A method for adjusting design storm peakedness to reduce bias in hydraulic simulations

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Abstract (150 – 200 words)

In the United Kingdom, decision-makers use hydraulic model outputs to inform funding, connection consent, adoption of new drainage networks, and planning applications. Current practice requires application of design storms to calculate sewer catchment performance metrics, such as flood volume, discharge rate, and flood count. With flooding incidents occurring more frequently than their designs specify (1 in 30-years), hydraulic modelling outputs required by practice are questionable. In this paper, the main focus is on the peakedness factor (ratio of maximum to average rainfall intensity) of design storms, adjudging that it is a key contributor to model bias. Hydraulic models of two UK sewer catchments are simulated under historical storms, design storms, and design storms with modified peakedness to test bias in modelling outputs and the effectiveness of peakedness modification in reducing the bias. Sustainable Drainage Systems (SuDS) has been implemented at catchment scale and the betterment achieved in the modelling outputs is tested. The proposed design storm modification reduces the bias that occurs when driving hydraulic models using design storms in comparison to historical storms. It is concluded that SuDS benefits are underestimated when using design rainfall because the synthetic rainfall shape prevents infiltration. Thus, SuDS interventions cannot accurately be evaluated by design storms, modified or otherwise.

Keywords chosen from ICE Publishing list

Floods & floodworks; Hydrology & water resource; Hydraulics & hydrodynamics

1. Introduction

Hydraulic models are widely used as numerical hydrodynamic simulation tools to describe the physical processes of stormwater flow across urban sewer catchments. In the United Kingdom (UK), decision-makers rely on outputs from hydraulic semi-distributed and fully distributed models to inform decisions related to funding, connection consent, adoption of new drainage networks and planning applications. The current modelling practice in the UK requires applicants to apply design (synthetic) rainfall events in specified durations and magnitudes to hydraulic models in order to demonstrate that sewer catchments will not fail except under rare conditions. Examples of approaches used to generate design storms include Flood Studies Report (FSR) Natural Environment Research Council (NERC, 1975) and Flood Estimation Handbook (FEH) (Institution of Hydrology, 1999).

Failure of urban drainage systems could be in the form of flooding or overflow from combined sewer systems to receiving waters. The accommodation of a storm event means that a network can collect and convey the runoff and discharge within the allowable discharge limit without flooding in any part of the network. Therefore, modelling outputs, such as flood volume, discharge rate and flood count, are used to satisfy various requirements defined by the respective authorities to secure the required funding or consent. For example, according to Section 104 agreement (under the Water Industry Act 1991), new drainage networks serving a proposed development can only be adopted by sewerage undertakers (e.g. water companies) once it is demonstrated via hydraulic modelling that the proposed drainage network can accommodate the critical storm of a 1 in 30-year return period; these adoptional standards and best practices are set in the Sewers for Adoption document (Water UK, 2018). Drainage systems that are not designed to adoptional standards (e.g. local authority carrier drains) must instead conform to the national requirements set in the British Standards EN752:2017, which also requires storm networks to comply with 1 in 30-year return period standards.

Despite closely following regulation, studies have observed that drainage networks typically flood more frequently than the ‘designed’ 1 in 30-year return period (Sayers et al., 2018). To understand why this may be the case, it is crucial to understand how the use of design storms may lead to under- or overestimation in evaluating the performance of a sewer network. This phenomenon is referred to in this paper as a hydraulic modelling simulation bias.

One-dimensional hydraulic models, the most commonly used for hydraulic assessment, first transform rainfall into runoff over subcatchments, which is then routed through a network. The temporal variability in this rainfall is one of the most critical elements to capture because it is the key input variable that defines the behaviour of various hydraulic structures and systems (Aronica et al., 2005). For rainfall forcing in the UK, the FSR and FEH data sets produce idealised storm profiles (design storms) to which a statistically based return period has been attached to (Butler & Davies, 2004). When designing drainage networks, the average rainfall intensity obtained from an intensity-duration-frequency (IDF) curve is often used to calculate the flow and then pipes' dimensions are iterated until the full-bore capacity corresponds to the calculated maximum flow.

