

Supplementary Material

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Section 1. EDM data and quality control

Annual EDM (i.e. spill duration and counts) data for 2021, 2020 per CSO for the nine Water and Sewerage Companies with overflows in England were acquired from the Environment Agency¹. These data are returned by the Water and Sewerage Companies to the Environment Agency as part of their regulatory return each year to fulfil their permitted conditions to discharge from these storm overflows under the Environmental Permitting Regulations. EDM data were processed for duplicates and missing/wrong permit numbers/names using as a reference the Environment Agency's Consented Discharges to Controlled Waters with Condition dataset². Some EDM returns had multiple meters on a single discharge activity, the higher of the reported spill durations and count per permit number were taken, unless the comment indicates that the meters were not working properly in which case, we nulled the value. EDM overflow type, locations, the date of permit issue, effective and revocation were extracted from the Environment Agency's Consented Discharges to Controlled Waters with Condition dataset². EDM records that could not be matched to a permit number in the consented discharges database have been excluded. The CSO permits declared by the sewerage companies, those included in EDM 2021 and EDM 2020 datasets and those that passed the quality control and were eventually included in the analyses are shown in the Supplementary Tables 1.1 and 1.2 respectively. For the CSOs included in the analyses also shown in Electronic Supplementary Table 1

Considering that these data were collected by companies, we acknowledge limitations related to the fact that monitors might not have been operational 100% of the reporting period. For example, during 2021 we found that about 87% of the records in EDM 2021 dataset for the CSOs that we studied, cover 90% or above of the reporting period which might have led to an underestimation of the wastewater system spill durations we report in this study for that year (see Supplementary Table 1.3).

Supplementary Table 1.1 CSO permits declared and included in EDM 2021 per water company and those that passed the quality control and were included in the analyses.

Water Company	CSO declared by water companies	All EDM dataset rows with CSO permit numbers	All EDM dataset rows with CSO permit numbers and durations	EDM CSOs (unique permit numbers) with durations	EDM CSOs (unique permit numbers) with durations connected to Consents	EDM CSOs with durations connected to Consents including multiple meters on a single discharge activity	EDM CSOs included in the analyses
Anglian	1,552	1,552	834	817	817	834	828
Northumbrian	1,567	1,519	1,399	1,358	1,356	1,397	1,373
Severn Trent	2,658	2,238	2,121	1,939	1,937	2,119	1,984

South-West	1,391	1,388	1,093	1,017	1,008	1,083	1,059
Southern	978	971	943	886	872	929	897
Thames	465	465	461	461	457	457	457
United Utilities	2,192	2,192	1,954	1,843	1,842	1,953	1,886
Wessex	1,297	1,275	1,046	1,015	991	1,022	1,017
Yorkshire	2,246	2,234	2,076	1,919	1,871	2,014	1,923
Totals	14,346	13,834	11,927	11,255	11,151	11,808	11,424

Regarding the 11,151 distinct CSO permit numbers of EDM 2021, which passed the quality control and were connected to consents dataset, there can be multiple outlet types or even multiple matters per outlet type (yielding 11,808 rows in the dataset.) From these the final list of 11,424 CSOs was derived containing 273 CSOs that have more than one outlet types: 251 WWTW (both at the inlet and storm tank), 11 Sewer network - Pumping station, 7 WWTW a- Sewer network, 3 WWTW - Pumping station, 2 Sewer network - Sewer network. These were investigated as separate CSOs.

Supplementary Table 1.2 CSO permits declared and included in EDM 2020 per water company and those that passed the quality control and were included in the analyses.

Water Company	CSO declared by water companies	CSO permit numbers in EDM 2020 datasets	EDM CSOs (unique permit numbers) connected to consents*	EDM CSOs included in the analyses (EDM CSOs connected to Consents* with duration)
Anglian	1,566	711	692	668
Northumbrian	1,520	1,485	1,373	1,373
Severn Trent	2,954	2,276	1,875	1,875
South-West	1,209	1,095	955	955
Southern	975	945	783	777
Thames	472	463	447	447
United Utilities	2,273	1,925	1,691	1,691
Wessex	1,289	971	919	919
Yorkshire	2,241	2,105	1,905	1,905
Totals	14,499	11,976	10,640	10,610

*Excluding duplicates, missing permit numbers, wrong permit numbers/names

Supplementary Table 1.3 EDM operation as percentage (%) of reporting period for 2021

