On top of this, the urbanisation observed in recent years has resulted in increased impervious surfaces, known as urban creep, and has been shown as one of the causes of the rise in overall runoff volumes and reduction in runoff lag time leading to increases in stormwater inflows. In fact, this has been used as a proxy to estimate the occurrence of overflows in various studies.[35,61,106–108]

As a result, most WWTWs are now treating a significantly higher volume of flow than they were designed and built to accept. About 79% of large works have treatment capacity less than 3 DWF, and more than 78% of all CSOs discharging are connected to them. The majority of these CSOs are also located at the inlet and storm tanks of WWTWs where the pollution load is much greater. Concerns that CSOs are used as a way to manage the under capacity of WWTWs have also been raised by other researchers.[109] In fact, the way sewerage systems are currently managed simply aims to protect the WWTWs, with their biochemical process designs based on averages but sedimentation processes based on anticipated hydraulic maxima.[3] The Water Industry National Environment Programme (WINEP) requires action from the water companies to increase FFT and storm tank capacity at WWTWs where the urban wastewater treatment regulations requirements are not being met.[110] The FFT must be increased above 3 DWF to prevent at least the dry day operation of overflows.[111,112] This is the problem driving the frequency and duration of the CSOs discharging in English rivers, so the discussion needs to focus on the state of the wastewater infrastructure in the country.

Infrastructure in need of replacement or upgrading

In fact, much of the aging drainage and wastewater infrastructure in the UK as a whole, the European Union, and the US needs urgent replacement or upgrading, to also address increases in demand, the effects of a changing climate and other emerging challenges such as the proliferation of AMR[113–115] and the need for advance wastewater treatment for removing emerging contaminants such as endocrine disrupting substances.[116–118] Aging infrastructure that has not been adequately maintained can result in higher infiltration into the sewer system (*i.e.*, *via* defective drains and sewer pipe joints), potentially contributing to increases in the frequency of CSOs spills, which can be triggered after a minor precipitation or even in dry weather conditions.[4,119–121] Typically, infiltration is estimated at 40% when sufficient flow data is not available for formal analysis, however this value can rise to well over 100% in older catchments, where the network has deteriorated significantly over time.[122] Between 2000 and 2008 just over 3000 km, or 1% of the sewers in England and Wales were replaced or rehabilitated.[118] Considering that much of the infrastructure has been built with a lifespan of 60–80 years, at that rate of replacement, it would take 800 years for this to happen for all the sewers in England and Wales.[20,118]

Moreover, most of the high frequency discharges of CSOs at pumping stations during 2021 were located at the network and could be down to legacy issues of lack of investment or bad design from the time around 20 years ago when hundreds of smaller WWTWs were closed and replaced by pumping stations connecting them to the larger systems they belong today. For example, United Utilities' pumping station at Cartmel in Cark (permit number 017380400) and Cark tank no. 1 pumping station (permit number 01LAK0076) spilled around 4700 hours and 1363 hours in 2021 respectively, initiating an investigation by the Environment Agency after complaints for operating at dry weather by local residents. The current system was installed in the early 2000s to replace the Cartmel treatment works which closed, with the sewage being pumped to Cark Pumping Station and thereafter onwards to the grange treatment works (Grange Over Sands WWTWs with permit number 017370128 and FFT/DWF as 3.14).[123] The Cark tank no. 1 pumping station (permit number 01LAK0076) spilled for a total of 8331 hours in 2000.

What is also clear is that the situation has been getting worse. Going back to 1994, the 2500 CSO discharges to watercourses reported then were mostly attributed to the thousands of recorded failures or partial failures of pumping installations,[124] when these today are only a small fraction compared to hydraulic capacity issues driving CSO events.[121]