When estimating pipe diameters using average intensity, the pipe diameter will be the same regardless of whether design or historic rainfall is used to size a pipe (Adams & Howard, 1986). However, when implementing measures on a catchment scale, it is not enough to ensure that individual pipes have adequate capacities to accommodate specified rainfall intensities as drainage networks can fail due to other reasons such as surcharged outfalls, backup flow, turbulence (localised headlosses) or other causes that are not related to pipes' full capacity. For these reasons, Adams & Howard (1986) described the design storm concept as a misleading concept with conceptual error when used to simplify engineering analysis by unrealistic assumptions.

Evaluating the bias resulting from design storms on catchment models has been a subject of interest for many researchers. Vaes & Berlamont (2001) showed that upstream retention, the water stored naturally in the catchment upstream of entering the network, can only be represented in catchment scale hydraulic models when using historical rainfall. This is because simulation results are highly sensitive to the initial storage, which can only be captured accurately by using forcing that considers the intrinsic temporal rainfall variability in the antecedent period to simulation. When the network is not surcharged, the system's hydraulic behaviour is linear and the pipes are the dominant factors. However, when the system becomes surcharged the storage structures become a dominant factor in the modelling results. The modelling outputs' bias will be larger as the emptying time (half-drain time) becomes dominant in driving the hydraulic simulation results. Niko Verhoest et al. (2010) also challenged the use of design storms on the basis of an unrepresentative antecedent wetness state of the catchment. They found the use of historical rainfall records overcame the antecedent wetness state issue and also enabled the probability of flooding to be accurately assessed (Verhoest et al., 2010). Grimaldi et al. (2013) introduced and tested a fully continuous hydraulic modelling framework for flood hazard mapping using long rainfall time series in order to avoid the use of design storms that constitute the main source of subjective analysis and bias. Three flood modelling approaches have been tested in this investigation using 2D hydraulic model in Rio Torbido catchment. The approaches included design storms (empirical rainfall input estimation procedure based on Intensity-Duration-Frequency), semi-continuous storms and fully-continuous storms. Grimaldi et al. (2013) concluded that design storms underestimated the runoff volume and introduced an uncertainty in the time of concentration.

Thornadahl et all (2008) presented a new methodology for the parameterisation of rainfall in analysis of failures in urban drainage systems and recommend evaluating flood risk and the combined sewer overflow with long historical rainfall series because they find the return period of flooding to be underestimated when using design storms. This means that a 30-year return period attached to a design storm could be equivalent to a 20-year return period in practice.

In the application of 2D flood mapping in which design storms are compared with 10 different historic storms, Bezak et al. (2018) finds that uncertainty in design storm parameters led to underestimation of flood extent, peak discharge and flood plain velocity. The 2D flood mapping was assessed by Bezak using design rainfall events on the 1D/2D integrated hydraulic modelling for 10 different storm durations and two storm magnitudes 10 years and 100 years return period. It was concluded that the flood extent (maximum flooded area) can be twice as large as the minimum flood extent, the peak discharge can be 1.4 times larger than the minimum peak discharge and the flood plain runoff velocity can be 10 times larger than the minimum flood plain velocity and this leads to biased planning decisions being made when implementing flood protection schemes (Bezak et al., 2018).

While the scientific evidence suggests that design storms are generally suitable for pipe sizing, catchment scale interventions are increasingly common. These are typically a combination of grey and green infrastructure solutions, the latter being implemented through a concept of Sustainable Drainage Systems (SuDS) (Babovic & Mijic, 2019). Yet the regulation of design for these projects is the same as traditional network infrastructure, i.e. with design storms, despite the limitations discussed above. For the industry, it is challenging to adopt the use of historical rainfall series in practice due to high computational effort and long simulations required to run years of historical rainfall events using standard simulation tools (e.g. InfoWorks ICM®). Beyond this, there is still a clear need for standardisation when it comes to regulation of SuDS design.

Developing a better understanding of the role of SuDS and its hydraulic performance has become a subject of interest for researchers with more SuDS being implemented and adopted since the introduction of Schedule 3 of the Flood and Water Management Act 2010 which became statutory requirements in 2010 and then the inclusion of new rules on surface water sewers that will apply from 1st April 2020. These rules will require English water and sewerage companies to adopt SuDS according to the adoption rules stated in the Design and Construction Guidance (DCG) document. In light of this, and because SuDS react differently to rainfall than traditional drainage systems due to being infiltration capacity dominated, it is believed that it is important to test the effects of rainfall temporal variation on SuDS.

