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Wastewater discharges and urban land cover dominate urban hydrology signals across England and Wales

Gemma Coxon[1,*], Hilary McMillan[2], John P Bloomfield[3], Lauren Bolotin[2], Joshua F Dean[1], Christa Kelleher[4], Louise Slater[5] and Yanchen Zheng[1]

[1] School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, United Kingdom
[2] Department of Geography, San Diego State University, San Diego, CA, United States of America
[3] British Geological Survey, Wallingford OX10 8BB, United Kingdom
[4] Department of Civil and Environmental Engineering, Lafayette College, Easton, PA, United States of America
[5] School of Geography and the Environment, University of Oxford, Oxford OX1 3QY, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: gemma.coxon@bristol.ac.uk

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Abstract

Urbanisation is an important driver of changes in streamflow. These changes are not uniform across catchments due to the diverse nature of water sources, storage, and pathways in urban river systems. While land cover data are typically used in urban hydrology analyses, other characteristics of urban systems (such as water management practices) are poorly quantified which means that urbanisation impacts on streamflow are often difficult to detect and quantify. Here, we assess urban impacts on streamflow dynamics for 711 catchments across England and Wales. We use the CAMELS-GB dataset, which is a large-sample hydrology dataset containing hydro-meteorological timeseries and catchment attributes characterising climate, geology, water management practices and land cover. We quantify urban impacts on a wide range of streamflow dynamics (flow magnitudes, variability, frequency, and duration) using random forest models. We demonstrate that wastewater discharges from sewage treatment plants and urban land cover dominate urban hydrology signals across England and Wales. Wastewater discharges increase low flows and reduce flashiness in urban catchments. In contrast, urban land cover increases flashiness and frequency of medium and high flow events. We highlight the need to move beyond land cover metrics and include other features of urban river systems in hydrological analyses to quantify current and future drivers of urban streamflow.

1. Introduction

Urbanisation is a critical driver of changes in streamflow. Urbanisation impacts annual and seasonal flood magnitudes (Prosdocimi *et al* 2015, De Niel and Willems 2019, Blum *et al* 2020, Slater *et al* 2024), mean flows (Anderson *et al* 2022), drying regimes (Price *et al* 2021), non-perennial flow regimes (Hammond *et al* 2021), flashiness (Booth and Konrad 2017), streamflow seasonality (Diem *et al* 2021), low flows and baseflow (Bloomfield *et al* 2009, Schwartz and Smith 2014, Han *et al* 2022). The impacts of urbanisation on these hydrological processes are not uniform across catchments (figure 1). Urbanisation results in diverse changes to water sources, storage and pathways in the catchment including increased impervious surfaces, surface and groundwater abstractions to feed public water supply, changes in channel morphology (i.e. channel straightening), stormwater control (water management schemes), urban drool from domestic irrigation, inputs from leaky transport and storage infrastructure and sewage treatment plants. These have confounding impacts on streamflow. For example, flashiness and high flows could increase from rural to more urban areas due to decreased infiltration and increased impervious areas (Blum *et al* 2020, Anderson *et al* 2022, Ariano and Oswald 2022), or decrease due to increased retention of stormwater from stormwater control measures (McPhillips *et al*

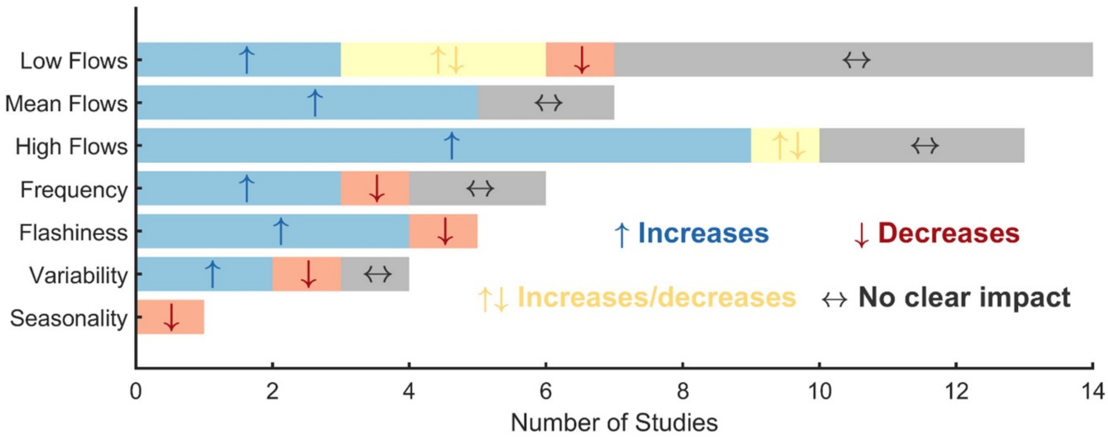

Figure 1. Synthesis of urbanisation impacts on streamflow from 25 large sample studies (we use a threshold of 10 catchments to define a large-sample study). The full list of studies can be found in table S1.

