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**TECHNICAL ARTICLE**

# The Influence of Built Form and Area on the Performance of Sustainable Drainage Systems (SuDS)

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In the face of increased housing demand and climatic change, sustainable urban drainage systems (SuDS) are often viewed as an alternative to traditional piped drainage networks, offering multiple benefits. However, whilst design guidelines for SuDS exist, there is little systematic understanding of how SuDS perform for different urban forms at a neighbourhood scale. This paper, therefore, explores the response of a one hectare urban area to rainfall events of varying magnitude under a range of different scenarios for the built environment (development density, SuDS type, residence type and SuDS deployment extent), using the Stormwater Management Model (SWMM). It finds that whilst increased development density leads to an increased peak runoff rate, in some cases lower SuDS deployment in higher density scenarios leads to lower runoff rates than higher deployment in a lower development density. The type of SuDS also has a considerable impact on runoff dynamics, with those constructed on existing infrastructure offering greater proportional reductions in runoff rates than those constructed on previously undeveloped land.

**Keywords:** Sustainable Drainage Systems (SuDS); Urban Density; Built Form; Sustainable Development; Stormwater Management

## Introduction

There is a longstanding debate about the relationship between the density of urban development and cities' sustainability. One aspect of this debate has concerned energy use (see Rode et al. 2014; Stevenson & Gleeson 2018), with more compact cities minimising energy use for transport, up to a point when the energy intensity of the most dense cities apparently increases. The debate is also reflected in discussion of the 'liveability' of cities, which idealise a walkable city environment and reduced urban sprawl, promoting a compact, dense city form, whilst calls for increased urban greenspace and the maintenance of nature networks seemingly demand the opposite (Artmann et al. 2019). When it comes to considering sustainable urban development, high and low density solutions present their own strengths and weaknesses, and thus a delicate balancing act is required in the development of urban spaces to create the best of both worlds (Lehmann 2016).

This balance is further complicated by the additional challenges of climatic change, which will have resultant impacts on urban conditions (e.g. surface runoff, urban heat island effects) that will need to be managed through urban design (Caparros-Midwood, Barr & Dawson 2017).

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Storm events are expected to become more frequent and bring higher volumes of precipitation (Zuniga-Teran et al. 2020), and thus stormwater management in urban contexts will be increasingly important. As well as developing appropriate methods and technologies to cope with these changes, the spatiality of these infrastructures and their integrated nature into the built environment are equally important considerations (Yazdanfar & Sharma 2015).

Irrespective of whether we densify existing cities or construct new settlements, urban development sees a proportional loss of permeable surfaces for impermeable (in traditional developments), which leads to the loss of natural drainage pathways (Miller & Hess 2017). This leads to a resultant increase in the surface runoff volume and rate from a catchment during a rainfall event, which can result in, or exacerbate, flooding. Traditional drainage networks use built infrastructure (usually underground) to capture and transport this water out of the urban area. Connecting new/infill developments to these can overload the existing network, requiring costly capacity expansion (Yazdanfar & Sharma 2015). Lennon, Scott & O'Neill (2014) argue that traditional hard engineering techniques will become increasingly inappropriate in the face of urbanisation and climatic changes, and thus promote the inclusion of green infrastructure techniques (such as sustainable drainage infrastructure (SuDS)) in urban design as a move towards mitigation and adaptation.

***Urban hydrology***

Appreciating the dynamics of the hydrological cycle in the urban domain requires consideration of both the natural water cycle and the manmade elements which interact with it, such as those for storage and conveyance (Barbosa, Fernandes & David 2012). Not only does this lead to more complex pathways through the cycle due to the increased number of elements involved, but creates challenges for data collection as often these manmade elements are owned by private companies, leading to uncertainties and difficulty in accessing information on channel (pipe) size and locations (Noh et al. 2016).

In addition, the processes and storages of the natural water cycle are also altered in the urban domain, with potential for some being reduced (see **Figure 1**). For example, the increased impermeable surface area relative to an undeveloped parcel leads to reduced infiltration and evapotranspiration, with a resultant increase in surface runoff (Anim et al. 2019). Reduced infiltration into permeable, undeveloped land also leads to reduced groundwater level and less resilience of the land to prolonged dry periods.

Management in the urban form usually results in attempts to control where the water is located, too, through the channelling of water into drains and pipes. This is then conveyed out of the populated area.  Consequently, when the inflow is greater than the outflow (during intense and/or persistent rainfall), problems are exacerbated as there is little storage capacity and water collects in these areas.

As a result, the spatial and temporal scale of the subprocesses in the hydrological cycle are much smaller in the urban domain than the rural. This led Niemczynowicz (1999) (and later Paz et al. 2019) to argue in their review of the field that data collection would ideally occur at this smaller scale to improve accuracy in the modelling and monitoring of these processes. The impracticality of this, however, means that many of our contemporary models operate using data from larger spatial scales. Whilst this presents a source of error in modelling such environments, the increased data availability at these scales and the ability of the models to provide sufficiently accurate simulations, means they are still widely utilised in contemporary drainage design (Yazdanfar & Sharma, 2015).

