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Continuous Simulation Supports Multiple Design Criteria for Sustainable Drainage Systems (SuDS)

Virginia Stovin*[1], Ruth Quinn[2] and Charles Rouge[3]

[*]Corresponding author

[1]Department of Civil and Structural Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK. Email: v.stovin@sheffield.ac.uk

[2]Atlantic Technological University, ATU Sligo, Ash Lane, Sligo, F91 YW50, Ireland. Email: Ruth.Quinn@atu.ie

[1]Department of Civil and Structural Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK. Email: c.rouge@sheffield.ac.uk

Abstract

Traditional (piped) drainage systems are designed to drain quickly. It is therefore reasonable to design a system assuming that it will be empty at the start of the rainfall event. However, the restoration of full capacity in Sustainable Drainage Systems (SuDS) or Low Impact Development (LID) is dependent on slower processes (e.g. evapotranspiration, infiltration, or the consumption of harvested rainwater). Current design guidance often does not advise on reasonable assumptions to make regarding SuDS retention capacity. In addition, SuDS have the capacity to control both runoff volumes and flow rates during both routine and extreme storm events. This presents two further interlinked challenges: firstly, to identify relevant metrics to define SuDS performance; and secondly, to define appropriate performance criteria for system design.

Using rainwater harvesting (RWH) as an example, it is argued that continuous simulation supports the calculation of a full range of performance metrics, properly accounting for retention, and empowering users to set design targets that are appropriate for a desired level of protection. Six independent metrics are considered to characterise performance in response to both routine and extreme rainfall events, and a scatter pie plot is introduced as a clear visual indicator of system performance across multiple targets.

While current UK guidance for SuDS prioritises flood risk mitigation and aims to provide protection up to the 1 in 100 year event, it is argued that such stringent expectations may be acting as a deterrent to SuDS uptake, particularly at the domestic scale. Here, lower design thresholds (for household SuDS) in the region of the 1 in 2 yr event and 95% of annual runoff, are recommended.

Introduction

Traditional (piped) drainage systems are designed to drain quickly. It is therefore reasonable to design a system assuming that it will be empty, i.e. at full capacity, at the start of the rainfall event. However, the restoration of full capacity in Sustainable Drainage Systems (SuDS; Low Impact Development (LID) in the U.S.) is often dependent on slower processes (e.g. evapotranspiration, infiltration, or the consumption of harvested rainwater) occurring at rates that may be hard to predict. Current design guidance (such as The SuDS Manual, Woods-Ballard et al., 2015) often does not provide clear guidance on reasonable assumptions to make regarding SuDS retention capacity. Instead, researchers and practitioners are increasingly advocating a probabilistic approach based on continuous simulation to characterise the all-round performance of these devices in their local climatic context (Guo and Urbonas, 1996; Stovin et al., 2017).

SuDS have the capacity to control both runoff volumes and flow rates during both routine and extreme storm events. This leads to two interlinked challenges: firstly, to identify relevant metrics to define SuDS performance; and secondly, to define appropriate performance criteria for system design. Quinn et al. (2021) established a set of metrics to characterise the stormwater quantity performance associated with rainwater harvesting systems, based on the use of continuous simulation. In addition to volumetric retention metrics, the following were included: i) metrics that represent the total volume and duration of flow above the predevelopment runoff rate; and ii) peak outflow rates and retention efficiencies associated with a representative sample of 'significant rainfall events' (Table 1). Note that for SuDS that offer outflow rate control once the design retention volume has been fully utilized, it is possible to ensure that any runoff is restricted to the relevant pre-development rate (i.e. to achieve an inflow control efficiency of 1.0). However, not all devices offer attenuation control; for example in a simple rainwater harvesting system, any inflow in excess of available retention storage will bypass the storage and directly become outflow.

These metrics provide standardised measures of performance, and Quinn et al. (2021) demonstrated how they permit performance comparisons between alternative system configurations. However, engineering design practice typically requires a design to meet specific, absolute, performance targets.

Guo and Urbonas (1996) provided a methodology for determining the detention volume for stormwater quality enhancement facilities (detention basins). The required volume is determined from a plot of volumetric retention against normalised storage volume, where the normalised storage volume is the storage volume divided by the storage required to fully retain the design inflow volume. The volumetric retention curve typically begins with a steep gradient, with the slope decreasing (i.e. increasingly diminishing returns) as storage volume increases. The relevant threshold value is defined as the maximum volume for which the slope is greater than 1, i.e. the point at which a unit increase in the normalised volume leads to a less than unit increase in performance. For a number of US locations, it was shown that the maximised detention volume captures 82-88% of the total annual runoff volume and 82-88% of the runoff events. This threshold implies a rainfall return period significantly lower than 1 in 2 years. Whilst the point at which the threshold is set is arbitrary, Guo and Urbonas (1996) argued that larger volumes introduce excessive redundancy, and may also have reduced effectiveness for treating routine events.

