https://doi.org/10.71573/0jtztp93

Statistical Analysis of Wastewater Drivers in All Large Treatment Plants of England

Robin Maes-Prior [1*] https://orcid.org/0000-0001-5513-7731, *Barnaby Dobson* [1] https://orcid.org/0000-0002-0149-4124 & *Ana Mijic*[1] https://orcid.org/0000-0001-7096-9405

[1]*Imperial College London, Department of Civil and Environmental Engineering, London, United Kingdom*
**Corresponding author email: rcm19@ic.ac.uk*

Abstract

The availability of geospatial data across the water cycle is expanding globally, with England offering a comprehensive range of high-quality, openly accessible datasets. Concurrently, wastewater systems face significant challenges, including network capacity limitations, an increasing number of spills, and the threat of emerging pollutants to water bodies and public health. To address these issues, we developed the first national dataset of wastewater signatures and sewershed characteristics across 799 sewershed and applied multiple linear regression (MLR) models to identify the key drivers and sources of wastewater flows and spills. Focusing on large wastewater treatment plants across England, the study incorporates diverse catchment characteristics and effluent signatures. Results indicate that precipitation is the primary driver of effluent flow variability and spills. This key relationship appears at the national scale, while at company/regional scale the signal becomes less clear, highlighting the value of national-scale analyses. These findings provide a foundation for further development of this dataset to aid in modelling of wastewater dynamics and the development of targeted management strategies.

Highlights

- Developed first national dataset of 799 sewersheds and their signatures and characteristics.
- Precipitation is the most significant factor driving effluent flows and spills in England.
- National scale approach reveals drivers not seen at company/regional scale.

Introduction

Wastewater systems are increasingly strained by capacity limitations and environmental impacts, as seen in rising combined sewer overflow (CSO) spills and emerging pollutants (Mathers, 2024; Rapp-Wright et al., 2023). These challenges are amplified by urban migration and climate change (Koop & van Leeuwen, 2017), with population growth intensifying network demand and extreme weather exacerbating peak inflows. Urban sewer discharges include sanitary sewage, infiltration/inflow (I/I), and stormwater (Gernaey et al. 2011), and understanding the drivers of these components is essential for informing effective management strategies.

While regional studies (Weiss, Brombach & Haller, 2002; Dirckx et al., 2009) have highlighted the impact of I/I, its national-scale effects remain poorly understood. Common methods for estimating I/I include ‘triangle’ or ‘moving minimum’ approaches, while more complex models allow scenario-based assessments (Karpf & Krebs, 2013; Ge et al., 2024). Historically managed at the sewershed level (the area draining into the sewer network), wastewater systems are now subject to national planning initiatives, such as the Drainage and Wastewater Management Plans (DEFRA, 2022) and a national strategy to reduce CSO spills by 2050 (Water UK, 2024). These efforts highlight the need for a comprehensive national analysis of wastewater system drivers.

The field of large sample hydrology and development of the national scale CAMELS datasets (Coxon et al. 2020; Addor et al. 2017) have provided hydrologists with the means to assess national and regional patterns and drivers in the natural water cycle (Coxon et al., 2024; Addor et al., 2018; Bloomfield et al., 2021; Zheng et al., 2023). In an increasingly integrated water system (Mijic, Dobson & Liu 2024) the need to curate a CAMELS equivalent for wastewater systems is necessary to understand variability in sewersheds and what controls managers have beyond pipe networks. This work seeks to develop an initial dataset towards this goal.

This study develops the first national dataset of wastewater signatures and characteristics to perform a multiple linear regression (MLR) analysis of wastewater drivers across England. Catchment characteristics will be assessed for their influence on effluent behaviour and spills, with a focus on statistical significance and variations across catchments and companies. This research aims to identify the primary drivers of wastewater flows in England.

Methodology

To evaluate the influence of sewershed characteristics on effluent and spill signatures, a national-scale dataset was assembled integrating hydrological, demographic and geological attributes with effluent flow and spill data. Multiple linear regression models were applied to quantify associations between sewershed features and observed effluent and spill patterns. The following sections describe the data sources, variable selection criteria, preprocessing methods, and statistical modelling framework.