CSO spills are a systemic issue across sewerage companies, and therefore in theory, provision has been made by the Water Services Regulation Authority (broadly known as Ofwat) to maintain sewerage assets and upgrade them to deal with additional loads from new developments as part of the water industry investment rounds which occur every five years. These assets include the sewerage network as well as wastewater treatment works, but clearly investment has not been keeping pace with the increased demand nor in some cases with the deterioration of assets,[20] and insufficient use has been made of this provision to cope with the scale of development, or indeed at place the pace of physical deterioration. According to Ofwat, investment in the industry has roughly doubled since privatisation in 1989, but capex (capital expenditure – money spent on assets) has remained the same between £5bn and £6bn a year, with a move towards a focus on total investment (including operating costs), which can result in less investment in capital costs with a return in future years compared to investments paying back now and in the short term (such as energy produced by biosolids treatment, or other processes for reducing costs and offering financial returns much sooner).[125] Ofwat is one of the three regulators of the UK water industry, with the duty to protect consumer's interests (bills and affordability) and ensure that efficiently run water companies are able to finance their functions, which means it sits on a thin line between putting pressure on water companies to keep water bills low but to keep spending enough on investments in water infrastructure. However, it is not just constraints in investment over the past 20 years that have led to many parts of the wastewater and drainage infrastructure having to operate at or over design capacity, longer term planning for sewerage infrastructure has had less focus than that for water supply. The 2018 National Infrastructure Commission report entitled "Preparing for a drier future: England's water infrastructure needs" did not mention wastewater infrastructure, other than a couple of references to wastewater's potential reuse for water supply.[126] Interestingly, while water reuse is increasingly considered as a potential sustainable source of water that can reduce over abstraction pressures, one of its barriers has to do with having enough effluent treated to put back to the environment to balance the amount abstracted, while still having effluent to reuse.[127] This is one of the benefits of combined sewer networks where often 3–6 times more rainfall is collected on top of the wastewater collected from municipal water use.[128] Still, this is only part of the reason why solutions put forward for replacing the combined sewer systems with separate ones, are problematic and have been shown to have unintended consequences (*i.e.*, disruptive, costly, and with inadequate follow-up by operations and maintenance often defeating the purpose and cost of overhauling the sewer system). For example, the complete separation of wastewater and stormwater systems (eliminating storm overflows) in England would be highly disruptive and complex to deliver nationwide, estimated to cost between £350 and £600 billion.[80] More importantly, in separate sewer systems, stormwater is often discharged to the environment without treatment, even though it is not exempt of pollution.[129] Stormwater can be polluted with hydrocarbons (PAHs, NOx, Ni, BTEX) from vehicle emissions, heavy metals (Cu, Ni, Zn, Ni, Sb, Pb, Cd) and polycyclic aromatic hydrocarbons (PAHs) from the wear of brakes, tyres, and vehicle body wear, platinum group elements (Rh, Pd, Pt) from catalytic converters, microplastics from road littering, fertilisers and suspended solids from gardening activities, biocides, or detergents used in cleaning, bird and animal faeces and spills.[130–133] In practice the risks to the environment remain significant, every so often exacerbated by unintentional or illegal wastewater connections to stormwater drainage systems (in most cases only detected by the severe foul stench that accompanies them), contributing significant pollutant loadings to receiving waters.[134]

Recommendations

Despite the overall high EDM coverage of their networks, water companies still need to further improve the reporting of EDM data. Indeed, there seems to be a general issue with the reporting of overflows, with operators may significantly under-reporting pollution incidents.[109] For example, individual WWTWs operators self-reported between 62% and 84% of identified pollution incidents in England in 2018; the public and third parties were responsible for reporting the remaining 395.[109] Northumbrian Water was found to have submitted incorrect sewage discharge figures for Hendon WWTWs and apparently "were forced to increase their figures by 4000% after a complaint was made" (from 15 hours and 52 minutes to 646 hours in 2019/20).[51,135] EDM relies on sewerage companies self-reporting of CSO spills, which means that for the numbers to be reliable, considering potential underreporting, the Environment Agency could play a more active role inspecting the process if not developing its own monitoring system, at least for the waterbodies that have already been identified failing to achieve good status because of CSOs.[136] In the absence of this, it is difficult to comprehend how can the agency be referring to the CSO EDM as a "robust and consistent way of monitoring how often and for how long storm overflows are used".[37] There is a lot that can be done to improve the quality of EDM data, and also additional information to be provided that can help the public understand potential risks. For example, data connecting CSOs to their wastewater systems and data on the volumes of CSO discharges, if were included in water company returns, could allow for a much "*more full and accurate picture*" of the state of wastewater infrastructure in the country.

Although, there is no doubt that everyone has a role to play to help reduce the frequency and duration of CSO events – consumers using less water and therefore producing less wastewater to be treated, as well as not discharging un-flushable products such as wet wipes and FOGs down the toilet or sinks; as well as local and planning authorities re-engineering existing infrastructure and landscapes to introduce nature back to our cities; the real power to solve this problem lies with the water industry and the need to invest to repair, replace, and extend our water infrastructure. From pumps to pipes, this infrastructure is often out of sight and out of mind. In fact, the frequent use of CSOs in England could simply be the symptom of an infrastructure deficit in need of funding and upgrading.

In well-designed and maintained combined systems, CSOs act as an essential relief valve, allowing excess storm water to be discharged into waterbodies during times of extremely heavy or prolonged rainfall. In those cases, whilst what is being discharged is untreated, the principle in their being storm overflows is that at times when they are discharging, the sewage should be diluted with large volumes of rainwater and the receiving watercourse would be swollen with rain and at high flow, providing additional dilution and further reducing the impact on water quality and ecosystems. There may also be a broad expectation that people would typically not be using such receiving waters recreationally in extreme storm conditions so would not be exposed to this pollution (though recreational use is not a consideration for permits on rivers currently but is a factor behind user groups seeking bathing water designations for inland waters).[83] However, even in dry weather conditions, risk from using waters recreationally remains downstream of WWTWs, as unless those waters are designated as bathing there is no requirement for the disinfection of their effluent.