In contrast, where mitigation of extreme flooding events is the primary driver for SuDS, engineers may be expected to meet far higher targets. In the UK, for example, The SuDS Manual (Woods-Ballard et al., 2015) suggests that facilities should be sized to control volumes associated with the 1 in 100 year 6-hour rainfall event. While the guidance encourages the use of ‘surface water management trains’, in which this requirement may be met via a combination of (smaller) source and (larger) site-based controls, such high expectations may be discouraging developers and property owners from using any SuDS to deal with runoff at the property scale. For example, in the case of a conventional rainwater harvesting (RWH) system, a considerable tank size (> 3 m^3 on an average British terraced house (30 m^2 roof area)) would be required, based on a 1 in 100-year 6-hour design storm. That is equivalent to 1 m^3 per 10 m^2 (~110 ft^2) of roof area.

Analysis of Performance

The water balance of a conventional household-scale RWH system was continuously simulated using a Yield-After-Spillage (YAS) approach (Fewkes and Butler, 2000). Please refer to Quinn et al. (2021) for further details on the model set-up. Initial losses (associated with depression storage on the roof) were assumed to be 0.2 mm after a 2-hr antecedent period, with an additional loss rate of 0.2 mm/day (Xu et al., 2018). Tank inflow was calculated from the net rainfall using an assumed roof area of 30 m^2. Tank volume varied between 0.5 m^3 and 5 m^3, and demand between 10 L/day and 300 L/day. The average non-potable water demand in the UK is 120 L/day per household (Quinn et al., 2021). Demand rates were assumed to be constant over time. A predevelopment runoff rate of 5 L/s/ha was assumed, equivalent to 0.015 L/s for the 30 m^2 house roof considered here. The rainfall input is a 30-year data set incorporating climate change projections disaggregated into 5-min time steps (see Stovin et al. (2017) for details). This time series represents a plausible mid-term future climate (2050) for Sheffield, UK.

In the context of a conventional RWH system, larger storage tank volume and household demand for water are expected to lead to better stormwater management performance. This relationship is non-linear, as illustrated by contour plots for each performance metric as a function of volume and demand (Figure 1). Panel (a) illustrates the common behaviour of the non-dimensional long-term performance metrics listed in Table 1; contours for E_{CQ} and T_{CQ} (not shown for brevity) mirror E_R because a conventional RWH system does not provide any flow control (detention) once its retention capacity has been exceeded. For the long-term performance metrics, each contour line is derived from the full 30-year rainfall time series. All configurations lying above the E_R = 0.95 contour line are capable of retaining 95% of the total inflow volume.

Following Quinn et al. (2021), 'significant events' were defined based on the 30 events with the highest total rainfall during a continuous 6 hour period in the 30-year time series. These events are therefore indicative of the 1 in 1 year event. A median event-based retention efficiency (SE_{R50}) of 1.0 implies that the tank inflow is fully retained in more than 50% of the events (i.e. at least 15 events). This means that a spillage is at worst a 1 in 2 year event. Similarly, complete retention in more than 90% of the events (i.e. at least 27 out of 30 events, SE_{R90}= 1) would indicate a spillage is at worst a 1 in 10 year event. For the event-based performance metrics (e.g. SE_R shown in Panel (b)), the presented contours correspond to spillage return periods of at worst 1 in 2, 10 and 30 years (i.e. the 50th, 90th and 97th percentiles). SE_{CQ} and SQ (not shown) mirror SE_R. Note that the statistical robustness of these return period assignments increases with the length of the time series utilised, and decreases with increasing return period.

Storage volume and demand rate are also presented in non-dimensional form, where the Storage and Demand Fraction (-) are respectively defined as storage volume and annual demand divided by annual runoff. The benefit of the non-dimensional values is that the plots can potentially be utilised to estimate sizing requirements for different catchment areas and/or different annual rainfall depths. However it should be noted that new simulations would be required to properly capture the filling and emptying dynamics where systems are to be designed for a location with different climatic characteristics.

Both panels highlight that the general trends for performance improvement with increased tank volume and household demand abate as storage (respectively demand) increases, as the system becomes demand-limited (respectively storage-limited).