Water Company Name	Below 50%	Equal or Over 60%	Equal or Over 70%	Equal or Over 80%	Equal or Over 90%	NA	Total	Percent from total (%)
Anglian	20	9	8	20	777	0	834	7%
Northumbrian	43	28	28	88	1210	0	1397	12%
Severn Trent	67	57	94	255	1646	0	2119	18%
South West	18	17	28	73	947	0	1083	9%
Southern	42	12	11	34	830	0	929	8%
Thames	6	7	8	19	417	0	457	4%
United Utilities	20	10	20	42	1790	71	1953	17%
Wessex	6	2	5	28	981	0	1022	9%
Yorkshire	64	41	76	149	1684	0	2014	17%
Total	286	183	278	708	10282	71	11808	100%
Percent from total (%)	2%	2%	2%	6%	87%	1%	100%	

Section 2. Method for connecting CSOs to their wastewater systems

Water company operating boundaries were acquired from OFWAT ³. The 11,424 EDM CSOs consist of 11,151 unique permit numbers and locations with 273 of them having more than outlets and types (251 WWTW (both at the inlet and storm tank), 11 Sewer network - Pumping station, 7 WWTW a- Sewer network, 3 WWTW - Pumping station, 2 Sewer network - Sewer network). We developed a stepwise approach that helped up connect CSOs to WWTWs:

2,043 CSOs located at WWTWs:

A total 2,043 EDM CSOs are located at the WWTWs, and therefore were connected to their corresponding works based on permit number (i.e. they had the same permit number).

2,401 CSOs that belong to England's largest wastewater systems

Maps of 81 largest sewerage systems (i.e. with load entering 100,000 P.E. and above) for Anglian Water; Severn Trent; Southern Water; Thames Water; Wessex Water; Yorkshire Water were acquired from open access datasets and reports ⁴⁻⁹ and for Northumbria Water's Howdon and Hendon ¹⁰ were georeferenced, and their boundaries were digitised to join 2,401 CSOs to the corresponding WWTW by location.

6,707 CSOs that belong to large, medium and small wastewater systems (other than located at WWTWs)

For the remaining 6,707 CSOs, the connection of CSOs to WWTWs was based on digital vector boundaries for Parishes and Non-Civil Parished areas in England and Wales ¹¹ and their distance from WWTWs. CSOs that belong to a parish with just one WWTW they were connected to the corresponding WWTW. CSOs that belong to a parish with multiple WWTWs, CSOs were connected to the closest WWTW within a radius of 500m and then the remaining to the WWTW with the highest DWF within the parish. The remaining CSOs that belong to a parish with not any WWTWs, were connected to the WWTW with max DWF among the neighbouring parishes.

The CSOs from both EDM 2021 and 2020 and the WWTWs that are connected to are shown in Electronic Supplementary Table 1. The accuracy of this approach was evaluated at 84%, by comparing our findings to a subset of 842 CSOs (7% of all EDM CSOs) for which data were available. By using the maximum spill duration reported amongst the CSOs connected to each system to indicate the spill duration per system, the accuracy of the approach can be higher, considering that our findings (see results) suggest that CSOs located at WWTWs had significantly higher average spill durations than those located on other parts of the sewer network.

Section 3. Hydraulic capacity as FFT/DWF ratio per WWTWs

From the 5,187 WWTWs, 4,107 had data on Dry Weather Flow (DWF) and 2,200 on Full Flow to Treatment (FFT) (See Supplementary Table 3.1), while for 151 additional WWTWs the FFT was obtained from the weir setting of the CSO at the inlet of the WWTWs. The hydraulic capacity of each WWTWs was estimated via the "FFT/DWF" ratio (Electronic Supplementary Table 2).

Supplementary Table 3.1 Wastewater treatment works (WWTWs) per sewerage company with data on Dry Weather Flow (DWF) and Full Flow to Treatment (FFT)

Water Company	WWTWs	WWTWs with DWF		WWTWs with FFT
	Number	Number	Aggregated DWF (m ³ /d)	Number
Anglian	1083	883	1,703,182.77	414
Northumbrian	328	225	923,589.11	138
Severn Trent	925	883	2,407,024.08	421
South-West	616	434	503,877.27	228
Southern	366	306	1,226,060.60	184
Thames	345	322	4,450,744.50	50
United Utilities	563	312	2,727,807.10	273
Wessex	374	356	827,504.00	214
Yorkshire	587	386	1,510,277.80	278
Totals	5187	4107	16,280,067.23	2,200

Section 4. Wastewater systems with available data

Out of the 5,187 consented to discharge WWTWs owned by water companies in England, 2,724 WWTWs found to be connected to the 11,424 CSOs (or 2,531 WWTWs connected to 9,275 CSOs other than pumping stations) monitored during EDM 2021. All 2,531 systems were included in the analyses and used to investigate our hypothesis.