2019, Bell *et al* 2020). Understanding these diverse and complex urban drivers of changes in streamflow dynamics is crucial, particularly as pressures on urban waterways increase with more than 5 billion people projected to live in cities by 2030 (Grimm *et al* 2008, Gerland *et al* 2014).

To characterise the impacts of urbanisation, most studies use urban land cover or population density (as a proxy for urban land cover percentage) as the primary catchment descriptor. From the 25 large-sample hydrology studies we reviewed, 22 studies solely used land cover to characterise urbanisation and two studies characterised built infrastructure in urban areas (Oudin *et al* 2018, Ariano and Oswald 2022). Only one study included data on wastewater discharges from sewage treatment works, using these data to provide evidence on the potential for the inflow and infiltration of extraneous water into sewers to reduce streamflow (Diem *et al* 2021). Incorporating other sources of data beyond urban land cover is challenging as water management and infrastructure data are typically either (1) not available because there is no data or the data are not allowed to be shared, (2) difficult to compile because they are held by multiple agencies in different formats and/or (3) limited temporally and/or spatially due to infrequent monitoring (Addor *et al* 2020, Oswald *et al* 2023). Therefore, urbanisation impacts are often difficult to detect and quantify, and the relative impact of these factors (i.e. the contribution of impervious surfaces and water management infrastructure to changes in streamflow) is currently poorly understood (Oswald *et al* 2023).

There is an opportunity with new water management data in large-sample hydrology datasets (e.g. CAMELS-GB; Coxon *et al* 2020a) to move beyond impervious cover and better characterise the impacts of urbanisation to develop an integrated understanding of water sources, stores and pathways in urban areas. This study uses catchment attributes describing urban land cover as well as abstractions and wastewater discharges from sewage treatment works to assess the impacts of urbanisation on streamflow dynamics for a large sample of catchments across England and Wales. We quantify urban impacts on streamflow using a wide range of hydrological signatures (i.e. metrics that quantify the statistics or dynamics of streamflow, McMillan 2021) representing the magnitude, variability, frequency, and duration of key streamflow dynamics. We apply random forest models with catchment attributes representing water management practices compiled from environmental regulators (surface-water abstractions, groundwater abstractions and treated wastewater returns from sewage treatment works) and urban land cover to answer the following research questions:

1. How does urbanisation impact streamflow dynamics across England and Wales?
2. Which has the greatest impact on urban streamflow, land cover or water management?

2. Catchment selection and data

2.1. Catchment selection

Urban areas currently account for ∼10% of land cover across England and Wales, with previous studies indicating a wide range of impacts of urbanisation on low flows, high flows and baseflow (Beran and Gustard 1976, Bloomfield *et al* 2009, Han *et al* 2022, Slater *et al* 2024). Critically, in England and Wales, we have access to high quality hydroclimatic, urban land cover and water management data to enable us to disentangle the impacts of water management practices and urban land cover on streamflow dynamics across a large sample of catchments for the first time.

In total, 711 catchments were selected across England and Wales from over 1500 gauges available in the United Kingdom National River Flow Archive (NRFA) based on three key criteria. Firstly, the catchments needed to have available water management data (abstractions and wastewater discharges), which limited the study area to England and some catchments in Wales. Secondly, the catchments needed to have at least 95% complete river flow data available from 1 October 1995–30 September 2015 to ensure robust calculation of hydrological signatures. Thirdly, we excluded 9 catchments that had a runoff ratio greater than one (mostly due to significant groundwater imports) as we found these outliers skewed some of the subsequent analysis. The large sample of catchments used in this study represent the climatic, hydrologic, and geologic diversity found across England and Wales.

2.2. Hydrological data for signature calculation

Daily streamflow data (mm d^{-1}) from 1 October 1995–30 September 2015 were collated for the 711 gauges from the UK NRFA. These data are collected by measuring authorities including the Environment Agency (EA) and Natural Resources Wales, and then quality controlled, on an ongoing annual cycle, before being uploaded to the NRFA site.

2.3. Catchment attributes

The catchment attributes used in this study were obtained from the CAMELS-GB large sample hydrology dataset (Coxon *et al* 2020a, 2020b) but calculated for a larger number of catchments. While a wide range of catchment attributes are available from CAMELS-GB, we selected nine catchment attributes that were not highly correlated (Spearman rank correlation <0.6) and have shown to be key controls on hydrologic signatures across Great Britain in previous studies (Bloomfield *et al* 2021, Zheng *et al* 2023).

Streamflow dynamics across England and Wales predominantly reflect climate and geology (Bloomfield *et al* 2009, Chiverton *et al* 2015, Zheng *et al* 2023) and therefore three catchment attributes characterising climate (aridity) and geology (the percentage of the catchment underlain by highly productive, fractured aquifers and the percentage of the catchment underlain by rocks with essentially no groundwater) are included. We also select catchment attributes characterising soils (percentage clay soils) and topography (catchment area) as these have been identified as key controls on baseflow in the UK (Bloomfield *et al* 2021). Finally, since the focus of this study is on urbanisation impacts, catchment attributes characterising urban land cover (urban percentage) and water management (surface water and groundwater abstractions and treated wastewater returns from sewage treatment works) were selected in this study. Despite the importance of reservoirs on streamflow dynamics across the UK (Salwey *et al* 2023) we did not include reservoir catchment attributes in this study as they are rarely present in urban catchments in the UK.