Using historical storms to drive hydraulic models has an associated computational cost penalty which makes them challenging for the industry to use for sewer design and planning purposes. Therefore, the aim of this paper is to address the hydraulic modelling bias that occurs due to the use of design storms for sewer system design and planning at a catchment scale by providing an alternative approach to traditional design storm application. A storm is defined by three attributes, total depth, duration and peakedness, which a design storm should aim to capture. As highlighted previously, there is agreement that storm peak intensity and timing significantly affect the runoff peaks simulated in urban catchments. As a result, the peakedness factor, defined as a ratio of maximum intensity to average rainfall intensity (Butler et al., 2007), has been chosen as a key factor that contributes to the bias in hydraulic modelling outputs. The hypothesis is that by applying a storm modification approach the bias caused by the use of design storms can be reduced. A novel storm modification process is proposed to allow the use of the readily available design rainfall data and available continuous rainfall datasets. Finally, the effectiveness of the proposed approach to estimate the role of SuDS at a catchment scale has been investigated and explored in the urban environment.

The Cranbrook and Norwich catchment models have been used as case studies to evaluate the above hypothesises and test the proposed storm modification method.

2. Study Area

Two catchment models with different characteristics have been selected as a proof of concept and have been used to test the hypotheses, answer the research questions and evaluate the storm modification technique presented in the following section.

The catchment models have been selected to confirm the consistency of the results on two different geographical locations, East and South of the UK, and two different catchment sizes 8.5km^2 and 98km^2. The catchments also have different drainage characteristics which are summarised in Table 1 below and depicted in Figures 1 and 2.

Table 1. Study Area Comparison

Figure 1. Cranbrook catchment – drainage network (black) and main rivers (blue)

Figure 2. Norwich catchment – drainage network (black) and main rivers (blue)

3. Methodology

Using design storms to drive hydraulic models may result in biased modelling outputs and in an underestimation of the role of SuDS. As proposed in the hypotheses above, it is believed that the bias is caused by the unrepresentative peakedness factor in design storms. Design storms are essential for standardisation of drainage and SuDS design in the United Kingdom. Therefore, the proposed methodology focuses on understanding the bias caused by design storms. The working principle is to compare hydraulic modelling outputs from design storms and historical storms and then adjust the peakedness of design storms. The bias reduction as a result of using this “Modified Design Storm” has been measured. Finally, to understand how design storms might underestimate the role of SuDS, SuDS on a catchment scale was implemented and the betterment using historical storms, design storms and modified design storms was compared.

The methodology summarised in the following diagram (see Figure 3) is divided into three main areas, storm selection and generation, design storm modification and hydraulic simulations.

Figure 3. Methodology diagram for selecting and modifying storms to be used in hydraulic simulations

3.1. Storm Selection and Storm Generation Methodology

Historical storms obtained from 1km^2 radar images (Met Office, 2003) with industry standard durations (15min, 30min, 60min, 120min, 240min, 360min, 480min, 960min and 1440min) were selected and applied on both Cranbrook and Norwich catchments to develop an understanding of a baseline catchment response to storms with various magnitudes and durations. A storm is isolated (separated) using the concept of minimum inter-event time (MIT) before and after the storm. The MIT value represents the dry weather period before and after the storm to allow the rainfall event be separated. The values for MIT in the literature vary between 15 minutes and 24 hours based on the simulation objective, imperviousness, and rainfall temporal resolution. For example, when the rainfall temporal resolution is 1 hour, in order to achieve a dry ground between runoff events, the recommended MIT value would be 12 hours (L. J. Bracken, 2008), while Aryal et al (2007) recommended a MIT value of 8 hours to allow complete recovery of all depression storage, and the Quebec government suggests a MIT of 6 hours to separate meteorological events from one another (Jean et al., 2018). However, to separate short storms in small urban catchments, MIT values could be as low as 10 minutes (Carbone et al., 2014) and (Yair & Raz-Yassif, 2004). Therefore, following a review of the literature and an assessment of the purpose of the simulations, and in line with the recommendations of Sanchis et al (2016) to adopt an MIT value of 1 hour (described as optimum MIT value), an MIT value of 1 hour has been selected in this investigation. The rainfall temporal resolution in this study is 5 minutes and the assessment is carried out on industry-standard storm durations that range between short and long storms (15 minutes to 1440 minutes).