Water is the most important commodity in the world, it is indispensable for life, yet it is also one of the cheapest.[130] In many circumstances, water is treated as a free good provided by nature, and therefore any investment in improving water and wastewater services comes difficult to justify. This is further exacerbated by the high costs of water and wastewater infrastructure, which benefits we are happy to enjoy when paid by previous generations but find it difficult to pay for when its benefits are to also be enjoyed by generations to come. We might take fresh supply of drinking water and the easy disposal of sewage and waste as basic human needs that we rarely give a second thought today, and take for granted, but the fact of the matter is that for the water and sewerage management systems found in our cities, towns, villages and countryside today, we've got the Victorians to thank for. A sobering thought is to consider how our cities would have looked today if responding to cholera epidemics the Victorians did not build sewers but instead went for more cost-effective options or waited for antibiotics, used as cholera treatment by their next generation. We all rely on water every day and we know how important it is for people being able to live healthy, fulfilled lives. We need to empower the industry to take a leading role delivering water and wastewater infrastructure, ensuring a provision that is resilient both to the conditions we face today and to the changes in population and weather patterns that we can expect in the future.

Conclusions

With the EDM data from storm overflows that water companies are now legally obliged to monitor and report becoming publicly available, increasing the transparency and accessibility of evidence that would otherwise been hidden from public and scientific scrutiny, we have a chance to have an open discussion on infrastructure resilience and investment, issues that perhaps most believe had already been addressed in high income countries like the UK. The EDM data revealed thousands of discharges into English rivers causing increasing political and public concern that in the 2020s – well over a century since the UK developed effective wastewater-treatment processes – raw sewage is still discharged at a high frequency into rivers. The increasing numbers of people using these rivers to swim, kayak and paddleboard during the last two years of Covid lockdowns have also brought the issue to the forefront of media attention.

Still, all the EDM data offer is the number of incidents and the total duration of operation for each CSO (including their location and permit number) with no easy way to know what is causing these events and therefore not clear what should be done about them.

By linking the operation of CSOs to the wastewater systems they are part of, the increases in their frequency and duration can to a different degree be attributed to population growth and wastewater system expansion, at rates that have not been matched by infrastructure growth. Our findings aim to inform policy makers about the causes of the problem and help the industry demonstrate the need for capital investment in infrastructure that is often taken for granted but is critical to our future prosperity. Unfortunately, the importance of such infrastructure is only recognised when it is not functioning, going mostly unrecognised and undoubtedly uncelebrated when it works properly. High quality drinking water, secure supplies to households and businesses, effective wastewater removal and treatment – in the future to be reused as a safe clean alternative water supply and a flourishing water environment, are fundamental to any thriving society and economy.

Conflicts of interest

There are no conflicts to declare.

References

1 Environment Agency, *Guidance: Calculating dry weather flow (DWF) at waste water treatment works*, 2018.
2 J. Tibbetts, Combined Sewer Systems: Down, Dirty, Out of Date, *Environ. Health Perspect.*, 2005, **113**, 465–467.
3 P. Green, in *WaPUG Autumn Meeting 1999*, 1999, pp. 1–5.
4 D. Butler, C. Digman, C. Makropoulos and J. W. Davies, *Urban Drainage*, CRC Press, 4th edn, 2018.
5 E. Bramley, R. Munt and P. Baker, *Pumping stations – A better way to manage risk*, 2008.
6 H. Korving, M. Geise and F. Clemens, Failure of sewage pumps: Statistical modelling and impact assessment, *Water Sci. Technol.*, 2006, **54**, 119–126.
7 National Rivers Authority, *Discharge Consents and Compliance - The NRA's Approach To Control Of Discharges To Water*, 1994.
8 Environment Agency, Guidance Water companies: environmental permits for storm overflows and emergency

overflows, https://www.gov.uk/government/publications/water-companies-environmental-permits-for-storm-overflows-and-emergency-overflows/water-companies-environmental-permits-for-storm-overflows-and-emergency-overflows#no-deterioration-objective, (accessed 10 December 2022).

9 R. Brook, *Water Quality Consenting Standards – AMP2 Guidelines*, 1994, pp. 1–97.

10 E. Gill, A. McConkey, K. Solts and J. Wicks, *Sewer network and WWTW Integration. Report Ref. No. 07/WW/22/4*, 2006.

11 M. H. Jansen-Vullers, P. A. M. Kleingeld and M. Netjes, Quantifying the Performance of Storm Tanks, *Inf. Syst. Manag.*, 2008, **25**, 332–343.