As the primary focus of this paper are the catchment attributes characterising urban land cover and water management, these attributes are described in more detail below. A detailed description of all the catchment attributes can be found in Coxon *et al* (2020a), and a full list of the catchment attributes (including their description, units, data sources etc) used in this study and their spatial maps can be found in table S2 and figure S1 respectively.

Land cover attributes for each catchment were derived from the 1 km UK Land Cover Map 2015 (LCM2015) produced by the UK Centre for Ecology and Hydrology (Rowland *et al* 2017). LCM2015 uses a random forest classification of Landsat-8 satellite images based on the joint nature conservation committee broad habitats, encompassing the range of UK habitats. The urban land cover represents the sum of both urban and sub-urban land cover.

The water management data consists of surface water abstraction, groundwater abstraction and wastewater discharges from sewage treatment works. The abstraction data consist of monthly recorded abstraction volumes reported by abstraction licence holders to the national environmental regulator (EA) covering the period from January 1999 to December 2014. These data are the actual abstraction returns and represent the total volume of water removed by the licence holder for each month over the time period. The discharge data consist of daily discharges of treated wastewater returns from sewage treatment works into water courses reported to the EA from 1 January 2005 to 31 December 2015. These data represent the total volume of treated wastewater added to rivers from sewage treatment works for each day over the time period. To generate a single static variable for each catchment, we calculate a mean daily abstraction and wastewater discharge rate by averaging and then summing all abstraction/wastewater discharges records that fall within each catchment boundary.

3. Methods

3.1. Hydrological signatures

We use the toolbox for streamflow signatures in hydrology toolbox (Gnann *et al* 2021) to calculate a range of hydrological signatures (see table 1). These signatures were chosen to capture diverse streamflow dynamics including flow magnitude, variability, frequency, and duration based on previous literature characterising urbanisation impacts on streamflow (see tables 1 and S1). They include:

1. Flow percentiles for low, median, and high flows as urbanisation has been shown to impact flow magnitudes across the flow range (e.g. Bhaskar *et al* 2020).
2. Richard-Bakers Flashiness Index and TQmean as key signatures of flow variability that have been

Table 1. Hydrological signatures used in this study including their description, unit and references for where they have been used in other large-sample urban hydrology analyses.

Streamflow dynamic	Hydrological signature	Description	Unit	References
Magnitude	Flow percentiles (Q_5, Q_{25}, Q_{50}, Q_{75}, Q_{95})	Flow percentiles representing low (Q_5, Q_{25}), median (Q_{50}) and high flows (Q_{75}, Q_{95})	mm day^{-1}	(Salavati *et al* 2016, Oudin *et al* 2018, Bhaskar *et al* 2020, Ledford *et al* 2020, Han *et al* 2022)
Variability	Richards-Baker flashiness index	The sum of the absolute values of day-to-day changes in mean daily flow normalised by total discharge	—	(Konrad and Booth 2002, Chelsea Nagy *et al* 2012, Martin *et al* 2012, Booth and Konrad 2017, McPhillips *et al* 2019, Ariano and Oswald 2022, Gannon *et al* 2022)
	TQmean	The fraction of time that the daily flow exceeds the mean flow over the time period		
Frequency	Number of low (Q5 and Q25) and high (Q75 and Q95) flow events	Average number of low/high flow events per year	days yr^{-1}	(Debbage and Shepherd 2018)
Duration	Duration of low (Q5 and Q25) and high (Q75 and Q95) flow events	Average duration of flow events—number of consecutive days less (more) than Q_5 and Q_{25} (Q_{75} and Q_{95})	days	

shown to capture urbanisation-driven hydrologic changes in previous studies (e.g. Booth and Konrad 2017).

3. Flow frequency and duration for low and high flows. These hydrological signatures are less commonly used in urbanisation analyses but represent important streamflow dynamics that can be impacted by urbanisation (e.g. Debbage and Shepherd 2018).

The 15 signatures in total were calculated using daily streamflow observations (in mm d^{-1}) for each catchment for the entire 20 year period. Spatial maps of the hydrological signatures calculated in this study are shown in figure S2.

3.2. Evaluating urbanisation impacts on streamflow dynamics

3.2.1. Random forest analysis

We use random forest models to explore the interplay between catchment attributes and hydrological signatures by analysing which catchment attributes have the strongest empirical relationships with different streamflow dynamics. Random forests are a machine learning model that creates and combines an ensemble of regression trees to produce predictions. They have been successfully applied in many previous hydrological studies to relate catchment attributes to streamflow signatures (for example, Addor *et al* 2018, Bloomfield *et al* 2021, Zheng *et al* 2023), including to assess the impacts of urbanisation on streamflow dynamics (e.g. Hammond *et al* 2021, Gannon *et al* 2022).