Of these, 2,064 WWTWs have both DWF and FFT data, of which 1,974 are connected to 7,154 CSOs that spilled during 2021 (from a total 8,056 CSOs that are connected to). These 1,974 systems correspond to 78% of all wastewater systems with EDM 2021 CSOs and was used in our analyses 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 (Table 3, Fig 3 of main text).

Supplementary Table 4.1 Wastewater systems studied with CSOs monitored during 2021 EDM, categorised based on data availability for Dry Weather Flow (DWF) and Full Flow to Treatment (FFT), spills and size

	WWTWs	CSOs		WWTW	WWTWs	CSOs		WWTW Size	WWTWs	CSOs	
		Spilled	All			Spilled	All			Spilled	All
Systems with both DWF FFT data	2,064	7,154	8,149	not Spilled	90	0	93	Large	47	0	49
								Small	43	0	44
				Spilled	1,974	7,154	8,056	Large	1,248	6,258	7,114
								Small	726	896	942

	WWTWs	CSOs		WWTW	WWTWs	CSOs		WWTW Size	WWTWs	CSOs	
		Spilled	All			Spilled	All			Spilled	All
Systems without DWF or FFT data	467	982	1,126	not Spilled	36	0	39	Large	12	0	12
								Small	24	0	27
				Spilled	431	982	1,087	Large	232	624	695
								Small	199	358	392

Similarly, 2,546 WWTWs found to be connected to 10,610 CSOs (or 2,316 WWTWs connected to 8,257 CSOs other than pumping stations) monitored in 2020.

Section 5. Method for estimating wastewater systems spill duration

In this section we present the comparison of aggregate spill duration of all CSOs in a system to the maximum spill duration between the CSOs of each system for both EDM 2021 and 2020 in Supplementary Tables 5.1 and 5.2 respectively. We classified the wastewater systems that spilled in 2021 and 2020 based on the number of CSOs (pumping stations excluded). For each group (CSOs per system) we provide: A) the mean spill duration based on the durations of all CSOs monitored per wastewater system (Mean aggregate duration), B) the system's mean spill duration on the duration of the CSO with the max spill duration per system (Mean max spill duration) and B) the ratio of the two variables, which indicates the percentage contribution of the max spilling CSO to the aggregated spill duration per system.

For works with up to four CSOs, the maximum and aggregated duration were found very similar, indicating that a single CSO drives a system's spill duration, releasing most of the excess flows when the system's hydraulic capacity is reached. In systems with a larger number of CSOs (mainly due to large spatial extend and agglomerations), the aggregated spill duration increases with the number of CSOs located on the network (accounting 73% of aggregated system durations, compared to 18% on storm tanks and 9% at the inlet of the works). The duration of the CSO with the maximum spill duration per system is therefore a better indicator to capture the link between the system's spill duration and its capacity.

For systems with one CSO spilling (1,375 systems), this is straightforward, as the duration the system spills is the one and the same with the CSO spilling. With 85% of the CSOs monitored (7,900 CSOs) being part of systems with more than one CSO, showing significant variation in CSO spill frequency and duration within each system, relating their frequency and duration to the operation of the system is more challenging.

Further we present the outputs from our analyses using the aggregated spill duration of CSOs per system for 2021. It includes:

Supplementary Table 5.3 that supplements the analyses presented in Table 2 (of the main text) can be used together with Supplementary Fig 5.1, which shows the comparison between two classification methods of wastewater systems for 2021.

Supplementary Fig 5.2 shows the aggregate spill duration of the CSOs (across several incidents) per wastewater system and per water company for 2021 – supplementing Fig 2 in the main text.

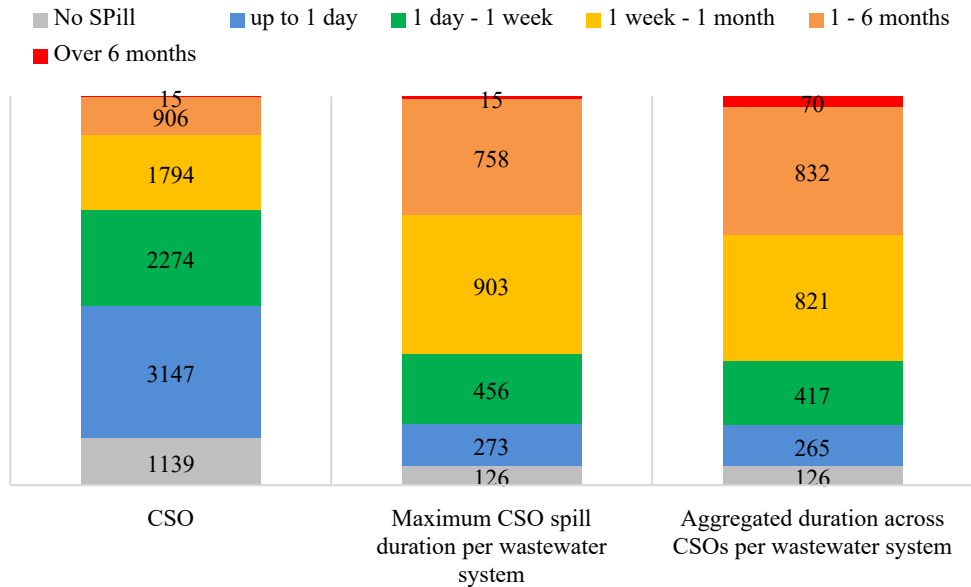
Supplementary Table 5.1 Classification of wastewater systems that spilled in 2021 based on the number of CSOs (pumping stations excluded). For each group (CSOs per system) we provide the mean spill duration, based on the durations of all CSOs monitored per wastewater system (Mean aggregate duration), and on the duration of the CSO with the max spill duration per system (Mean max spill duration). We also provide the ratio of the two variables, which indicates the percentage contribution of the max spilling CSO to the aggregated spill duration per system.