12 D. Woods, *Urban Wastewater Management - An Introductory Guide*, Foundation for Water Research, 2010, vol. 44.

13 Scottish Environment Protection Agency, *Water Use, Regulatory Method (WAT-RM-07), Sewer Overflows, Version: v3.1 Released: Feb 2014*, 2014, pp. 1–32.

14 Entec, *Water Quality and wastewater treatment*, 2008.

15 R. Miller, M. R. Miller and J. Almond, *Audel plumber's pocket manual*, John Wiley & Sons, Ltd, 10th edn, 2004.

16 I. Jalliffier-Verne, R. Leconte, U. Huaringa-Alvarez, A. S. Madoux-Humery, M. Galarneau, P. Servais, M. Prévost and S. Dorner, Impacts of global change on the concentrations and dilution of combined sewer overflows in a drinking water source, *Sci. Total Environ.*, 2015, **508**, 462–476.

17 A. Mailhot, G. Talbot and B. Lavallée, Relationships between rainfall and Combined Sewer Overflow (CSO) occurrences, *J. Hydrol.*, 2015, **523**, 602–609.

18 DEFRA, *Creating a River Thames fit for our future An updated strategic and economic case for the Thames Tideway Tunnel*, 2015, pp. 1–19.

19 Surfers Againts Sewage, *Surfers Against Sewage 2020 Water Quality Report*, 2020, pp. 1–48.

20 WWF, *Flushed away: how sewage is still polluting the rivers of England and Wales*, 2017.

21 D. Morgan, L. Xiao and A. McNabola, Evaluation of combined sewer overflow assessment methods: case study of Cork City, Ireland, *Water Environ. J.*, 2017, **31**, 202–208.

22 F. Mascher, W. Mascher, F. Pichler-Semmelrock, F. F. Reinthaler, G. E. Zarfel and C. Kittinger, Impact of combined sewer overflow on wastewater treatment and microbiological quality of rivers for recreation, *Water*, 2017, **9**(11), 1–10.

23 EurEau, *Overflows from collecting systems*, 2016, vol. 32, pp. 1–6.

24 T. Hofer, A. Montserrat, G. Gruber, V. Gamerith, L. Corominas and D. Muschalla, A robust and accurate surrogate method for monitoring the frequency and duration of combined sewer overflows, *Environ. Monit. Assess.*, 2018, **190**(4), 1–18.

25 Milieu, *Assessment of impact of storm water overflows from combined waste water collecting systems on water bodies (including the marine environment) in the 28 EU Member States*, 2016.

26 European Environment Agency, *European waters Assessment of status and pressures 2018*, 2018.

27 G. Dirckx, Ch. Thoeye, G. de Gueldre and B. van de Steene, CSO management from an operator's perspective: a step-wise action plan, *Water Sci. Technol.*, 2011, **63**, 1044–1052.

28 U.S. Environmental Protection Agency, *Protecting America's Waters: EPA Needs to Track Whether Its Major Municipal Settlements for Combined Sewer Overflows Benefit Water Quality*, 2015.

29 American Society of Civil Engineers, *2017 Infrastructure report card*, 2017, vol. 53.

30 Riverkeeper, *Combined Sewage Overflows*, https://www.riverkeeper.org/campaigns/stop-polluters/sewage-contamination/cso/, (accessed 10 December 2022).

31 A. Pistocchi and C. Dorati, in *New Trends in Urban Drainage Modelling*, ed. G. Mannina, Springer, 2019, pp. 937–941.

32 B. Petrie, A review of combined sewer overflows as a source of wastewater-derived emerging contaminants in the environment and their management, *Environ. Sci. Pollut. Res.*, 2021, 32095–32110.

33 Environment Agency, *Combined Sewer Overflows Explained*, https://environmentagency.blog.gov.uk/2020/07/02/combined-sewer-overflows-explained/, (accessed 10 December 2022).

34 D. Morgan, L. Xiao and A. McNabola, *Technologies for Monitoring, Detecting and Treating Overflows from Urban Wastewater Networks*, Wexford, Ireland, 2018, vol. 280.

35 J. T. García, P. Espín-Leal, A. Vigueras-Rodriguez, L. G. Castillo, J. M. Carrillo, P. D. Martínez-Solano and S. Nevado-Santos, Urban runoff characteristics in Combined Sewer Overflows (CSOs): Analysis of storm events in southeastern Spain, *Water*, 2017, **9**(5), 1–16.