The random forest analysis was performed using the 'randomForest 4.6–14' *R* package (Breiman 2001, Cutler and Wiener 2022). Random forest models were first built for each of the 15 hydrological signatures (described in section 3.1) using all catchment attributes (described in section 2.3) from all the 711 catchments. We calculated the coefficient of determination between predicted and measured signature values ($R_d^{\,2}$) to evaluate the performance of the random forest model prediction and determined the importance of each catchment attribute by calculating the increase in the mean square error (IncMSE). To further evaluate model performance, a tenfold cross-validation was employed. For more details on the evaluation metrics and random forest analysis please see text S1.

This analysis was repeated using a subset of catchments with varying urban land cover thresholds (exceeding 5%, 10% and 15%) to isolate the key controls within urban catchments. These thresholds were identified from previous studies as suitable thresholds for identifying impacts of urbanisation (Oudin *et al* 2018), while still ensuring a large enough sample of catchments for the random forest to be robust (5%, 10% and 15% urban thresholds result in a total of 327, 198 and 144 catchments respectively). The results for a 10% threshold are presented in the paper, while the results for 5% and 15% urban thresholds (which show similar patterns) are presented in the supplementary information (see figures S4–6 and table S3).

3.2.2. Paired catchments

To explore the large-sample results in more detail, we identified a subset of paired catchments for a visual evaluation of differences in hydrograph dynamics. The paired catchments were chosen to be similar except for their urbanisation characteristics including pairs that had (1) high urban land cover (>50%) but contrasting wastewater discharges and (2) low wastewater discharges (i.e. <0.05 mm d^{-1}) but contrasting urban land cover. All pairs were chosen to have similar geophysical characteristics by selecting catchments that were within 10% of catchment area and mean annual rainfall, 20% of the percentage of the catchment underlain by highly productive, fractured aquifers, and gauging stations that were within 60 km (as close gauging stations tend to be highly correlated; Kiraz *et al* 2023). Finally, all pairs were manually checked to retain catchments where the primary difference in catchment form was either the impact of urban land cover or wastewater discharges and not other human influences (such as reservoirs or abstractions). Identifying pairs where one major driver of catchment form can be isolated is challenging, and therefore the resulting number of catchment pairs is limited.

4. Results

4.1. Urban land cover and water management are linked across England and Wales

Figure 2 shows the spatial distribution of urban fraction, abstractions, and wastewater discharges. In our sample, urban land cover ranges from 0%–83% of the catchment area with a mean of 10% (figure 2(b)). Catchments with the highest urban land cover are found in the South-East and Midlands region of England, focused in major cities (figure 2(a)). For water management, wastewater discharges from sewage treatment works range from 0 to 1 mm d^{-1} (mean of 0.06 mm d^{-1}) and exceed 25% of the mean flow in 6% of catchments. There is a non-linear relationship between wastewater discharges and urban land cover, where many catchments that are highly urbanised also have high volumes of wastewater discharges (figures 2(a), (b) and S3(c)).

Surface and groundwater abstractions range from 0 to 9 mm d^{-1} and 0–1 mm d^{-1}, with a mean of 0.1 and 0.04 mm d^{-1} respectively. These fluxes can represent a large component of the flow volume, with abstractions exceeding 25% of the mean flow in 17% of catchments (figures 2(d) and (e)). The largest groundwater abstractions are concentrated in regions with major aquifers (particularly Chalk aquifers) in the South-East of England (figure 2(e)), whilst the largest surface water abstractions are concentrated in the central regions and South of England (figure 2(d)). Catchments with high percentages of urban land cover tend to have low surface-water abstractions (figure S3(a)). In contrast, several catchments with high percentages of urban land cover also have high groundwater abstractions (figure S3(b)).

4.2. Controls on streamflow dynamics across England and Wales

Climate, geology, and human influences are key controls on streamflow dynamics for catchments across England and Wales (figure 3; larger/darker circles show more influential controls).

When considering all catchments, climate (aridity) is the most influential predictor of river flow magnitude, while geology (the percentage of the catchment underlain by highly productive, fractured aquifers) is the most influential predictor for flow variability (Richards-Baker Flashiness Index) and event duration (figure 3(a)). As expected, increasing aridity leads to decreasing flow magnitudes ($p < 0.001$) and increasing highly productive aquifers leads to decreasing flashiness ($p < 0.001$) and increasing event duration ($p < 0.005$). The strong association between climate and flow magnitudes, and geology and event duration/frequency are confirmed by the similarities in their spatial maps (see figures S2 and S3). For event frequency, geology and urban land cover percentage are the most influential predictors with increasing urban land cover and/or decreasing highly productive aquifers leading to increasing frequency of events. The random forest models achieve the best prediction accuracy in predicting flow magnitudes ($R_d^2 > 0.8$ for mean flow, Q_{75} and Q_{95}), followed by event frequency, flashiness, and event duration (see table S3). The random forest models have the poorest prediction accuracy for low flow dynamics, particularly for predicting low flow event frequency and duration ($R_d^2 < 0.4$).