While the performance contour plots clearly demonstrate the interactions between tank volume, household water demand and stormwater management performance, they do not explicitly direct a design engineer to select an appropriate tank volume. Pipe-based stormwater management systems for urban settings are typically designed to 2 or 10 year return period rainfall events, depending on the perceived risk of failure. The following discussion therefore focuses on whether the lower (2-year) or higher (10-year) design standard may be appropriate for application to household-scale SuDS.

For a typical UK household demand of 120 L/day the tank volumes required to make spillage a 2 or 10 year return period event are 1.9 and 3.2 m^3 respectively. A tank volume of 3.2 m^3 is likely to be viewed as unreasonable (too large, too costly) by the majority of developers or householders in a domestic setting.

Figure 1 suggests that the 1 in 2 and 1 in 10 year event-based thresholds lead to storage volumes that approximately correspond with long-term performance metrics targets of 0.95 and 0.99 respectively. It is proposed that these two performance thresholds are therefore paired with the 1 in 2 and 1 in 10 year event based targets respectively to provide two alternative (lower vs higher) combined performance requirements for which the event-based and long-term performance requirements are non-conflicting (i.e. lead to comparable design requirements). It should be noted that the lowest threshold considered here (i.e. 1 in 2 years for the significant event metrics and 0.95 (or 95%) for the long term performance metrics) is significantly higher than the threshold originally proposed by Guo and Urbonas (1996). Figure 1(a) shows that a standard based on the retention of 88% of annual runoff would require a tank of 1.0 m^3, approximately one half of the 2 year return period standard.

Figure 2 combines all six performance metrics and shows how they vary depending on demand and storage volume in a single scatter pie plot. Pie charts are plotted at fixed values of storage volume and demand; a pie chart segment represents each metric, with green shades (left) representing long-term performance metrics and blue shades (right) representing event-based performance metrics. Filled segments indicate that a specified performance threshold has been met; therefore a completely filled pie chart indicates that all performance criteria have been achieved. Figure 2(a) confirms that design standards based on 1 in 2 year event-based performance targets combined with performance target of 0.95 for the long-term metrics (i.e. 1 in 2 yr/0.95) is well-balanced in terms of indicating the same design dimensions across a broad range of metrics. The more stringent 1 in 10yr/0.99 performance target combination is similarly well-balanced (Figure 2(b)).

Design standard decisions are made locally, in response to local drivers and priorities, but in light of these results, it is recommended that the design requirements for household-scale SuDS devices – including Rainwater Harvesting Systems – are reduced to frequent events (i.e. 1 in 2 years), even when flood mitigation is the primary driver. Note that in some locations, for example North-West Scotland in the UK, high rainfall totals may lead to impractically large tank sizes, even for low return period events.

In addition to their reduced cost-effectiveness, devices designed for extreme events may operate less effectively for stormwater treatment purposes compared with those designed to deal with more routine inflows. The multiple benefits associated with the smaller devices' abilities to deal with all but the largest events are all lost if no device is installed at all. In most urban catchments, these benefits will include reductions in CSO spills and in the resources/costs required to treat combined surface water runoff and sewage flows at treatment works. 800-litre tanks have been successfully deployed in the UK in situations where domestic re-use for toilet flushing occurred (Quinn et al., 2020). Increasing the tank size to 1.9 m^3 (1 in 2 year requirement) may be justifiable and feasible in certain circumstances, but it seems highly unlikely that the fourfold increase in volume required to achieve the 1 in 10 year protection would be considered feasible or acceptable in typical urban household settings. This is particularly true in the context of retrofitting to existing building stock, where RWH represents one of the few viable approaches.

The overall flood risk can be mitigated by directing excess flows through appropriate conveyance to downstream facilities sized to deal with the exceedance flows associated with higher return period events. The sizing of downstream facilities will be proportionately reduced due to the presence of the household-scale source controls. This proposal is consistent with the UK SuDS Manual's (Woods-Ballard et al., 2015) ‘surface water management train’, and with the concept of a ‘treatment train’ in which SuDS in series build in system redundancy and resilience with a wider range of potential treatment mechanisms. It is also consistent with a UK guide to retrofitting SuDS (Digman et al., 2012) which advocates taking any available ‘opportunities’, irrespective of whether or not they have the capacity to fully control a high return period event.