36 EPA, *Report to Congress: Combined Sewer Overflows into the Great Lakes Basin*, 2016.

37 Environment Agency, *Event duration monitoring – lifting the lid on storm overflows*, https://environmentagency.blog.gov.uk/2021/03/31/event-duration-monitoring-lifting-the-lid-on-storm-overflows/, (accessed 10 December 2022).

38 Environment Agency, *Event Duration Monitoring - Storm Overflows - Annual Returns*, https://data.gov.uk/dataset/19f6064d-7356-466f-844e-d20ea10ae9fd/event-duration-monitoring-storm-overflows-annual-returns, (accessed 10 December 2022).

39 US EPA, *Characterization of CSOs and SSOs*, 2004.

40 J. Gasperi, S. Zgheib, M. Cladière, V. Rocher, R. Moilleron and G. Chebbo, Priority pollutants in urban stormwater: Part 2 - Case of combined sewers, *Water Res.*, 2012, **46**, 6693–6703.

41 A. Bachmann-Machnik, Y. Bruning, A. E. Bakhshipour, M. Krauss and U. Dittmer, Evaluation of combined sewer system operation strategies based on highly resolved online data, *Water*, 2021, **13**, 1–20.

42 I. Jalliffier-Verne, M. Heniche, A. S. Madoux-Humery, M. Galarneau, P. Servais, M. Prévost and S. Dorner, Cumulative effects of fecal contamination from combined sewer overflows: Management for source water protection, *J. Environ. Manage.*, 2016, **174**, 62–70.

43 A. S. Madoux-Humery, S. Dorner, S. Sauvé, K. Aboulfadl, M. Galarneau, P. Servais and M. Prévost, The effects of

combined sewer overflow events on riverine sources of drinking water, *Water Res.*, 2016, **92**, 218–227.

44 Environment Agency, *Consented Discharges to Controlled Waters with Conditions*, https://data.gov.uk/dataset/55b8eaa8-60df-48a8-929a-060891b7a109/consented-discharges-to-controlled-waters-with-conditions, (accessed 10 December 2022).

45 Natural Resources Wales, *Additional guidance for: Water Discharge and Groundwater (from point source) Activity Permits (EPR 7.01)*, 2014.

46 European Commission, *European Commission Urban Waste Water website*, United Kingdom, https://uwwtd.eu/United-Kingdom/content/home-page, (accessed 10 December 2022).

47 National Audit Office, *Water supply and demand management, Department for Environment Food and Rural Affairs*, 2020.

48 R Core Team, *R: A language and environment for statistical computing*, R Foundation for Statistical Computing, Vienna, Austria, 2020.

49 QGIS Development Team, *QGIS Geographic Information System*, Open Source Geospatial Foundation Project, 2020.

50 G. B. Thomas and D. Crawford, London Tideway Tunnels: tackling London's Victorian legacy of combined sewer overflows, *Water Sci. Technol.*, 2011, **63**, 80–87.

51 Whitburn Neighbourhood Forum, *Reducing Sewage Pollution at Whitburn June 2021*, 2021.

52 European Parliament, *Petition No 0207/2018 by Robert Latimer (British) on the contamination of Whitburn beach, UK*, 2021.

53 C. Mclarnon and D. Groark, Whitburn Spill Reduction, *WaterProjectsOnline*, 2018, pp. 1–6.

54 Tideway, *Bazalgette Holdings Group Interim Report and Financial Statements for the six months ended*, 2021.

55 National Audit Office, *Thames Tideway Tunnel : early review of potential risks to value for money*, 2014.

56 A. Montserrat, L. Bosch, M. A. Kiser, M. Poch and L. Corominas, Using data from monitoring combined sewer overflows to assess, improve, and maintain combined sewer systems, *Sci. Total Environ.*, 2015, **505**, 1053–1061.

57 A. Rono, Evaluation of TSS, BOD5, and TP in Sewage Effluent Receiving Sambul River, *Journal of Pollution Effects & Control*, 2017, **5**, 1–5.

58 C. Engelhard, S. De Toffol and W. Rauch, Suitability of CSO performance indicators for compliance with ambient water quality targets, *Urban Water J.*, 2008, **5**, 43–49.

59 Environment Agency, *Discharge of raw sewage lands firm in hot water*, https://www.gov.uk/government/news/discharge-of-raw-sewage-lands-firm-in-hot-water, (accessed 10 December 2022).

60 J. P. Nickel and S. Fuchs, Micropollutant emissions from combined sewer overflows, *Water Sci. Technol.*, 2019, **80**, 2179–2190.

61 G. Moreira, J. Cools, K. Jurkiewicz, Y. Kuipers, D. Petrović and T. Zamparutti, *Assessment of impact of storm water overflows from combined waste water collecting systems on water bodies (including the marine environment) in the 28 EU Member States*, Brussels, 2016.