Overall, water management practices of treated wastewater returns, surface water and groundwater abstractions, are not as influential on streamflow dynamics as climate, geology, and land cover when considering all catchments (figure 3(a)). However, when we focus the analysis on urban catchments (i.e. catchments with >10% urban land cover), we find that the volume of wastewater discharges is the most influential predictor of the magnitude of low flows (Q_5 and Q_{25}) and appears as the second most influential predictor (following aridity) of mean and high flows (figure 3(b)). Interestingly, the proportion

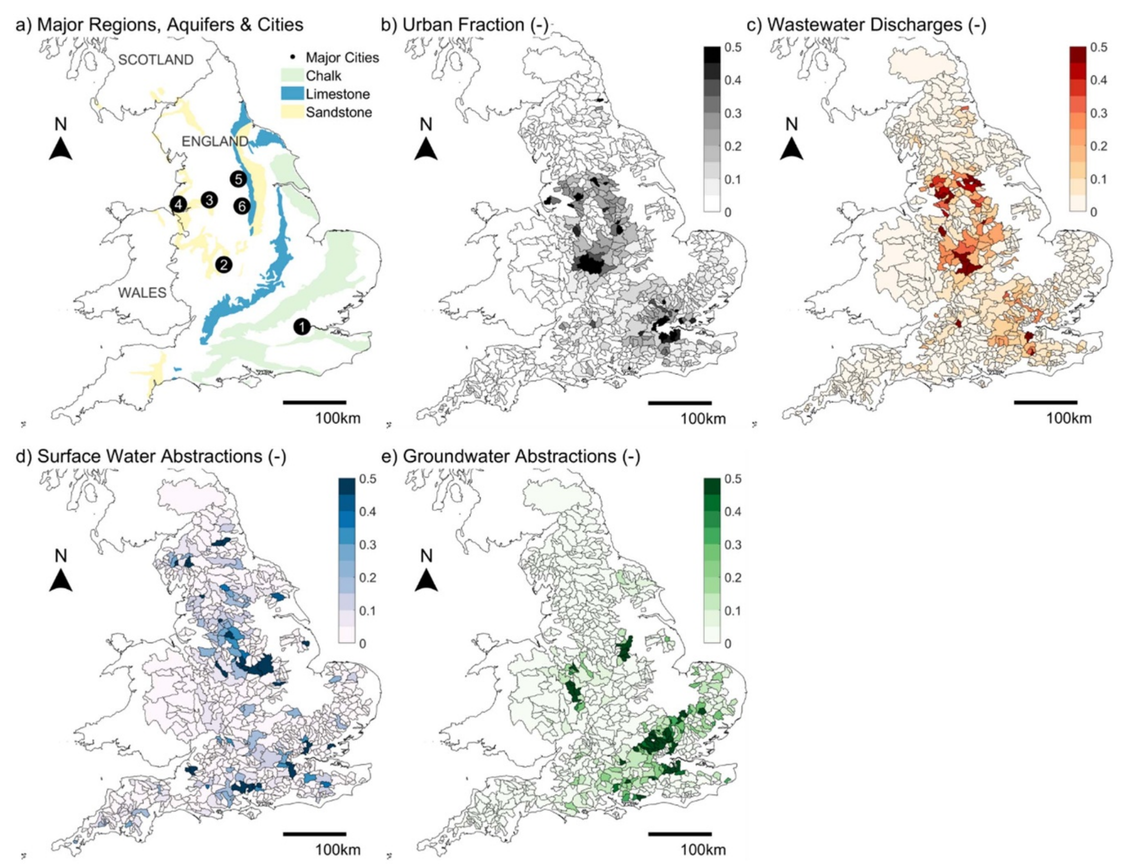

Figure 2. Context for Great Britain, urban land cover and water management catchment attributes. (a) Map showing major regions, aquifers, and cities in Great Britain. The six largest cities by population are shown; (1) London, (2) Birmingham, (3) Manchester, (4) Liverpool, (5) Leeds, (6) Sheffield. Then catchment maps show the spatial distribution of (b) urban fraction (−), (c) mean daily wastewater discharges from sewage treatment works normalised by mean flow (−), (d) mean daily surface water abstraction normalised by mean flow (−), (e) mean daily groundwater abstraction normalised by mean flow (−).

of urban land cover has little influence on the magnitude of mean or high flows but remains the most influential predictor of event frequency signatures. Surface water abstractions appear to increase flow magnitudes while groundwater abstractions decrease flow magnitudes. However, overall both surface water and groundwater abstractions have less influence on streamflow dynamics in urban catchments in England and Wales. We found similar predictive accuracy of the random forest models for flow magnitudes and flashiness in urban catchments as compared to all catchments (table S3). However, the predictive accuracy for event duration and low flow event frequency decreases substantially in urbanised catchments. We find similar patterns and outcomes for different thresholds of urban land cover (see figures S4–S6).