Once the historical storms were separated and selected, FEH13 point rainfall (Institution of Hydrology, 2013) data were purchased for both Norwich and Cranbrook catchments in order to generate design storms equivalent to the selected historical ones. MicroDrainage software (Innovyze, 2020) rainfall generator has been used for this purpose and the aim was to get equivalent design storms with matching total depth, duration and return period as the historical selected storms with different temporal variation.

For each catchment, the available rainfall data was filtered to eliminate the dry period intensity values and unreasonable intensities (higher than 100-year maximum intensity of the shortest storm). The peakedness factor is then calculated for the filtered historical rainfall data as well as generated design rainfall:

Peakedness factor = maximum intensity / average intensity

The results are provided for the above standard durations, but the plots show the 360-minute storm to illustrate key mechanisms. This duration was selected for illustration because it is adjudged by practitioners to provide an equal combination of flooding being driven by rainfall depth (the dominant driver for long duration storms) and peak intensity (the dominant driver for shorter durations).

3.2. Design Storm Modification Process

The first step in the modification process is to identify the centric part of the storm, in this study a 5% buffer was used on both sides from the centre point of the design storm. A buffer of 10% and 15% were also tested to check the sensitivity of the storm modifications, the 5% buffer produced the best match in terms of flood volumes and flood count with historical storm simulations. The 10% and the 15% resulted in a higher percentage of the rainfall depth concentrated in the centric part of the storm profile which caused a bias on the opposite direction (higher flood volumes and higher flood count). Once defined, the centric part of the storm is multiplied by an uplift factor. The uplift factor is defined as the ratio of the historical storm peakedness factor to the design storm peakedness factor.

As this process increases the depth of the storm, a reduction factor was calculated in order to ensure that the total rainfall depth over the entire duration remains unchanged. Thus, the other 90% non-centric part of the storm was reduced by the reduction factor to ensure that the new modified design storm has the same total rainfall depth but with different temporal variation of intensity.

The end result is a design storm that has a maximum intensity closer to that of a historical storm, and thus potentially alleviating the bias resulted by the peakedness factor (see Figure 6 as an example).

Figure 4. An example of a modified rainfall event that highlights the application of uplift and reduction factors – This specific storm is 360-minute storm in Norwich

3.3. Hydraulic Simulations and Bias Calculations

InfoWorks ICM® software has been used in this investigation to carry out the hydraulic simulations (Sewer Edition; Innovyze Ltd, Oxfordshire). InfoWorks is an industry-standard advanced integrated catchment modelling software that enables users to model complex hydraulic and hydrologic networks and processes accurately. It is widely used around the world in both research as well as in industry and all UK water companies have their catchment models validated and calibrated in InfoWorks ICM, hence the decision to adopt the software in this investigation.

The parameters listed in Table 2 have been used in the simulation settings.

Table 2. Simulation parameters for the hydraulic simulations

The flood volumes and flood count over the entire simulation period are then exported for each scenario/simulation and compared.

3.4. SuDS Modelling

For this experiment SuDS at a catchment scale was implemented in both catchments (Norwich and Cranbrook). The aim is to test the hydraulic effectiveness of implementing SuDS when using design rainfall against historical rainfall. In this work we define the hydraulic effectiveness (betterment hereafter) as the percentage reduction in flood volume and flood count. InfoWorks ICM® has a built-in method to divert runoff from subcatchments into SuDS structures and thus represent the behaviour of SuDS interventions. We used this method (named as SuDS Controls) to implement 10% SuDS in the form of rain gardens across the catchment.

A code in SQL has been written in order to automate the process and introduce SuDS in the form of rain gardens as a percentage in all subcatchments and switch this SuDS percentage from an impermeable area into SuDS features that outfall into the subcatchments outlet node.

4. Results

4.1. Initial Examination of Storm Peakedness Factor

Following an investigation on a range of storm durations and return periods, it was observed that the peakedness factor of historical rainfall events could reach values of 11 for some summer storms, which means that the maximum rainfall intensity could be 11 times higher than the average intensity. However, when generating design storms in various geographical locations, it was observed that, for durations between 15min and 1440min the peakedness factor, had a range between 3.5 to 3.9 for summer storms and between 2.4 to 2.5 for winter storms (Figure 5). It was also observed that, for a given duration, the peakedness factor is fixed for various return periods because of the statistical method used when generating the storms.

As discussed, in Section 3.2, the historical rainfall peakedness factor was used to inform the storm modification process.