***SuDS & their impacts on urban hydrology***

SuDS are an alternative to traditional drainage, mimicking natural drainage processes (Anim et al. 2019). They can also create habitats for nature, opportunities for water reuse, and offer water quality improvements (Ellis & Lundy 2016). Some types of SuDS offer storage of surface runoff, whilst others focus on increased drainage of surface water through increased permeability (Liao, Deng & Tan 2017). In this research, we focus primarily on the latter since, as Liao, Deng & Tan (2017) emphasise, demands for surface and sub-surface space are already high in urban contexts, and thus the relative depth requirements for infiltration-based SuDS can be better suited to the built environment whilst still offering surface runoff reductions. It is worth noting, however, that post-infiltration, all three modelled systems also have the potential for storage. We also distinguish between two categories of SuDS in our study – infrastructure-based SuDS, which look to alter imperme-

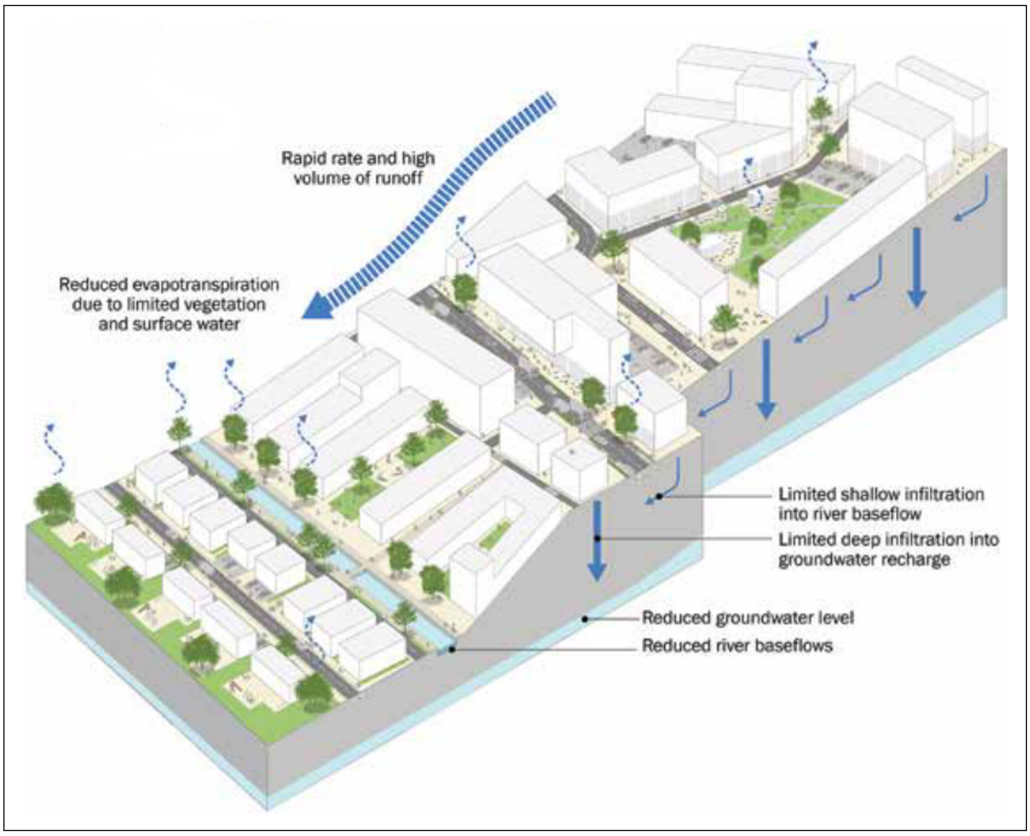


**Figure 1:** The impacts on the hydrological cycle of urban development (CIRIA 2015).

able surfaces to increase their permeability, and freespace SuDS, which boost the permeability of an already-permeable area.

SuDS work to mimic processes of the natural water cycle through addressing one or more of the changes discussed in the previous section. **Table 1** illustrates which of these changes (as identified by CIRIA 2015) is addressed by which of the common SuDS methods. Three different SuDS methods were chosen for modelling in this study, covering the full breadth of the five influences, and offering infrastructure-based and freespace alternatives – bioretention areas, green roofs and permeable surfaces.

Bioretention areas are landscaped regions designed with engineered soils and vegetation to promote infiltration – both from the surface into the bioretention area, and also from the bioretention area into the existing underlying soil. In so doing, surface runoff is reduced, increased evapotranspiration promoted, and underlying groundwater recharge supported (Eckart, McPhee & Bolisetti 2017). Bioretention areas also typically contain a considerable storage potential, allowing water to be retained in the catchment from large rainfall events and released slowly, reducing peak runoff rates and volumes, and helping to maintain groundwater and soil water during drier periods (Liao, Deng & Tan 2017). As a freespace infrastructure, the maximum potentials of bioretention areas are limited by available undeveloped land in the urban locale, but it can simultaneously act as an urban greenspace (Filazzola, Shrestha & MacIvor 2019).