62 Environment Agency, *Water companies: environmental permits for storm overflows and emergency overflows*, 2018.

63 A. Montserrat, O. Gutierrez, M. Poch and L. Corominas, Field validation of a new low-cost method for determining occurrence and duration of combined sewer overflows, *Sci. Total Environ.*, 2013, **463–464**, 904–912.

64 DEFRA, *Regulatory impact assessment - sewage collection and treatment for London*, 2007, p. 67.

65 M. Abdellatif, W. Atherton, R. M. Alkhaddar and Y. Z. Osman, Performance de l'évaluation quantitative du débordement d'égout en relation avec le changement climatique dans le Nord-Ouest de l'Angleterre, *Hydrol. Sci. J.*, 2015, **60**, 636–650.

66 K. S. Evans, K. Athearn, X. Chen, K. P. Bell and T. Johnson, Measuring the impact of pollution closures on commercial shellfish harvest: The case of soft-shell clams in Machias Bay, Maine, *Ocean Coast. Manag.*, 2016, **130**, 196–204.

67 W. Ahmed, K. Hamilton, S. Toze, S. Cook and D. Page, A review on microbial contaminants in stormwater runoff and outfalls: Potential health risks and mitigation strategies, *Sci. Total Environ.*, 2019, **692**, 1304–1321.

68 A. R. McFarland, L. Larsen, K. Yeshitela, A. N. Engida and N. G. Love, Guide for using green infrastructure in urban environments for stormwater management, *Environ. Sci.: Water Res. Technol.*, 2019, **5**, 643–659.

69 C. F. Hunt, W. H. Lin and N. Voulvoulis, Evaluating alternatives to plastic microbeads in cosmetics, *Nat. Sustain.*, 2021, **4**, 366–372.

70 M. Wagner and S. Lambert, *Freshwater Microplastics - The Handbook of Environmental Chemistry 58*, 2018.

71 R. Dris, J. Gasperi and B. Tassin, in *Freshwater Microplastics: Emerging Environmental Contaminants?*, ed. M. Wagner and S. Lambert, Springer International Publishing, Cham, 2018, pp. 69–83.

72 C. Baresel and M. Olshammar, On the Importance of Sanitary Sewer Overflow on the Total Discharge of Microplastics from Sewage Water, *J. Environ. Prot.*, 2019, **10**, 1105–1118.

73 German Environment Agency, *Antibiotics and antibiotic resistance in the environment*, 2018.

74 R. Honda, C. Tachi, K. Yasuda, T. Hirata, M. Noguchi, H. Hara-Yamamura, R. Yamamoto-Ikemoto and T. Watanabe, Estimated discharge of antibiotic-resistant bacteria from combined sewer overflows of urban sewage system, *npj Clean Water*, 2020, **3**, 1–15.

75 A. C. Singer, Q. Xu and V. D. J. Keller, Translating antibiotic prescribing into antibiotic resistance in the environment: A hazard characterisation case study, *PLoS One*, 2019, **14**, e0221568.

76 H. T. Olds, S. R. Corsi, D. K. Dila, K. M. Halmo, M. J. Bootsma and S. L. McLellan, High levels of sewage contamination released from urban areas after storm events: A quantitative survey with sewage specific bacterial indicators, *PLoS Med.*, 2018, **15**, e1002614.