Figure 5. Summer and winter design storm peakedness factors for design storms

The results for the peakedness factor and the uplift calculations are summarised in Table 3 below:

Table 3. Peakedness Factor and Uplift Factor Results

4.2. Baseline Comparison Results

Figure 6 below illustrates the correlation between the total rainfall depth (applied over various durations) and the bias introduced by design storms in the Norwich catchment. A design storm of a given rainfall depth consistently underestimates sewer performance when compared to using historical rainfall to drive the sewer model. In assessment of flood volume, the design storm underestimated total volume by 12.7% and 44.7% in Cranbrook and Norwich catchments, respectively. These results suggest that when using design rainfall, the flood volumes and flood count (distribution) are underestimated regardless of the storm frequency and duration. This bias means that when a drainage network is designed to accommodate the 1 in 30-year return period using design storms, as per the common practice in the industry, the actual hydraulic performance of the drainage network might result in flooding when less severe storms land on the catchment. This also explains the reason for sites experiencing flooding that is more frequent that once every 30 year even though most of these sites have been designed to be resilient to the 1 in 30year return period.

Figure 6. Norwich Catchment – Bias correlation with rainfall depth

4.3. Modified Storms Results

The historical rainfall hydraulic simulation outputs were used as reference to allow the inter-comparison with other hydraulic simulation outputs simulated from models driven by design storms and modified design storms Figures 7 and 8 illustrate the 360-minute storm simulation comparison between hydraulic simulation outputs from models driven by design storms, modified design storms and historical storms. The comparison demonstrates that flood volumes in design storm simulations were consistently lower than equivalent historical storm simulations. In all hydraulic simulations run as part of this investigation, using design storms to drive the sewer model resulted in a bias in estimating both flood volumes and flood counts and using modified design storms reduced this bias. The results are presented in full in Tables 4 and 5. Thus, in the study catchment, design storms are associated with underestimations of flood volumes and flood count which would ultimately lead to misinformed technical and commercial decisions being made in the context of flood alleviation implementation. This bias can be significantly alleviated by applying the proposed storm modification technique.

Figure 7. An example of the flood volume results from the Norwich catchment hydraulic simulations

Figure 8. An example of the flood count results from the Norwich catchment hydraulic simulations

Modifying design storms helped reduce the bias and improved the hydraulic simulation outputs as flood volumes and flood count values were closer to the baseline results (simulations driven by historical rainfall).

Table 4. Absolute percentage point reduction in bias – Cranbrook Catchment

Table 5. Absolute percentage point reduction in bias- Norwich Catchment

4.4. SuDS Representation Results

All of the rainfall storms (historical, design and modified design) used in the above comparisons were also used to drive the catchment models with SuDS implemented on a catchment scale in order to investigate the representation of SuDS and confirm whether SuDS is being under-estimated when simulated using design storms.

The simulation outputs demonstrate that the hydraulic effectiveness of SuDS is underestimated when using design storms to drive models with SuDS implemented on a catchment scale. The SuDS representation bias was slightly reduced (up to 5% reduction) when driving the hydraulic models using modified design storms.

Figure 9. Flood Volume Reduction - SuDS betterment analysis – 360min storm duration – Norwich

Figure 10. Flood Count Reduction - SuDS betterment analysis – 360min storm duration – Norwich

Figures 9 and 10 demonstrate that the betterment from SuDS is consistently underestimated when using design rainfall and modified design rainfall, this is due to the synthetic shape of the rainfall which does not allow infiltration to take place between varying rainfall intensities.

Modelling SuDS involves complex processes and new factors introduced to the hydraulic equations such as half-drain time, time of concentration, time of entry, time of retention, infiltration rate and hydraulic conductivity. Therefore, using historical rainfall events in assessing the performance of SuDS is more accurate as the timestep gaps between rainfall intensities and the peak ratio factor allow the physical reality of the factors described above to be represented more accurately.

Figure 11 demonstrates the correlation between the percentage bias in SuDS representation between design storms and historical storms and the storm duration used in simulations. The trend line demonstrates that for longer storm durations, the bias in the role of SuDS is higher (up to 40% in Norwich catchment and up to 16% in Cranbrook catchment). The trend line also demonstrates that the modified design storm improves SuDS representation as the modified design storm line is lower than the design storm trend line which suggests that the bias has been reduced by up to 5%.