CSOs per system (n)	Mean aggregate duration (h)	Mean max spill duration (h)	Systems (n)	Mean max spill duration / Mean aggregate duration
1	574.87	574.87	1375	100%
2	853.71	729.60	423	85%
3	930.31	726.76	182	78%
4	794.69	590.15	72	74%
5	1,121.62	712.52	63	64%
6	1,237.68	855.49	45	69%
7	1,293.16	728.48	35	56%
8	1,534.17	777.99	32	51%
9	1,400.27	761.76	19	54%
10	1,303.45	623.10	23	48%
11	1,508.36	560.91	9	37%
12	1,517.18	720.84	12	48%
13	1,487.91	790.33	9	53%
14	2,228.59	877.38	7	39%
15	1,695.78	913.25	4	54%
16	3,014.43	1,813.40	5	60%
17	1,539.03	650.68	6	42%
18	1,629.27	700.07	2	43%
19	4,487.51	2,410.59	8	54%
20	2,188.31	1,113.41	6	51%
21	4,469.38	733.03	1	16%
22	3,462.85	1,039.19	6	30%
23	4,232.88	2,113.85	5	50%
24	1,903.71	565.37	4	30%
25	2,947.41	1,073.07	7	36%
26	2,828.59	1,212.07	2	43%
27	6,591.13	2,850.69	2	43%
30	5,010.34	1,157.40	1	23%
31	6,949.06	1,981.97	1	29%
33	4,145.75	845.47	2	20%
34	5,125.98	1,365.86	3	27%
37	4,176.56	1,204.00	1	29%
38	4,646.55	1,251.80	3	27%
40	19,590.51	4,110.41	1	21%
41	8,827.37	4,902.75	1	56%
46	7,930.41	2,471.03	2	31%
47	5,883.15	886.92	2	15%
48	8,517.30	1,911.06	2	22%
49	1,304.96	349.69	1	27%
50	8,341.00	1,110.80	1	13%
52	10,135.56	1,134.14	1	11%
53	2,007.51	465.60	1	23%
57	4,549.17	934.20	1	21%
58	4,785.47	1,028.20	1	21%
60	3,010.18	685.24	1	23%
61	12,252.18	1,924.17	1	16%
64	4,253.20	973.33	1	23%
71	13,152.75	2,273.89	2	17%
88	2,811.50	656.80	1	23%
105	10,308.70	1,053.80	1	10%
106	5,733.68	1,023.24	1	18%
108	10,763.30	1,914.15	2	18%
117	9,295.74	1,733.20	1	19%
126	18,321.50	3,243.60	1	18%

147	16,008.30	1,301.10	1	8%
183	7,373.00	1,154.90	1	16%
233	4,905.56	570.90	1	12%
238	29,124.08	4,396.75	1	15%

Supplementary Table 5.2 Classification of wastewater systems that spilled in 2020 based on the number of CSOs (pumping stations excluded). For each group (CSOs per system) we provide the mean spill duration, based on the durations of all CSOs monitored per wastewater system (Mean aggregate duration), and on the duration of the CSO with the max spill duration per system (Mean max spill duration). We also provide the ratio of the two variables, which indicates the percentage contribution of the max spilling CSO to the aggregated spill duration per system.