77 J. Passerat, N. K. Ouattara, J. M. Mouchel, V. Rocher and P. Servais, Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River, *Water Res.*, 2011, **45**, 893–903.
78 S. King, J. Exley, E. Winpenny, L. Alves, M.-L. Henham and J. Larkin, *The Health Risks of Bathing in Recreational Waters: A Rapid Evidence Assessment of Water Quality and Gastrointestinal Illness*, London, 2014.
79 S. L. McLellan, E. P. Sauer, S. R. Corsi, M. J. Bootsma, A. B. Boehm, S. K. Spencer and M. A. Borchardt, Sewage loading and microbial risk in urban waters of the Great Lakes, *Elementa*, 2018, **6**, 1–15.
80 E. Gill, B. Horton, J. Gilbert, S. Riisnaes and E. Partridge, *Storm Overflow Evidence Project*, 2021.
81 L. Rosenberger, J. Leandro, S. Pauleit and S. Erlwein, Sustainable stormwater management under the impact of climate change and urban densification, *J. Hydrol.*, 2021, **596**, 126137.
82 M. Davis and S. Naumann, *Making the Case for Sustainable Urban Drainage Systems as a Nature-Based Solution to Urban Flooding*, 2017.
83 CIWEM, *River water quality and storm overflows: A systems approach to maximising improvement*, 2022.
84 C. Alda-Vidal, A. L. Browne and C. Hoolohan, "Unflushables": Establishing a global agenda for action on everyday practices associated with sewer blockages, water quality, and plastic pollution, *Wiley Interdiscip. Rev.: Water*, 2020, **7**, 1–15.
85 Water UK, *Fine to Flush*, https://www.water.org.uk/policy-topics/managing-sewage-and-drainage/fine-to-flush/, (accessed 10 December 2022).
86 Water UK, *Disposal of Fats, Oils, Grease and Food Waste: Best Management Practice for Catering Outlets*, 2007.
87 U.S. EPA, Controlling fats, oils, and grease discharges from food service establishments, *National Pretreatment Program (40 CFR 403)*, 2012, pp. 1–5.
88 C. Hernández-Crespo, M. Fernández-Gonzalvo, M. Martín and I. Andrés-Doménech, *New Trends in Urban Drainage Modelling*, Springer, Cham, Switzerland, 2019.
89 D. Meyer, P. Molle, D. Esser, S. Troesch, F. Masi and U. Dittmer, Constructed wetlands for combined sewer overflow treatment-comparison of German, French and Italian approaches, *Water*, 2013, **5**, 1–12.
90 K. Tondera, Evaluating the performance of constructed wetlands for the treatment of combined sewer overflows, *Ecol. Eng.*, 2019, **137**, 53–59.
91 UKWIR, *22/WW/04/20 - Effluent disinfection: what is the cost?, Prepared by Isle Utilities*, 2022.
92 U. Dittmer, D. Meyer and G. Langergraber, Simulation of a subsurface vertical flow constructed wetland for CSO treatment, *Water Sci. Technol.*, 2005, **51**, 225–232.
93 DEFRA, *National Policy Statement for Waste Water: A framework document for planning decisions on nationally significant waste water infrastructure*, London, 2012.
94 D. Carver, *Sewage (Inland Waters) Bill 2019–2021 - Briefing Paper*, 2020.
95 J. Hughes, K. Cowper-Heays, E. Olesson, R. Bell and A. Stroombergen, Impacts and implications of climate change on wastewater systems: A New Zealand perspective, *Clim. Risk Manag.*, 2021, **31**, 100262.
96 UKWIR, *Climate change and the hydraulic design of sewerage systems*, 2002, vol. 3.
97 Met Office, *UK Climate Projections: Headline Findings*, 2021, pp. 1–12.
98 M. Kendon, M. McCarthy, S. Jevrejeva, A. Matthews, T. Sparks and J. Garforth, State of the UK Climate 2019, *Int. J. Climatol.*, 2020, **40**, 1–69.
99 M. Kendon, M. McCarthy, S. Jevrejeva, A. Matthews, T. Sparks and J. Garforth, State of the UK Climate 2020, *Int. J. Climatol.*, 2021, **41**, 1–76.
100 Met Office, *2021: the UK's weather in review*, https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2021/2021-a-year-in-weather-a-review, (accessed 10 December 2022).
101 T. Nasrin, A. K. Sharma and N. Muttil, Impact of short duration intense rainfall events on sanitary sewer network performance, *Water*, 2017, **9**, 1–17.
102 M. È. Jean, S. Duchesne, G. Pelletier and M. Pleau, Selection of rainfall information as input data for the design of combined sewer overflow solutions, *J. Hydrol.*, 2018, **565**, 559–569.
103 US EPA, *A Screening Assessment of the Potential Impacts of Climate Change on Combined Sewer Overflow (CSO) Mitigation in the Great Lakes and New England Regions*, 2008.
104 European Environment Agency, *Urban waste water treatment for 21st century challenges*, https://www.eea.europa.eu/publications/urban-waste-water-treatment-for, (accessed 10 December 2022).
105 Government Office for Science, *Trend Deck 2021: Urbanisation*, https://www.gov.uk/government/publications/trend-deck-2021-urbanisation/trend-deck-2021-urbanisation, (accessed 10 December 2022).
106 J. Lau, D. Butler and M. Schütze, Is combined sewer overflow spill frequency/volume a good indicator of receiving water quality impact?, *Urban Water*, 2002, **4**, 181–189.
107 Y. Gong, Y. Chen, L. Yu, J. Li, X. Pan, Z. Shen, X. Xu and Q. Qiu, Effectiveness analysis of systematic combined sewer overflow control schemes in the sponge city pilot area of Beijing, *Int. J. Environ. Res. Public Health*, 2019, **16**, 1–18.
108 S. J. McGrane, Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review, *Hydrol. Sci. J.*, 2016, **61**, 2295–2311.
109 P. Hammond, M. Suttie, V. T. Lewis, A. P. Smith and A. C. Singer, Detection of untreated sewage discharges to watercourses using machine learning, *npj Clean Water*, 2021, **4**, 1–10.
110 DEFRA, *Water industry strategic environmental requirements (WISER)*, https://www.gov.uk/government/publications/developing-the-environmental-resilience-and-flood-risk-actions-for-the-price-review-2024/water-industry-strategic-environmental-requirements-wiser, (accessed 10 December 2022).