Conclusion

A framework for evaluating SuDS performance based on continuous simulation with long time-series rainfall inputs has been established. This approach is necessary to capture the slow restoration of retention capacity associated with SuDS devices. It also allows routine events, which are important for water quality considerations, to be considered alongside the high return period events that are relevant from a flood protection perspective. Continuous simulation supports the application of six metrics (Quinn et al., 2021) which, between them, characterise the system’s day-to-day and extreme event performance, in terms of spill volumes and flowrates. Based on an interpretation of the costs, benefits and practicalities associated with selecting 1 in 2 or 1 in 10 year levels of protection, 1 in 2 year design objective was proposed for the extreme event analysis, alongside a 95% of maximum possible performance threshold for the long-term performance metrics. Importantly, it was demonstrated that this combination of metrics led to consistent design decisions, relieving the designer/regulator of the responsibility of balancing potentially conflicting objectives. Where there is a strong flood protection driver, the 1 in 100 year level protection may be delivered through the installation of site-scale facilities further downstream in the catchment. The sizing of downstream facilities will be proportionately reduced due to the presence of the household-scale source controls.

There are likely to be other metrics that are pertinent to decision making in certain contexts. For example, Xu et al. (2018) focused on baseflow restoration for their dual function RWH systems. The basic approach outlined here can easily be adapted to accommodate additional metrics. The RWH system modelled here is hydrologically straightforward, with constant losses (demand for water) and no temporary storage once spill occurs. In vegetated systems, losses due to ET and infiltration replace the potable water demand considered here. Other SuDS incorporate significant temporary storage, leading to detention effects (peak runoff reduction) not seen in the RWH system response. These additional factors may make it harder to homogenise the performance metrics, and there is a clear need to trial the approach on other SuDS, using suitable modelling tools.

Data availability statement: The rainfall input and simulated runoff time-series used to generate Figure 1(a) are available from the corresponding author upon reasonable request.

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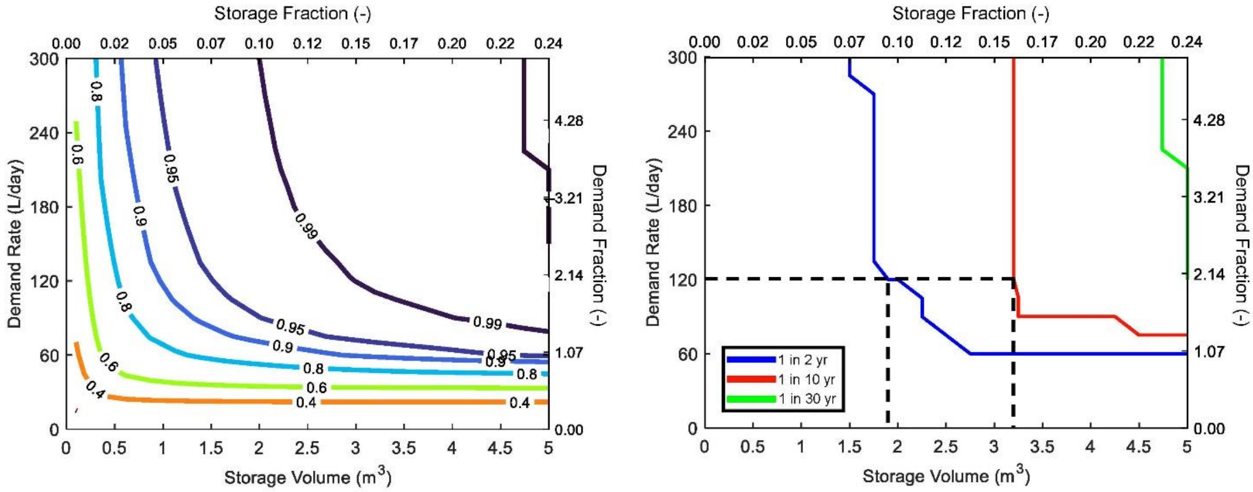
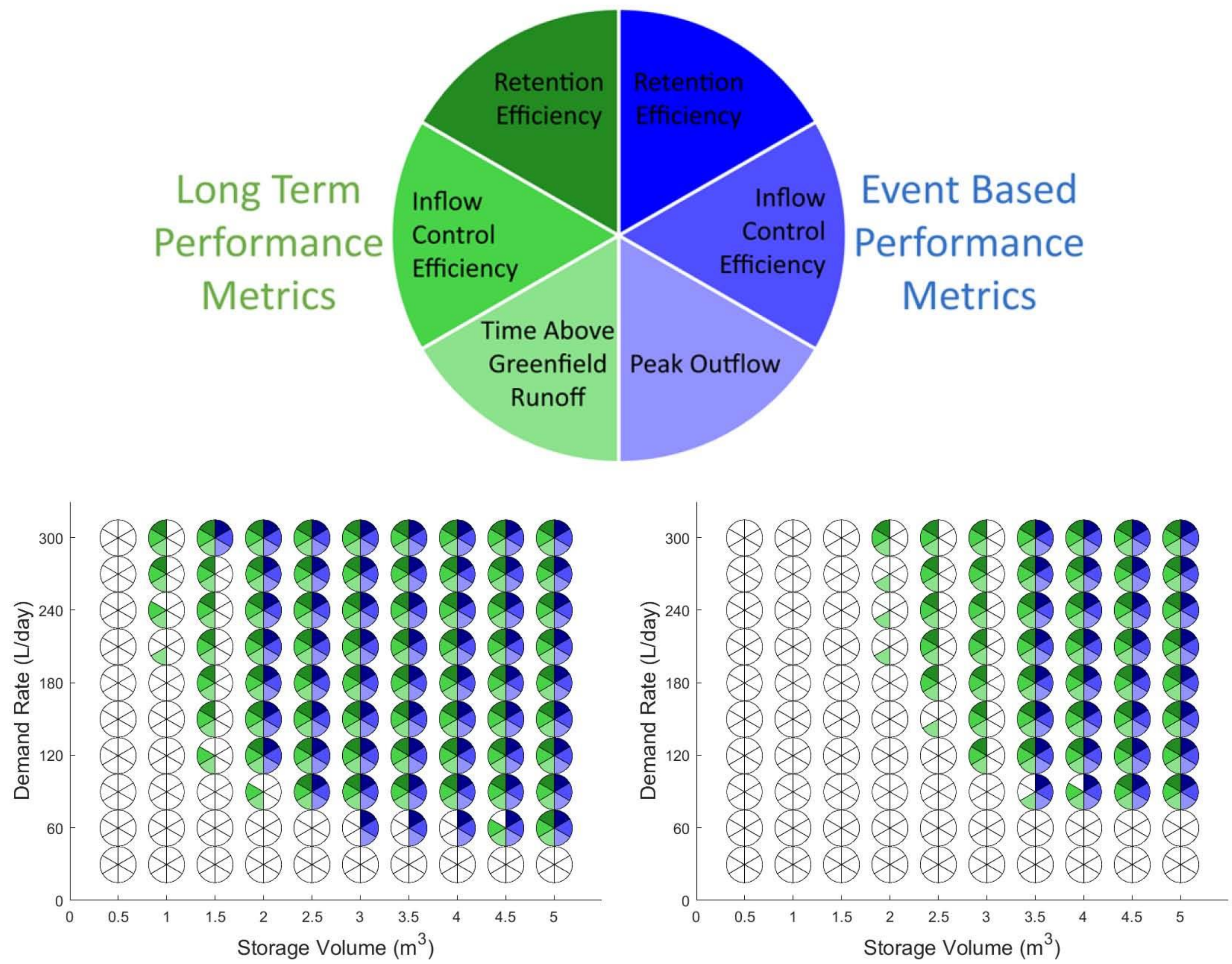
Table 1 - Summary of Stormwater Management Performance Metrics (based on Quinn et al., 2021)