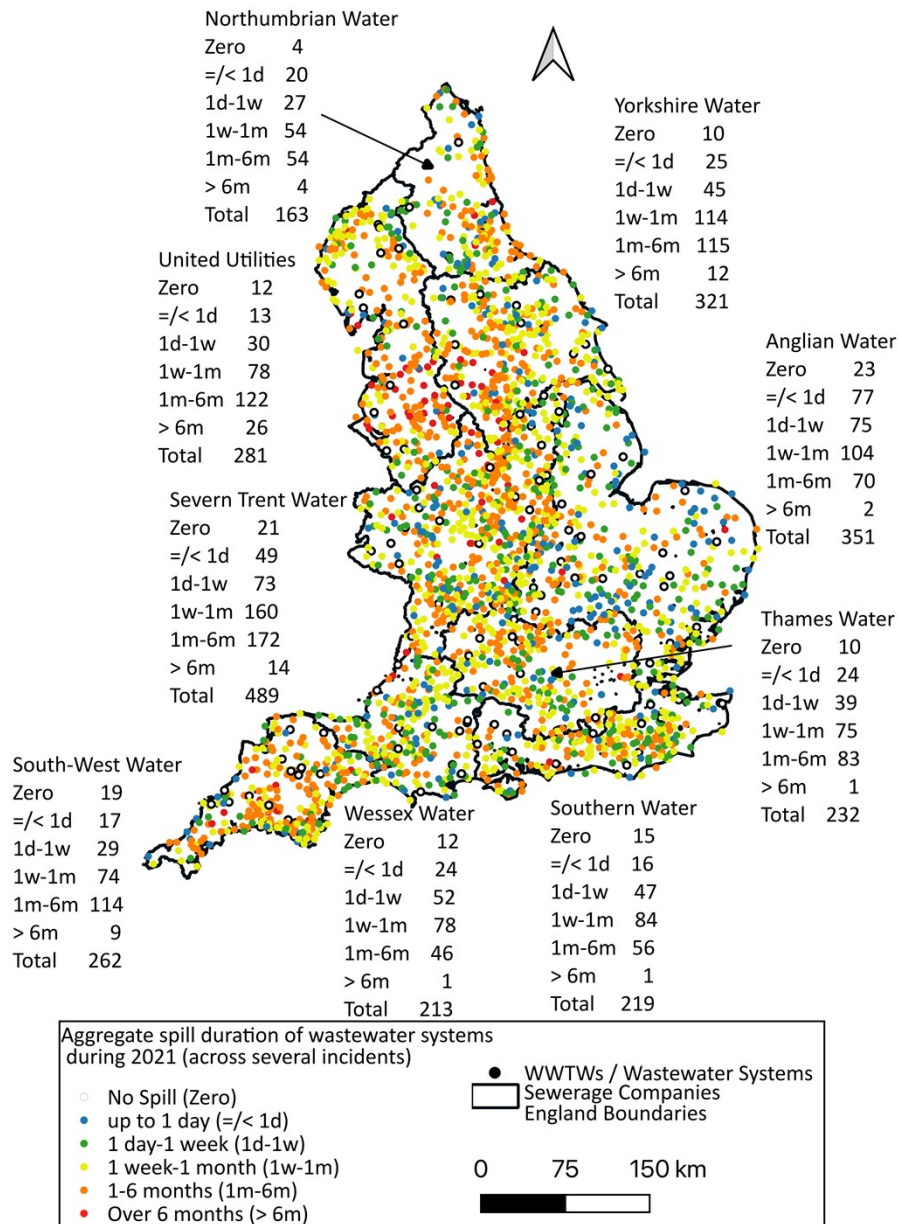
CSOs per system (n)	Mean aggregate duration (h)	Mean max spill duration (h)	Systems (n)	Mean max spill duration/ Mean aggregate duration
1	799.18	799.18	1149	100%
2	1,043.00	928.54	263	89%
3	1,221.59	1,031.05	111	84%
4	1,438.50	1,148.06	73	80%
5	1,501.79	1,100.39	44	73%
6	1,575.46	1,064.83	29	68%
7	2,007.95	1,290.98	21	64%
8	1,097.19	637.27	25	58%
9	1,904.57	975.99	12	51%
10	1,706.98	953.05	10	56%
11	2,832.38	1,912.33	8	68%
12	2,803.75	1,755.65	10	63%
13	2,364.76	1,329.74	7	56%
14	2,452.20	1,202.68	4	49%
15	3,619.96	1,178.18	4	33%
16	2,451.63	1,622.87	4	66%
17	4,195.29	1,690.30	2	40%
18	3,186.81	1,436.99	5	45%
19	2,206.18	746.67	4	34%
20	2,664.94	1,662.15	2	62%
21	12,570.25	3,316.41	2	26%
22	2,964.54	1,179.73	2	40%
23	4,482.26	1,594.76	4	36%
24	4,286.51	828.07	1	19%
25	6,312.84	1,635.78	2	26%
26	8,149.85	1,406.35	4	17%
27	2,451.66	545.73	1	22%
28	8,813.78	2,174.17	1	25%
29	4,729.91	1,406.51	2	30%
30	6,519.77	3,193.67	1	49%
32	5,104.99	1,429.38	2	28%
33	4,571.16	1,045.62	2	23%
34	7,764.50	5,276.70	1	68%
36	4,248.49	2,108.15	2	50%
37	5,374.62	1,004.21	1	19%
38	5,802.21	1,078.06	3	19%
39	4,163.14	1,152.89	1	28%
41	6,369.16	994.07	1	16%
42	6,272.16	2,220.27	2	35%
44	14,228.06	3,649.09	1	26%
49	5,618.96	1,228.32	1	22%
54	7,031.89	1,280.32	1	18%
55	4,304.98	811.06	1	19%
62	15,464.64	3,417.30	1	22%
77	6,628.43	1,707.00	1	26%
79	9,541.83	1,885.00	1	20%
85	11,041.24	2,094.10	1	19%
88	12,336.32	1,146.37	1	9%
90	13,226.40	3,748.00	1	28%
97	15,723.67	6,231.29	1	40%
119	16,007.37	1,879.78	1	12%
134	9,553.05	1,849.00	1	19%
178	16,457.40	3,693.30	1	22%
189	17,669.40	3,986.39	1	23%