Figure 11. SuDS betterment bias analysis – Norwich

The hydraulic modelling outputs are summarised in Tables 6 and 7 below

Table 6. Summary of the hydraulic modelling results – Cranbrook Catchment

Table 7. Summary of the hydraulic modelling results – Norwich Catchment

The results shown in Tables 6 and 7 demonstrate the consistent bias in both flood volumes and flood count (distribution) resulted from the use of design storms and the bias reduction offered when using modified design storms to drive hydraulic simulations.

It can be observed that the bias reduction provided by design storm modification is significantly less in the case of SuDS.

5. Discussion and Conclusion

The peakedness of design storms (see Figure 5) is underestimated in comparison to hydraulically equivalent historical storms. Hydraulic modelling was used to show that this results in a false assessment of the sewer networks, as measured by bias in modelling outputs. This agrees with the assertions made in Thorndahl & Willems (2008) and Adams & Howard (1986). The peakedness factor for a design storm can sometimes be less than half the peakedness encountered in equivalent historical storms. This observation was the basis of developing a storm modification technique to utilise FEH13 design storms and address the bias introduced by the conceptual peakedness factor generated in design storms.

The investigation demonstrated that design storms contain conceptual errors and so produce questionable results when used to run catchment models, to undertake optioneering assessment or to make funding decisions which are purely based on flood volumes and flood count/distribution. The proposed design storm modification reduces the bias that occurs by adopting the practice of using design storms in comparison to continuous data (as illustrated in Figures 7 and 8). It is suggested that, should the use of design storms be required, then a modification process be applied.

It is demonstrated in Figures 9 and 10 that the betterment from SuDS is underestimated when using design rainfall or modified design rainfall. This is due to the synthetic shape of the rainfall which does not allow infiltration to take place between varying rainfall intensities. Modelling SuDS involves complex processes and new factors introduced to the hydraulic equations such as half-drain time, time of concentration, time of entry, time of retention, infiltration rate and hydraulic conductivity. Therefore, using historical rainfall events in assessing the performance of SuDS is more accurate as the timestep gaps between rainfall intensities and the peak ratio factor allow the physical reality of the factors described above to be represented more accurately.

For long term planning, interventions are planned and modelled on a catchment scale using different approaches such as Adaptation Tipping Point (ATP). The ATP approach can be utilised to investigate the impact of rainfall depth and intensities on urban drainage systems and this assessment is often followed by planning a set of adaptation pathways to assess the adaptation of drainage systems when a range of infrastructure interventions (solutions) (Babovic & Mijic, 2019). When using design storms in assessing these interventions, the time component is lost and therefore it will not be possible to establish the order of interventions and the best combination of intervention in a particular time.

It is recommended to test the storm modification method on more catchments with different characteristics and different rainfall pattern. It is also recommended to compare other hydraulic modelling outputs such as discharge volume/rate, infiltration rate/volume, flows and velocities within the system. The behaviour of design storms and the modified design storms can be tested in the context of evaluating the effectiveness of different types of interventions (e.g. traditional drainage solutions). Future work may focus on using Machine Learning (ML) for flood prediction (Mosavi et al., 2018) in order to train the storm modification method on the historical rainfall characteristics of each site and improve the storm modification process.

6. Closing Remarks

The purpose of developing design storms is to give the industry a standardised, transparent and consistent basis for drainage system design, hydrological impact assessment and land development impact assessment. Associating frequencies with rainfall intensities has supported the development of IDF curves from rainfall records and communicated a standard approach to drainage design practice. The novel rainfall modification method enables and facilitates the use of the readily available FEH13 design storms to generate modified design storms that can drive hydraulic models and reduce the bias in the modelling outputs. However, our results also highlight that design storms have fundamental issues, and in particular for assessment of SuDS. If using historical rainfall data in the industry is not practical due to availability and standardisation concerns, then we believe new and better standards and regulations are required that account for these issues – some of which have been known for over 30 years!

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Conflict of Interest

The authors declare no conflict of interest. The founding sponsors (Project Centre Limited, Innovyze and Imperial College London) had no role in the design of the study, in the collection, analysis, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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Figures captions

Figure 1. Cranbrook catchment – drainage network (black) and main rivers (blue)

Figure 2. Norwich catchment – drainage network (black) and main rivers (blue)treatment plant indicated by the cyan circle

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