4.3. Urbanisation has conflicting impacts on streamflow dynamics

Water management practices and urban land cover in urban catchments have conflicting impacts on flow magnitudes, variability, and frequency (figure 4). We use a visual comparison of hydrographs from catchments that are similar except for their urban land cover and water management attributes to untangle and illustrate these interacting impacts. In total, we identified four pairs of catchments for water management (high urban land cover, contrasting wastewater discharges) and two paired catchments for urban land cover (contrasting urban land cover, minimal wastewater discharges). Here, we highlight two of the paired catchments related to our two key findings on the effects of wastewater discharges (figure 4(a)) and urban land cover percentage (figure 4(b)). We find similar results for both these examples in other paired urban catchments (see figures S7, S8 and table S4).

Figure 4(a) illustrates the impacts of wastewater discharges, by comparing two nearby catchments with very similar levels of urbanisation (77%–78%), but river flow is augmented by wastewater discharges in catchment 39 005 by 0.67 mm d^{-1} (this accounts for 67% of the mean flow). Wastewater discharges from sewage treatment works in this catchment are associated with increases in flow magnitudes (dark blue line is higher throughout the year). This effect causes a secondary impact on streamflow flashiness: the elevated baseflows means that flashiness is

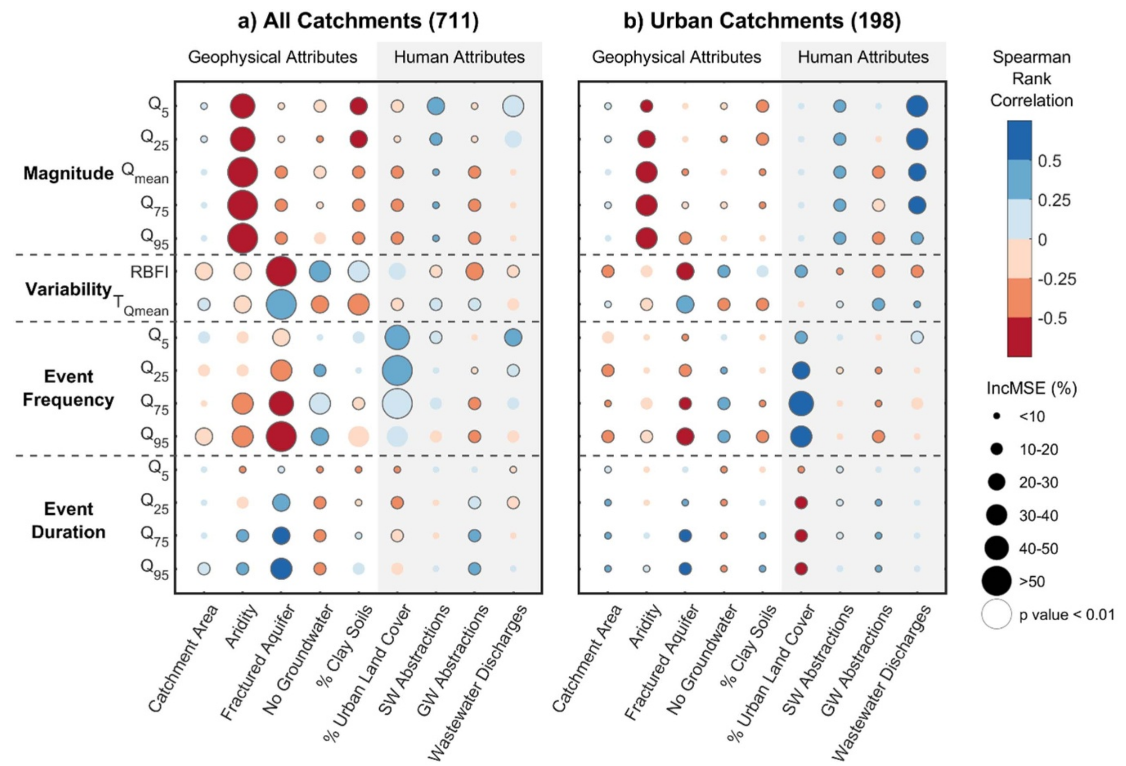

Figure 3. Association between each catchment attribute and hydrological signature for the random forest models based on (a) all 711 catchments and (b) a subsample of 198 catchments with >10% urban land cover. The dots are coloured by the strength of the Spearman rank correlation coefficient between the attribute and hydrological signature. A black outline around the dot indicates a significant *p*-value (<0.01). The dots are sized by the increase in mean squared error when excluding that attribute from the random forest model (IncMSE %) which quantifies the influence of the predictor in the random forest. Q_5 represents low flow while Q_{95} represents high flow.

lower in catchment 39 005 (0.32 compared to 0.5 in 39 058).

Figure 4(b) illustrates the impacts of urban land cover percentage, by comparing two nearby catchments with different percentages of urban land cover (62% compared to 4%), but identically zero wastewater discharges. This example shows that urban land cover can increase flashiness (flashiness index of 0.54 in the highly urbanised catchment compared to 0.2) and frequency of high flow events. The high urban land cover catchment experiences higher summer baseflows and summer event flows compared to the low urban land cover catchment.