Supplementary Fig 5.1 Number of CSOs and wastewater systems (in 6 categories) based on aggregated spill duration across several incidents per CSO, and per system: i) based on the aggregated duration across the CSOs spilling in each system and ii) based on the CSO with maximum spill duration in each system, classified the following six categories: did not spill (no spill); spilled up to a day ($\leq 1d$); spilled between a day and a week (1d-1w); spilled between a week and 1 month (1w-1m); spilled between 1 and 6 months (1m-6m); and spilled more than 6 months ($> 6m$).

Supplementary Table 5.3 Classification of wastewater systems based on the aggregated spill duration of CSOs per system for 2021, as follows: did not spill (no spill); spilled up to a day ($\leq 1d$); spilled between a day and a week (1d-1w); spilled between a week and 1 month (1w-1m); spilled between 1 and 6 months (1m-6m); and spilled more than 6 months ($> 6m$).

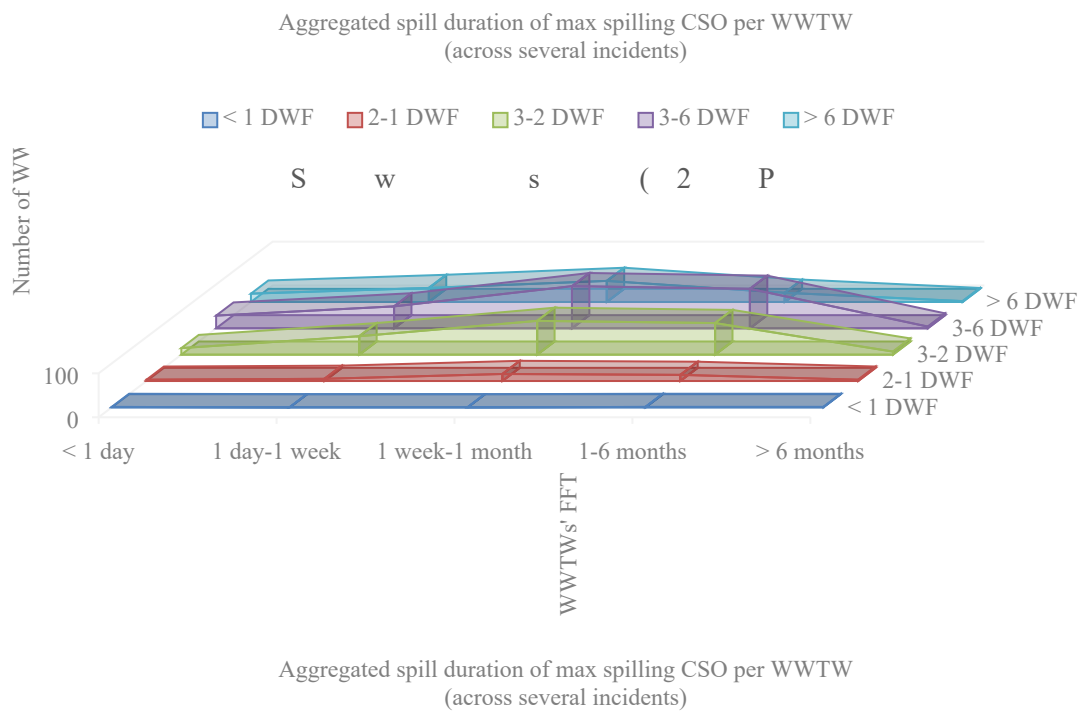
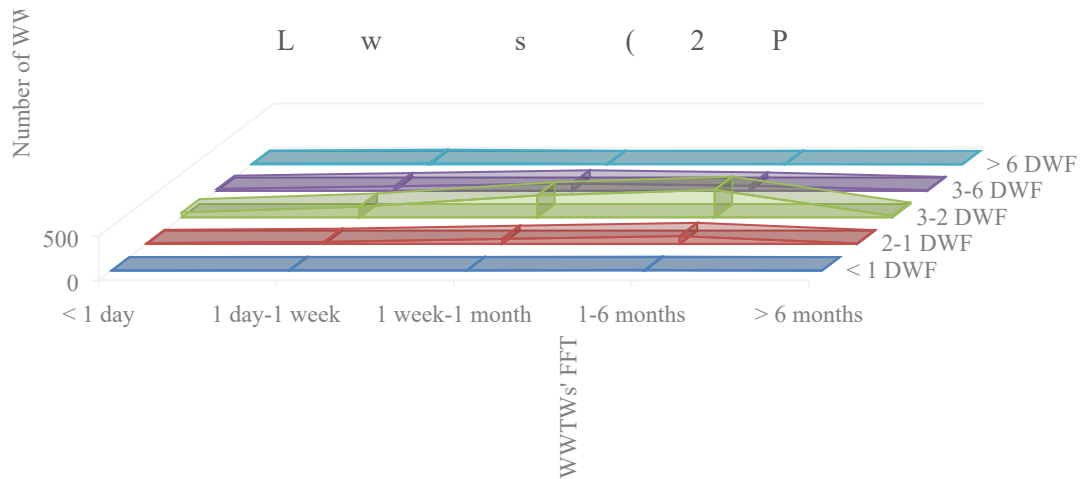
Classification of systems	Average number CSO per system (n)	No of systems	Mean duration (h)	ST	I	N