Catchment Selection

Data were selected based on availability, relevance, and alignment with the study's spatial and temporal requirements. Open-access datasets were prioritised; however, effluent flow data were obtained via a Freedom of Information request to the UK Environment Agency, given their limited public availability. As effluent flow and spill data formed the core of the analysis, all supporting datasets were constrained to the same spatial extent (England) and temporal coverage (2020–2023).

The selected temporal window (2020–2023) was primarily constrained by the availability of Event Duration Monitoring (EDM) data, as widespread installation of EDM monitors across England has only occurred since 2020 (EA, 2025a). Consequently, national-scale spill data are only available from 2020 onwards. Although effluent flow data were available for a longer period (2011–2023), comparative analysis of flow distributions and results with and without the inclusion of spill data revealed minimal variation between the full dataset and the 2020–2023 subset. Therefore, the 2020–2023 period was selected to ensure consistency across constituent datasets and to enable integration of spill data into the analysis.

To ensure robust signature development, only wastewater treatment works (WWTWs) with a minimum of 95% completeness in their effluent flow time series during the study period were retained. This threshold was selected to balance data quality with spatial coverage and aligns with similar criteria used by Coxon et al. (2024). An additional inclusion criterion required that WWTWs fall under the scope of the Urban Wastewater Treatment Directive (UWWTD). Under this directive, treatment plants must serve a population equivalent (PE) greater than 2,000 for inland discharges or greater than 10,000 for coastal discharges to be subject to regulatory oversight (EA, 2025b). Facilities meeting these thresholds are strictly regulated and have reported data. As of 2025, there were 1,481 treatment plants in England, of which 799 satisfied the UWWTD thresholds and data completeness requirements. These 799 WWTWs were retained for the dataset and analysis.

Sewershed Dataset and Preprocessing

The dataset used in this study integrates system output data (referred to as *signatures*) with a range of influencing characteristics that govern system behaviour. Tables 1 and 2 summarise the individual datasets used to extract the signatures and characteristics, including their parameters, sources, and the preprocessing steps applied. The sewersheds represented in the dataset vary considerably in scale, with contributing areas ranging from 0.51 to 248.62 km². This variation in spatial extent is closely associated with differences in population size, which is expected to be a primary driver of variability in the observed signatures. To explore the influence of broader catchment characteristics, system signatures and selected physical descriptors, namely capacity and area, are normalised by population (or by number of CSO locations for spills).

Table 1. Breakdown of datasets used in forming the wastewater signatures component of the national dataset, including the parameter names for the analysis, preprocessing method and source of the data.

Dataset	Signature	Preprocessing	Source
Effluent Flow Timeseries	Skew	Mean/Median normalised by population	FOI request from EA
	Std	Standard deviation normalised by population	
	Median	Median standardised by population	
	Mean	Mean standardised by population	
	BFI	Minimum annual average 7-day flow, divided by mean	
	Q5	Q5 flow normalised by population	
	HFD	Q90/Median	
	Q95	Q95 flow normalised by population	
	HFVar	Coefficient of variability of the annual number of flows above Q75	
	LDVar	Coefficient of variability of annual mean duration below Q25	
	Mean30d Max	Mean of annual max 30-day average flow over median flow	
	RBI	Richards-Baker flashiness index	
Spills	Counted Spills	All spill locations in the sewershed summed together to give values at sewershed scale. Mean annual spill count in sewershed normalised by number of spill sites	EA, 2025a
	Duration	Mean annual duration of spilling in sewershed normalised by number of spill sites	

Table 2. Breakdown of datasets used in forming the wastewater characteristics component of the national dataset, including the parameter names for the analysis, preprocessing method and source of the data.

Dataset	Characteristic	Preprocessing	Source
Precipitation	Days with precipitation	1km resolution climate data averaged to mean across the sewershed. Mean annual number of days with precipitation (requires rain above 5mm)	Met Office et al., 2025
	Mean precipitation	Mean rainfall per day in sewershed	
UWWTD	Capacity PE	Capacity of treatment plant in people equivalent normalised by population	EA, 2025b
Land use	Urban	10m resolution landcover data converted into % cover of different classifications. % land cover of sewershed with urban classification	Morton et al., 2024
	Suburban	% land cover of sewershed with suburban classification	
Sewershed Shape	Area	Area of sewershed normalised by population	Hoffmann et al., 2022
Elevation	Elevation std	30m resolution DEM data. Standard deviation of elevation pixels in the sewershed	NASA JPL, 2021
Building Age	Pre 1973	% cover of sewershed where average age of buildings in LSOAs is before 1973	ONS & VOA, 2024
Geology	Bedrock High Perm	% cover of sewershed of this geology group from hydrogeology map	BGS (n.d. b)
	Bedrock Moderate Perm	% cover of sewershed of this geology group from hydrogeology map	