5. Discussion

5.1. Wastewater discharges and urban land cover dominate urban hydrology signals

This study demonstrates that wastewater discharges from sewage treatment works and urban land cover dominate urban hydrology signals across England and Wales. In these regions, sewage treatment works are typically located close to large population centres in urban areas and thus the fraction of urban land cover and wastewater discharges from sewage treatment works in each catchment are closely linked. Here, we find that these two features of urban hydrologic systems have conflicting impacts on different streamflow dynamics.

Treated wastewater discharges increase flow magnitudes, particularly at low and medium flows. In contrast, urban land cover is not identified as a key control on flow magnitudes in urban catchments in our study area. Urban land cover has previously been found to impact flow magnitudes in studies from the UK (Han *et al* 2022), US (DeWalle *et al* 2000, Oudin *et al* 2018, Blum *et al* 2020, Anderson *et al* 2022), Belgium (De Niel and Willems 2019) and Germany (Tetzlaff *et al* 2005). This contrast in results may be due to a number of factors. Firstly, urban catchment behaviour differs from place to place due to differences in the built environment, local catchment characteristics and the interaction between the two (Bhaskar *et al* 2020). Secondly, previous studies have highlighted the variability in results due to different statistical methods employed for attributing changes in streamflow to land cover (Anderson *et al* 2022). Many urbanisation impact studies focus on changes over time, with their methods estimating the average effect of increasing urban extent within individual catchments (e.g. Han *et al* 2022, Slater *et al* 2024). Our method uses only one value per catchment and therefore focuses on explaining the differences between catchments, where the effect

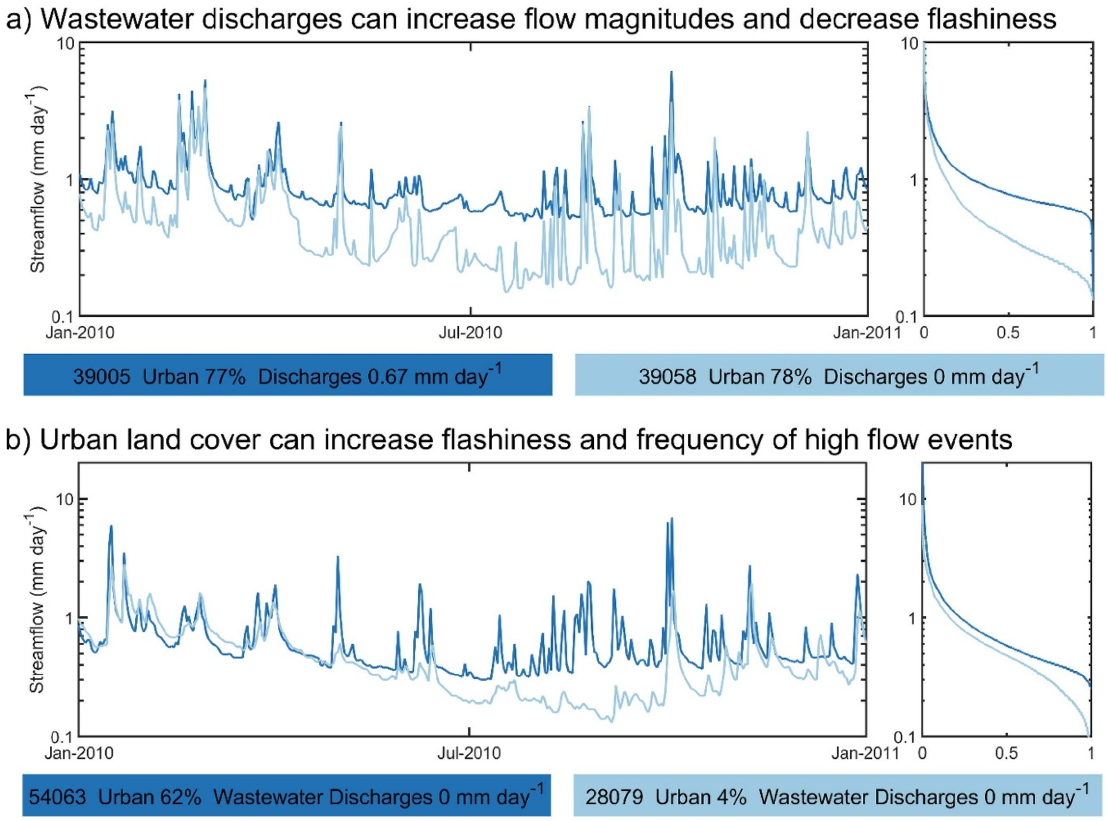

Figure 4. Annual hydrographs and flow duration curves for two sets of paired catchments with similar climate and geology, but differing land use or water management practices. Paired catchments shown are 39 005 (Beverley Brook at Wimbledon Common) and 39 058 (Pool River at Winsford Road), and 54 063 (Stour at Prestwood Hospital) and 28 079 (Meece Brook at Shallowford). Additional paired catchment examples can be found in figures S7 and S8. Catchment attributes and hydrological signatures for each paired catchment are detailed in table S4.

of urban extent on streamflow dynamics might be harder to detect than at the individual catchment level.