No Spill	1	(126)	0			
< 1d	1	265	8.97	115	76	161
1d-1w	2	417	86.25	251	128	300
1w-1m	2	821	403.58	559	272	883
1m-6m	4	832	1,601.97	682	267	2,575
> 6m	41	70	7,424.28	65	33	2,776
Total		2,405	878.00	1,672 (18%)	776 (9%)	6,695 (73%)



Supplementary Fig 5.2 Map of wastewater systems in England based on the location of their wastewater treatment works (WWTWs) showing the aggregate spill duration of their CSOs (across several incidents) per water company for 2021

Section 6. Results for 2020

In this section, we present the figures and tables from the analyses of EDM 2020 datasets which is covered in the main text.



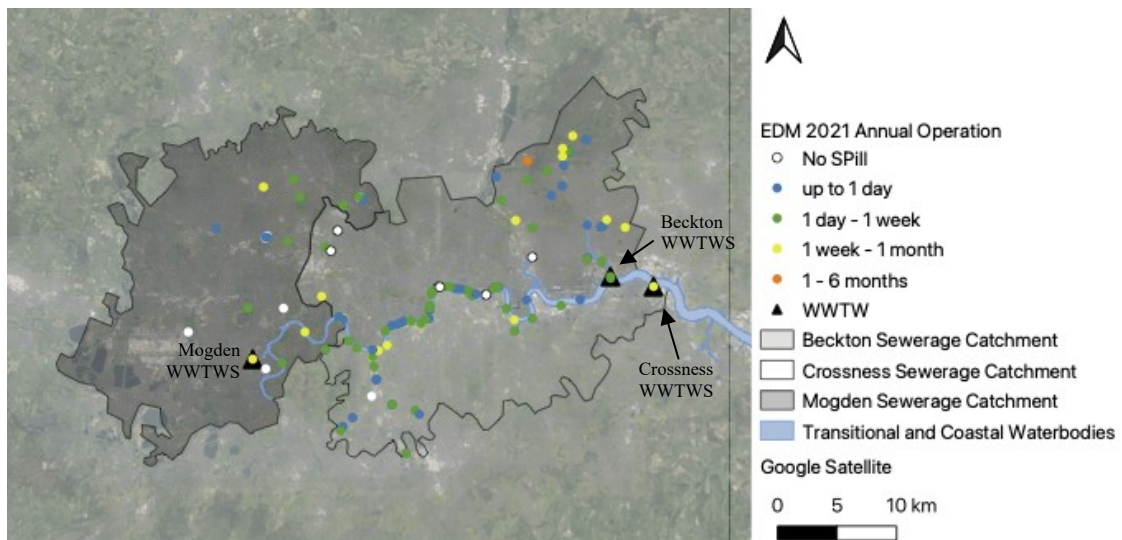
Supplementary Figure 7.1 Spill duration of wastewater systems during 2020 and the Flow to Full Treatment (FFT) of their wastewater treatment works (WWTWs) expressed as multiples of Dry Weather Flow (DWF) in five categories: spilled up to a day ($\leq 1d$); spilled between a day and a week ($1d-1w$); spilled between a week and 1 month ($1w-1m$); spilled between 1 and 6 months ($1m-6m$); and spilled more than 6 months ($> 6m$).