Bedrock Low Perm	% cover of sewershed of this geology group from hydrogeology map	
Superficial High Perm	% cover of sewershed of this geology group from geology map	BGS (n.d. a)
Superficial Low Perm	% cover of sewershed of this geology group from geology map	

Regression Analysis

Following the creation of the dataset, MLR models were employed to analyse the relationships between catchment attributes and wastewater signatures. A similar MLR approach has been applied at a city scale in the US to assess the significance of catchment characteristics on I/I (Sebo & McDonald, 2022). Here, we extend this methodology to a national scale in England.

MLR fits regression lines across a series of independent variables to describe the dependent variable. Equation 1 below shows the general MLR model. The model fits a coefficient to each dependent variable (predictor) describing the magnitude and direction of impact. The model also fits a constant value and an error value. Ordinary least squares (OLS) regression was employed to estimate the relationships between wastewater signatures and associated system or demographic characteristics. Model fitting was conducted using the statsmodels package in Python. Statistical significance of the estimated coefficients was evaluated using p-values derived from the regression output. Two levels of statistical significance were used to evaluate confidence in the results. A conventional threshold of $p < 0.05$ was applied to identify statistically significant relationships. Additionally, a more stringent threshold corresponding to four standard deviations from the mean (4σ) was included to highlight relationships with exceptionally high confidence. Following initial modelling, water company-based subsets of catchments were analysed to explore variations in wastewater dynamics on a regional scale.

$$y = \beta_0 + \sum \beta_i x_i + \epsilon \qquad (1)$$

Before modelling, a multicollinearity check was used to remove characteristics which had a Pearson correlation with another characteristic greater than 0.9. Above this threshold one of the two correlated fields would be removed from the analysis. This was to prevent overfitting the model. The data was then standardised to make the results across different parameters comparable. This was done using a z-score transformation, resulting in model coefficients showing the impact of a standard deviation change in the input variable. The transformation was performed for both signatures and characteristics to produce comparable results across models as well as input variables.

Results and discussion

This section is divided into three parts. First, we provide a summary of the coverage of the dataset with a regional breakdown. This contextual overview serves to establish the significance of analysis results and clarity on the sampled population. Second, we present the results of the linear regression analysis, exploring the relationships between catchment characteristics (e.g., precipitation, geology, urbanisation, and infrastructure age) and the observed system signatures. The following discussion highlights the most robust and interpretable associations, with emphasis on both expected patterns and novel insights emerging from the data. Finally, we present results from the company-based subsets, alongside a discussion on the relevance of a national approach.

Dataset Coverage

This dataset represents a preliminary attempt to develop a wastewater-focused equivalent of the CAMELS hydrological dataset. While the integration of multiple data sources was partially successful, full coverage across all urban wastewater treatment plants (UWWTD) could not be achieved due to limitations in data availability and quality. Nationally, 799 out of 1,424 UWWTDs (56.1%) were successfully processed. If South West Water is excluded—due to a complete lack of available shapefiles—this figure increases slightly to 59.8%.

Among the water companies, Northumbrian Water and Anglian Water exhibited the highest inclusion rates, with 93.9% and 78.2% of their UWWTDs represented in the final dataset, respectively. In contrast, Southern Water and Thames Water showed significantly lower retention rates (38.7% and 18.5%, respectively), primarily due to poor quality or incomplete effluent data. South West Water had no data included, as key spatial data (shapefiles) were unavailable. Despite these regional disparities, the dataset still enables robust national-level analyses. However, caution is warranted when drawing conclusions at the regional level.

Regression Analysis Results

The bubble plot (Figure 1) provides a comprehensive overview of the relationships between effluent flow and spill-related signatures and a suite of catchment characteristics, with bubble size denoting significance (p-value) and colour representing the magnitude and direction of the regression coefficient. Each bubble represents a hypothesis of whether the relationship between the characteristic and signature is significant, with the black circles indicating the fitted relationship is significant.