Treated wastewater discharges from sewage treatment works decrease flashiness, while urban land cover increases flashiness and event frequency across all sizes of events. Conflicting impacts of urbanisation are a common finding for urban hydrology analyses (Salavati *et al* 2016, Oudin *et al* 2018, Dudley *et al* 2020). Indeed, past work examining trends in low and high flow magnitude in response to urbanisation found a range of behaviours in different US cities (Bhaskar *et al* 2020), emphasising that the impacts of urbanisation are not uniform across urban areas. One reason for the diverging responses are different drivers (and buffers) of urban flows that are caused by urban land cover and water management practices that will vary from city to city (and equally catchment to catchment) as shown here. We anticipate that wastewater discharges and urban land cover will dominate hydrology signals in many urban catchments globally, and this stresses the need to better understand the key controls of different aspects of urbanisation (see also discussion for future work below).

5.2. Future work and limitations

Our findings emphasise the significance of moving beyond metrics of impervious land cover and including metrics that capture water management schemes in urban hydrology analyses. Such characterisations are needed to better interpret the impacts of urbanisation and to develop an integrated understanding of water sources, stores, and pathways in urban areas (Oswald *et al* 2023). There are a host of other potential water sources to urban streams (as well as situations that favour losing conditions; McPhillips *et al* 2019) that require further investigation, such as leaky water infrastructure (Pangle *et al* 2022), urban green infrastructure (Jarden *et al* 2016), irrigation return flows (Fillo *et al* 2021), canals (Carlson *et al* 2019), and storm water control measures (Gold *et al* 2019). The challenge of quantifying the impacts of these sources on urban hydrology will be twofold; firstly, capturing these data across large samples of catchments to generate process understanding across different urban systems (Oswald *et al* 2023) and secondly, analysing how best to characterise these impacts.

In this study, we consider a range of streamflow dynamics related to mean annual flow magnitudes, variability, event frequency and duration. However, we have not investigated the impact of water management practices on seasonal hydrological signatures or whether water management practices vary seasonally. Urbanisation has been shown to impact seasonality of streamflow and linked to the inflow and infiltration of extraneous water into sewers (Diem *et al* 2021). Furthermore, ongoing work has highlighted the complexity of baseflow responses in urban areas (Bhaskar *et al* 2016), with baseflow sometimes rising (as we observe for some catchments in our study, e.g. figure 4) or falling, depending on local setting. Analysing seasonal changes in wastewater discharges and the impacts of urban land cover on seasonal streamflow dynamics are key areas for future research.

We found that the random forest models struggled to predict low flow event frequency and event duration in urban catchments (table S3). Event frequency and duration metrics are generally more challenging to predict than magnitude metrics (Addor *et al* 2018) and low flow signatures can be particularly sensitive to discharge uncertainties (Westerberg *et al* 2016). Future work should develop a better understanding of the processes driving low flow event frequency and duration, and consider other relevant predictors that might be important to characterise low flow catchment behaviour, including seasonal abstraction metrics and other land cover descriptors (Chiverton *et al* 2015).

6. Conclusions

This study used catchment attributes describing abstractions, wastewater discharges from sewage treatment works and urban land cover to assess the impacts of urbanisation on streamflow dynamics for a large sample of catchments across England and Wales. Our findings demonstrate that urban land cover and water management practices are linked, a key control on flow magnitudes, variability, and frequency, and have conflicting impacts on streamflow dynamics. This highlights the need to move beyond land cover metrics and include other features of urban river systems in hydrological analyses to quantify current and future drivers of urban streamflow.

More broadly, our findings also highlight the significant contribution of treated wastewater discharges to streamflow and their importance in changing streamflow dynamics in urban river systems. Wastewater discharges from sewage treatment works can help in sustaining low flows and can be used as part of water reuse schemes to increase resilience of water supplies (Murgatroyd *et al* 2022). However, they are also important for urban water quality, biogeochemical cycling, and ecosystem function. Urban rivers commonly have low dissolved oxygen and high nutrient loads (Zhi *et al* 2023) which are attributed to a combination of flashy runoff providing inputs from urban surfaces and household and industrial wastewater, followed by periods of slow water movement between high flows (Blaszczak *et al* 2019). Urban rivers can also have high carbon dioxide and methane loads, which have been linked to outflows from sewage treatment plants (e.g. Yu *et al* 2017, Brown *et al* 2023). If wastewater discharges are key drivers of urban hydrology as shown here, then management of urban river systems must go beyond interventions such as sustainable urban drainage systems to slow runoff processes and focus on the amount and chemical composition of water released as treated wastewater discharges.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iDs

Gemma Coxon https://orcid.org/0000-0002-8837-460X
Hilary McMillan https://orcid.org/0000-0002-9330-9730
John P Bloomfield https://orcid.org/0000-0002-5730-1723
Lauren Bolotin https://orcid.org/0000-0002-0295-9544
Joshua F Dean https://orcid.org/0000-0001-9058-7076
Christa Kelleher https://orcid.org/0000-0003-3557-201X
Louise Slater https://orcid.org/0000-0001-9416-488X
Yanchen Zheng https://orcid.org/0000-0002-2212-9134

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