Supplementary Table 7.1 Classification of wastewater systems spill duration in 2020 across five categories; spilled up to a day ($\leq 1d$); spilled between a day and a week (1d-1w); spilled between a week and 1 month (1w-1m); spilled between 1 and 6 months (1m-6m); and spilled more than 6 months ($> 6m$), and based on the type of their CSO (other than pumping stations) with the max spill duration in 2021 (as type I = Inlet, N = Network, ST = Storm Tank) related to the hydraulic capacity of each WWTWs, with Flow to Full Treatment (FFT) expressed as multiples of Dry Weather Flow (DWF).

Size	FFT	DWF (m ³ /d)					No of WWTWs		CSOs	Mean duration per system (h)
		Min	Median	Mean	Max	CV	Percentage (in brackets)			
Large > 2,000 PE	< 1 DWF	1,070.00	8,400.00	29,731.85	171,140.00	175%	13 (1%)		79	638.73
	2-1 DWF	290.00	3,153.50	31,215.27	1,344,000.00	389%	180 (19%)	943 (79%)	1368	1,238.53
	3-2 DWF	288.00	2,224.00	8,024.15	340,000.00	267%	750 (80%)		3238	952.01
	3-6 DWF	291.00	1,464.00	6,478.08	225,000.00	308%	218 (89%)	246 (21%)	866	753.74
	> 6 DWF	286.00	505.00	1,840.25	28,129.00	286%	28 (11%)		79	311.37
				All				1189		5630
Small < 2,000 PE	< 1 DWF	72.00	141.00	119.00	144.00	34%	3 (1%)		3	3,412.91
	2-1 DWF	18.00	146.00	149.95	280.00	50%	41 (8%)	257 (81%)	52	1,305.26
	3-2 DWF	7.00	130.00	132.59	285.00	61%	213 (40%)		266	970.67
	3-6 DWF	5.80	117.00	122.95	285.00	63%	269 (51%)		328	804.96
	> 6 DWF	5.00	75.00	88.84	275.00	77%	122 (19%)		139	587.92
				All				648		788

Section 7. The case of Beckton, Crossness and Mogden wastewater systems

In 2021, 62 CSOs (out of the 68 monitored) of the Becton sewerage network spilled, with the max spilling CSO (Beech Hall Crescent- permit number: CLCR.0032) spilling for 116 times to a total of 1,028 hours. In Crossness, 30 CSOs (out of the 31 monitored) spilled, with the max spilling CSO (Bell Lane Creek - permit number: TEMP.2438) spilling for 71 times to a total of 531.89 hours. In Mogden, 14 CSOs (out of the 21 monitored) spilled, with the CSO at the storm tank at the WWTWs (permit number: CNTD.0085) spilling for 43 times to a total of 438.3 hours. All three works (Becton, Crossness and Mogden) still have a hydraulic capacity of less than 2 DWFs.



Supplementary Fig 7.1. Map of Beckton, Crossness and Mogden wastewater systems showing the duration of spill events during 2021 EDM (across several incidents)

Section 8. Primary reason reported by the sewerage companies for the EDM CSOs with high spill frequency during 2021

Supplementary Table 8.1. Primary reason reported by the sewerage companies for the EDM CSOs with high spill frequency during 2021

High Spill Frequency - Operational Review - Primary Reason	CSOs	
	Number	Percent
Data collection - Confirmed exceptional weather	20	1.3%
Data collection - EDM non-representative location	33	2.1%
Data collection - Tidal / river inundation	15	1.0%
Not asset maintenance - Hydraulic capacity	1242	79.4%
Performance - Asset configuration (e.g. PS/rising main/storm tanks)	78	5.0%
Performance - Asset power failure	4	0.3%
Performance - GW inundation	14	0.9%
Performance - Infiltration	114	7.3%
Performance - Other maintenance / capital works (e.g. jetting)	23	1.5%
Performance - Partial / no capacity due to blockage or restriction (e.g. roots / grid) - maintenance issue	12	0.8%
Performance - Pump failure / issue	10	0.6%
	1565	100.0%

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