111 Anglian Water, *Wholesale Wastewater Expenditure*, 2019.
112 Northumbrian Water, *3.3.6 Wastewater WINEP*, 2019.
113 The Review On Antimicrobial Resistance, *Tackling Drug-Resistant Infections Globally: Final Report And Recommendations*, 2016.
114 H. Bürgmann, D. Frigon, W. H. Gaze, C. M. Manaia, A. Pruden, A. C. Singer, B. F. Smets and T. Zhang, Water and sanitation: An essential battlefront in the war on antimicrobial resistance, *FEMS Microbiol. Ecol.*, 2018, **94**, 1–14.
115 N. Ashbolt, A. Pruden, J. Miller, M. V. Riquelme and A. Maile-Moskowitz, in *Water and Sanitation for the 21st Century: Health and Microbiological Aspects of Excreta and Wastewater Management (Global Water Pathogen Project)*, Michigan State University, 2019.
116 D. Sedlak, *How Development of America's Water Infrastructure Has Lurched Through History*, Pew Charitable Trusts, 2019.
117 European Commission, *Evaluation of the Urban Waste Water Treatment Directive*, 2019.
118 DEFRA, *Water for Life*, 2011.
119 X. Su, T. Liu, M. Beheshti and V. Prigiobbe, Relationship between infiltration, sewer rehabilitation, and groundwater flooding in coastal urban areas, *Environ. Sci. Pollut. Res.*, 2020, **27**, 14288–14298.
120 K. De Bondt, F. Seveno, G. Petrucci, F. Rodriguez, C. Joannis and P. Claeys, Potential and limits of stable isotopes (δ18O and δD) to detect parasitic water in sewers of oceanic climate cities, *J. Hydrol. Reg. Stud.*, 2018, **18**, 119–142.
121 T. Liu, X. Su and V. Prigiobbe, Groundwater-sewer interaction in urban coastal areas, *Water*, 2018, **10**, 1–18.
122 Chichester District Council, *Strategic Growth Study Wastewater Treatment Options for Chichester District*, 2010.
123 Minutes of Lower Holker Parish Council Meeting on Wednesday 3rd November 2021.
124 Foundation for Water Research, *Reliability And Impact Of Failure At Sewage Pumping Installations*, 1994.
125 OFWAT, *Investment in the water industry*, **https://www.ofwat.gov.uk/investment-in-the-water-industry/**, (accessed 10 December 2022).
126 National Infrastructure Commission, *Preparing for a drier future*, 2018, pp. 1–31.
127 W. I. H. Wan Rosely and N. Voulvoulis, Systems thinking for the sustainability transformation of urban water systems, *Crit. Rev. Environ. Sci. Technol.*, 2022, 1–21.
128 T. Giakoumis, C. Vaghela and N. Voulvoulis, *The role of water reuse in the circular economy, in Wastewater treatment and Reuse – Present and future perspectives in technological developments and management issues*, ed. P. Verlicchi, Elsevier, 2020, vol. 5, pp. 227–252.
129 P. Vanrolleghem, S. Tik and P. Lessard, *Advances in Modelling Particle Transport in Urban Storm- and Wastewater Systems*, 2019, pp. 907–914.
130 E. J. Hoffman, J. S. Latimer, C. D. Hunt, G. L. Mills and J. G. Quinn, Stormwater runoff from highways, *Water, Air, Soil Pollut.*, 1985, **25**, 349–364.
131 H. M. Hwang, M. J. Fiala, D. Park and T. L. Wade, Review of pollutants in urban road dust and stormwater runoff: part 1. Heavy metals released from vehicles, *Int. J. Urban Sci.*, 2016, **20**, 334–360.
132 A. Müller, H. Österlund, J. Marsalek and M. Viklander, The pollution conveyed by urban runoff: A review of sources, *Sci. Total Environ.*, 2020, **709**, 1–18.
133 A. James, in *Encyclopedia of Physical Science and Technology (Third Edition)*, ed. R. A. Meyers, Academic Press, New York, 3rd edn, 2003, pp. 699–719.
134 Z. Xu, H. Yin and H. Li, Quantification of non-stormwater flow entries into storm drains using a water balance approach, *Sci. Total Environ.*, 2014, **487**, 381–388.
135 R. Salvidge, *How the Environment Agency and a water firm discussed plans to silence residents over sewage pollution*, Ends Report, 2021.
136 T. Giakoumis and N. Voulvoulis, Water Framework Directive programmes of measures: Lessons from the 1st planning cycle of a catchment in England, *Sci. Total Environ.*, 2019, **668**, 903–916.