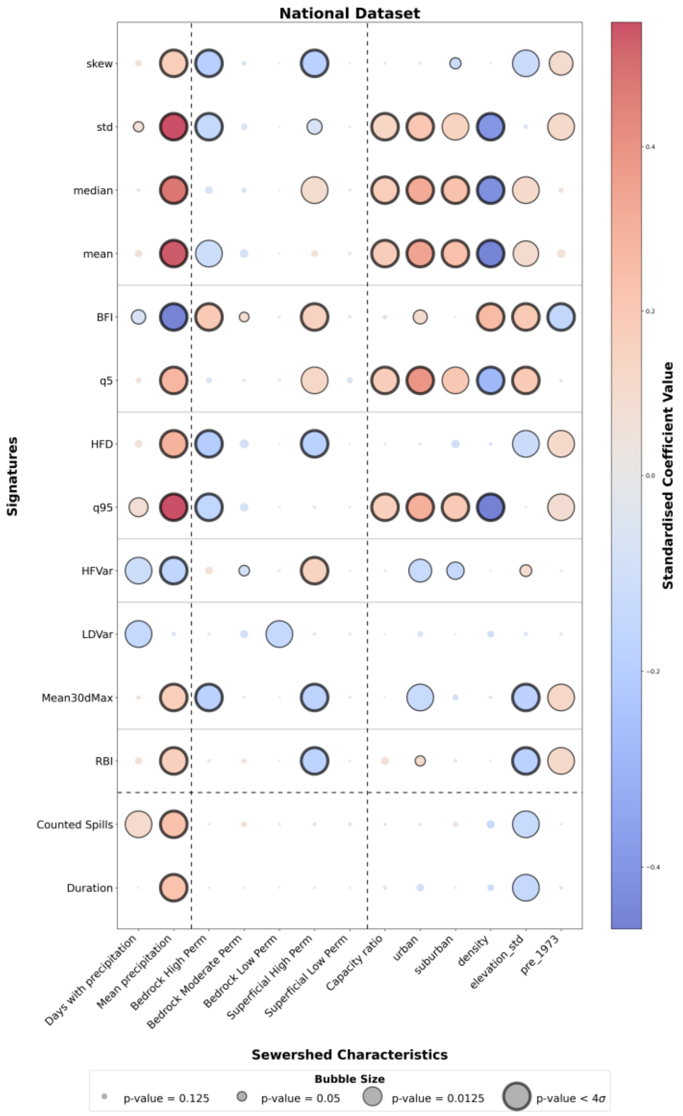

Figure 1. Bubble plot showing how coefficients and p-values varied across the MLR models. Each bubble represents a relationship between signature and characteristic. Bubble size is the inverse of p-value, and colour refers to coefficient sign and magnitude. Black circles indicate significant results with thinner circles indicating $p<0.05$ and thicker indicating $p<4\boldsymbol{\sigma}$.

Precipitation emerges as the most influential driver across most flow and spill signatures. It accounts for the highest number of statistically significant relationships, particularly those surpassing the stricter significance threshold ($p < 4\sigma$), and is associated with the largest absolute coefficient values. This suggests a strong control of precipitation on system performance, particularly on effluent flow signatures. Increases in precipitation are strongly associated with higher mean and high flows, alongside a notable reduction in baseflow index (BFI). These patterns are expected in combined sewer systems, where both stormwater and wastewater are conveyed together, leading to heightened flow variability during wet weather events. Interestingly, low flows also show a positive, albeit weaker, relationship with precipitation. This likely reflects the influence of rain-derived inflow and infiltration (RDII), where rainfall enters the sewer network indirectly through structural defects or connections to permeable surfaces. This phenomenon underscores the dual impact of precipitation on both extreme and baseflow conditions. Precipitation also has a dominant role in influencing spill behaviour. Significant positive relationships are observed with both spill count and duration. The dataset showed approximately 50% of sewersheds operate close to design capacity (PE/population ratio between 1 and 1.5), indicating even modest increases in rainfall are likely to cause exceedance of system capacity and trigger spills—highlighting the sensitivity of such systems to climatic drivers.

Catchments with high permeability bedrock geology show reduced effluent flow magnitudes because rainfall infiltrates rapidly, bypassing typical RDII pathways such as pipe cracks and joints (Zeydalinejad, Javadi & Webber, 2024). High permeability superficial deposits show a similar response in reducing max flows, but in contrast increases the Q5 and median flows. These permeable units are linked to higher BFIs and smoother hydrographs. The remaining permeabilities have a minimal number of significant relationships, highlighting the greater role and impact high permeability geology has on effluent discharges.