	Performance Metric, Symbol (Units)	**Description**	**Maximum Performance**
Long-term Performance	Retention Efficiency E_R (-)	Proportion of inflow prevented from entering the downstream drainage network	$E_R = 1$ All runoff retained.
	Inflow Control Efficiency E_{CQ} (-)	Proportion of inflow controlled to predevelopment runoff rate	$E_{CQ} = 1$ All runoff controlled to predevelopment runoff rate.
	Annual Time Above Predevelopment Runoff Rate, T_{CQ} (hours/year)	Average annual time when outflow is above predevelopment runoff rate	$T_{CQ} = 0$ Time above predevelopment runoff rate is 0 hours/year.
Event-based Performance	Retention Efficiency, SE_R (-)	Proportion of inflow prevented from entering the drainage network over the sample of significant events.	e.g. $SE_{R50} = 1$ 1 in 2 year events completely retained.
	Inflow Control Efficiency, SE_{CQ} (-)	Proportion of inflow controlled to pre development runoff rate over the sample of significant events.	e.g. $SE_{CQ50} = 1$ Runoff during 1 in 2 year events completely controlled to predevelopment rate.
	Peak Outflow SQ (L/s/ha)	Peak outflow over the sample of significant events.	e.g. $SQ_{50} = 0$ Peak flow during 1 in 2 year events reduced to 0 L/s/ha.



(a) Overall Retention Efficiency. E_R (-) (b) Event Retention Efficiency. SE_R(-) = 1

Figure 1 – Selected Performance Metrics for a Conventional RWH System in Sheffield, UK



(a) Long Term – Design Criteria = 0.95
Event-based – 1 in 2 year

(b) Long Term – Design Criteria = 0.99
Event-based – 1 in 10 year

Figure 2 – Scatter Pie Plots for all Performance Criteria for Sheffield, UK