Urban land cover demonstrates significant positive correlations with effluent flow magnitude and is inversely correlated to variability in high flow frequencies. This suggests a more consistent, elevated loading of the system in urbanised settings, where impervious surfaces expedite rainwater delivery to sewer networks and reduce opportunities for infiltration or attenuation. The proportion of buildings constructed prior to 1973 also exhibits strong and consistent relationships, particularly with high flow magnitude signatures. Older building stock is a strong proxy for the prevalence of combined sewer systems, where stormwater and wastewater share the same infrastructure. These systems are more likely to channel rainwater directly to treatment facilities, increasing flow volumes and magnifying the hydrological response during wet weather events.

Regional vs National Scales

Following the initial national-scale analysis, the investigation was repeated at the level of individual water companies. Interestingly, the results diverged markedly from those of the aggregated dataset. This contrast is best explained by differences in the variability of precipitation characteristics across spatial scales. While precipitation emerged as a significant and impactful driver in the national dataset, it became largely insignificant at the company level. Only two companies, United Utilities and Yorkshire Water, exhibited any statistically significant relationships, and even then, only for a limited number of flow signatures.

To explore this discrepancy, we tested a simple hypothesis: high effluent flows (Q95) are driven by precipitation. Figure 2 presents a scatter plot of mean precipitation versus Q95, coloured by company. As expected, the regression line fitted across all data reveals a clear positive relationship. However, when viewed by company, the data points form distinct clusters along the line, reflecting regional precipitation regimes. Within individual company boundaries, mean precipitation tends to vary only slightly, diminishing its explanatory power. This spatial homogeneity limits the potential for detecting significant precipitation–flow relationships at smaller scales.

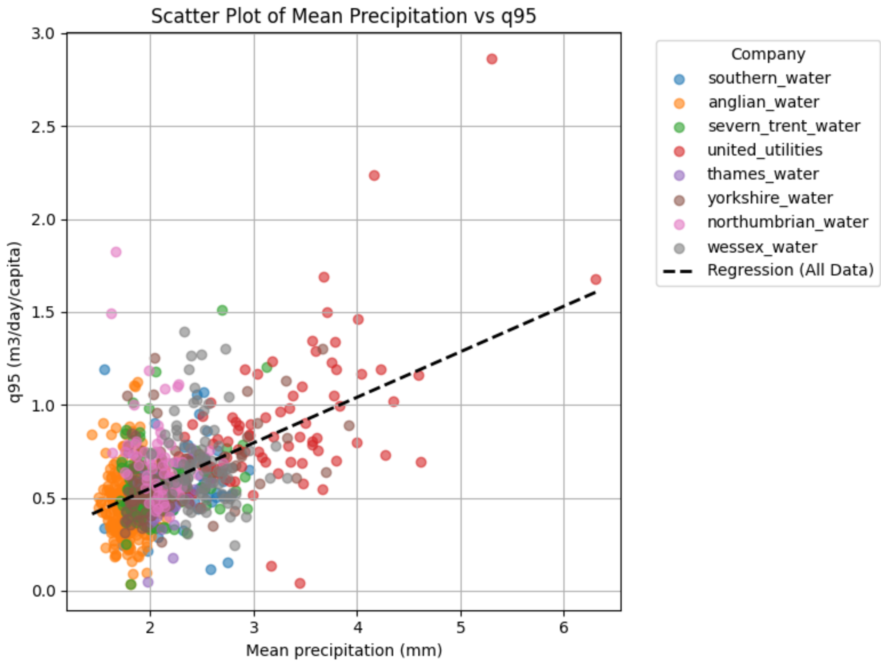

Figure 2. Scatter plot of mean precipitation against Q95 effluent flows. Colour indicates the water company operating the sewershed and WWTW. Dotted line is the national dataset regression fit.

This finding underscores the importance of national-scale analyses, where wider climatic gradients provide stronger signals. Individual companies, working in isolation, may fail to detect key drivers, such as precipitation, simply because of limited internal variability. Therefore, combining datasets across regions not only enhances statistical power but also enables the detection of broader-scale patterns that would otherwise remain obscured.

Conclusions and future work

This study applied multiple linear regression to identify key catchment characteristics influencing effluent flows and spills across England. A national-scale dataset was developed by integrating effluent discharge records with open-source datasets to derive sewershed signatures and relevant physical and operational characteristics, facilitating the analysis. Precipitation emerged as the primary driver of effluent flows and CSO spills across England, with additional influence from geology, urban land cover, and the age of sewer infrastructure, underscoring the integrated nature of wastewater systems. National-scale regression analysis was essential for detecting these drivers, as company-level subsets showed limited variability and weaker statistical signals. Future work will extend this methodology to investigate pollutant loads and their spatial-temporal drivers, with a particular focus on emerging contaminants such as microplastics PFAS. The insights from this study will directly inform the development of a national simulation model for wastewater flows and water quality. The dataset and methods presented here support the development of a national wastewater systems model, directly informing spills management and the planning of Drainage and Wastewater Management Plans.

References

Addor N., Newman A. J., Mizukami N., & Clark M. P. (2017). The CAMELS data set: catchment attributes and meteorology for large-sample studies, Hydrol. Earth Syst. Sci., 21, 5293–5313, https://doi.org/10.5194/hess-21-5293-2017.

Addor N., Nearing G., Prieto C., Newman A. J., Le Vine N. & Clark M. P. (2018) A ranking of hydrological signatures based on their predictability in space Water Resour. Res. 54 8792–812, https://doi.org/10.1029/2018WR022606.

BGS (n.d. a). *BGS Geology 625K.* [Data set]. Available at https://www.bgs.ac.uk/datasets/bgs-geology-625k/ (Accessed 31/07/25). Contains public sector information licensed under the Open Government Licence v3.0.

BGS (n.d. b). *Hydrogeology 625K digital hydrogeological map of the UK.* [Data set]. Available at https://www.bgs.ac.uk/datasets/hydrogeology-625k/ (Accessed 31/07/25). Contains public sector information licensed under the Open Government Licence v3.0.

Bloomfield J., Gong M., Marchant B., Coxon G. & Addor N. (2021). How is baseflow index (BFI) impacted by water resource management practices? Hydrol. Earth Syst. Sci. 25 5355–79, https://doi.org/10.5194/hess-25-5355-2021.

Coxon G., Addor N., Bloomfield J. P., Freer J., Fry M., Hannaford J., Howden N. J. K., Lane R., Lewis M., Robinson E. L., Wagener T. & Woods R. (2020) CAMELS-GB: hydrometeorological time series and landscape attributes for 671 catchments in Great Britain, Earth Syst. Sci. Data, 12, 2459–2483, https://doi.org/10.5194/essd-12-2459-2020.

Coxon G. McMillan H. Bloomfield J. Bolotin L. Dean J. Kelleher C. Slater L. & Zheng Y. (2024). Wastewater discharges and urban land cover dominate urban hydrology signals across England and Wales. Environmental Research Letters, 19, 084016, https://doi.org/10.1088/1748-9326/ad5bf2.

DEFRA. (2022). Guiding principles for drainage and wastewater management plans. https://www.gov.uk/government/publications/drainage-and-wastewater-management-plans-guiding-principles-for-the-water-industry/guiding-principles-for-drainage-and-wastewater-management-plans.

Dirckx G., Bixio D., Thoeye C., De Gueldre G., & Van De Steene B. (2009). Dilution of sewage in Flanders mapped with mathematical and tracer methods. Urban water journal, 6(2), 81-92, https://doi.org/10.1080/15730620802541615.

EA. (2025a). *Event Duration Monitoring – Storm Overflows – Annual Returns.* [Data set]. Available at https://environment.data.gov.uk/dataset/21e15f12-0df8-4bfc-b763-45226c16a8ac (Accessed 31/07/25). Contains public sector information licensed under the Open Government Licence v3.0.

EA. (2025b). *Urban Waste Water Treatment Directive Treatment Plants.* [Data set]. Available at https://www.data.gov.uk/dataset/0f76a1c3-1368-476b-a4df-7ef32bfd9a8b/urban-waste-water-treatment-directive-treatment-plants (Accessed 31/07/25). Contains public sector information licensed under the Open Government Licence v3.0.

Ge J., Li J., Qiu R., Shi T., Zhang C., Huang Z. & Yuan Z. (2024). A data-driven method for estimating sewer inflow and infiltration based on temperature and conductivity monitoring. Water Research, 261, 122002, https://doi.org/10.1016/j.watres.2024.122002.

Gernaey K. V., Flores-Alsina X., Rosen C., Benedetti L. & Jeppsson U. (2011). Dynamic influent pollutant disturbance scenario generation using a phenomenological modelling approach. Environmental Modelling & Software, 26, 1255-1267, https://doi.org/10.1016/j.envsoft.2011.06.001.

Hoffmann T., Bunney S., Kasprzyk-Hordern B. & Singer A. (2022). Wastewater catchment areas in Great Britain. *ESS Open Archive,* https://doi.org/10.1002/essoar.10510612.2.

Karpf C. & Krebs P. (2013). Modelling of groundwater infiltration into sewer systems. Urban Water Journal, 10, 221-229, https://doi.org/10.1080/1573062X.2012.724077.

Koop S. & van Leeuwen, C. (2017) The challenges of water, waste and climate change in cities. Environ Dev Sustain 19, 385–418, https://doi.org/10.1007/s10668-016-9760-4.

Mathers M. (2024). Raw sewage spills into rivers and seas in England reached record high last year. Independent. https://www.independent.co.uk/news/uk/home-news/raw-sewage-spills-river-sea-b2519286.html (Accessed 31/07/25).

Met Office, Hollis D., Carlisle E., Kendon M., Packman S. & Doherty A. (2025): HadUK-Grid Gridded Climate Observations on a 1km grid over the UK, v1.3.1.ceda (1836-2024). NERC EDS Centre for Environmental Data Analysis, *01 July 2025*, https://doi.org/10.5285/f02cc6ddd92f45b18b9ab6ab544df7d9.

Mijic A., Dobson B. & Liu L. (2024). Towards adaptive resilience for the future of integrated water systems planning. Cambridge Prisms: Water, 2, e11, https://doi.org/10.1017/wat.2024.9.

Morton R. D., Marston C. G., O'Neil A. W. & Rowland C. S. (2024). **Land Cover Map 2023 (10m classified pixels, GB)**. NERC EDS Environmental Information Data Centre, https://doi.org/10.5285/7727ce7d-531e-4d77-b756-5cc59ff016bd.

NASA JPL (2021). *NASADEM Merged DEM Global 1 arc second V001*. Distributed by OpenTopography, https://doi.org/10.5069/G93T9FD9. Accessed 2025-07-31.

ONS & VOA (2024). *Dwelling Ages and Prices.* [Data set]. Available at https://data.geods.ac.uk/dataset/dwelling-ages-and-prices (Accessed 31/07/25). Contains public sector information licensed under the Open Government Licence v3.0.

Rapp-Wright H., Regan F., White B. & Barron L. (2023). A year-long study of the occurrence and risk of over 140 contaminants of emerging concern in wastewater influent, effluent and receiving waters in the Republic of Ireland. Science of The Total Environment, 860, https://doi.org/10.1016/j.scitotenv.2022.160379.

Sebo, S. & McDonald, W. (2022), Influence of Sewershed Characteristics on Rainfall-Derived Inflow and Infiltration. J Am Water Resour Assoc, 58: 1483-1496, https://doi.org/10.1111/1752-1688.13051.

Water UK. (2024). National Storm Overflows Plan for England. https://www.water.org.uk/sites/default/files/2024-03/WEB_Water%20UK%20National%20Storm%20Overflows%20Plan%20for%20England_0.pdf (Accessed 31/07/25).

Weiss G., Brombach H., & Haller B. (2002). Infiltration and inflow in combined sewer systems: long-term analysis. Water Science and technology, 45(7), 11-19, https://doi.org/10.2166/wst.2002.0112.

Zeydalinejad N., Javadi A. A. & Webber J. (2024). Global perspectives on groundwater infiltration to sewer networks: A threat to urban sustainability. Water Research, 262, 122098, https://doi.org/10.1016/j.watres.2024.122098.

Zheng Y., Coxon G., Woods R., Li J. & Feng P. (2023). Controls on the spatial and temporal patterns of rainfall-runoff event characteristics—a large sample of catchments across Great Britain Water Resour. Res. 59 e2022WR033226, https://doi.org/10.1029/2022WR033226.