Green roofs are vegetated areas constructed on building roofs. Adapting a traditionally impermeable surface to become more permeable, they reduce surface runoff volumes and rates, and instead promote the infiltration of water into their systems (Haowen et al. 2020). Compared to bioretention areas, the storage potentials associated with green roofs are often much smaller, decreasing peak flows in the system and increasing the lag time for runoff, rather than dramatically decreasing water volumes draining from the catchment. Green roofs are often connected to other SuDS infrastructures, such as disconnected drainpipes or rainwater harvesting, but in this study they are used in isolation to examine their individual role.

Permeable surfaces are an alternative to traditional impermeable surfaces in the constructed urban environment, being designed to enable and promote infiltration. This water is then typically filtered (offering water quality benefits) before being stored and/or conveyed out of the catchment (Eckart, McPhee & Bolisetti 2017). In promoting infiltration, surface runoff rates and peak volumes are reduced, whilst storage potentials allow for deeper infiltration into the underlying soil profile, with benefits for groundwater and base flows/heights of local natural water bodies. Traditionally, these materials are used as permeable paving for pavements and driveways, but recent research and case study sites have identified their potential for a wider use, such as in low-duty, residential roads (see Weiss et al. 2017).

### *The uptake and design of SuDS*

Since the end of the last millennium, there has been an increase in the use of SuDS (Fletcher, Andrieu & Hamel 2013), with well-publicised examples of uptake in China, Scandinavia and Australia (Fu et al. 2019; Yazdanfar & Sharma 2015; Zuniga-Turan et al. 2020). The United Kingdom has seen a regionally-divided uptake, largely attributed to the differing planning policies and statutory guidance issued in its constituent nations (Vilcan & Potter 2020). The use of SuDS in new developments is mandatory in Scotland and, under certain conditions (e.g. development size), in England and Wales, however, Ellis & Lundy (2016) note that policy loopholes mean that no real impact on uptake can be seen, particularly in England, which also lacks any statutory standards for SuDS (Vilcan & Potter 2020). In 2019, new legislation came into effect in Wales, adopting Schedule 3 of the National Flood and Water Management Act (NFWMA), which looks to support and encourage SuDS uptake through the implementation of national standards and local SuDS Approval Bodies (Green 2019). It is thus expected for increased SuDS uptake to be seen in Wales in the near future. Furthermore, as part of this change, national statutory standards

**Table 1:** Common SuDS infrastructure and the urban hydrology processes they look to address.

| | Limited shallow infiltration | Limited deep infiltration | Reduced surface runoff rate and high volumes | Reduced evapotranspiration | Reduced groundwater flows/lower groundwater levels |
|---|---|---|---|---|---|
| Bioretention areas | ✓ | ✓ | ✓ | ✓ | ✓ |
| Detention basins | | | ✓ | | |
| Drainpipe disconnection | ✓ | ✓ | | | ✓ |
| Green roofs | | | ✓ | ✓ | |
| Permeable surfaces | ✓ | ✓ | ✓ | | ✓ |
| Rainwater harvesting | | | ✓ | | |
| Retention basins | | | ✓ | ✓ | |
| Swales | ✓ | | ✓ | ✓ | |
| Wetlands | | | ✓ | ✓ | ✓ |

are required to be introduced in this devolved nation, and the improved understanding of the relationship between urban design and SuDS performance can contribute to these in maximising system efficiency and resilience.

The increased prevalence of SuDS schemes has led to a simultaneous increase in SuDS-based research, particularly concerning the influence of the SuDS design on its efficiency in regards to water quality and quantity. There has been less focus, however, on how different urban layouts influence potential options for SuDS schemes, despite the relationship between urban design and 'green' technology potentials being identified as a key area for further research by the Pitt Review (2008). Bach et al. (2013) identified how different densities and soil types found in Melbourne, Australia impact infiltration and runoff, but did not consider other conditions, such as slope or housing typology. Similarly, Hargreaves (2015) surveyed existing urban housing stock to illustrate the impacts of different housing typologies on density, and how this may impact upon potentials for 'green' technologies and decentralised infrastructure. However, beyond this, a better appreciation is required of how elements of urban design (such as building density) impact the potentials for, and performance of, SuDS.

As a result of the close interaction between surfaces in the urban built form, the effect of SuDS in a development is dependent on the features and design of this form. For example, since by their definition infrastructure-based SuDS require infrastructure to be constructed upon, denser settlements, which provide a greater proportion of these surfaces (e.g. roads, buildings) within a given area, hold a greater potential for infrastructure-based SuDS over freespace (those requiring underlying permeable surfaces). If only freespace SuDS types are being used in a development catchment, this means that not only is there a reduced area for SuDS interventions, but increased runoff into the system from the increased surface area of impermeable infrastructure.

Many other characteristics of the catchment can also influence the available surface areas for different SuDS types, and affect other aspects of SuDS designs (e.g. slope). Hargreaves (2015) illustrated that many of these are inextricably linked to housing typology, with the different densities that can be offered in a given-sized space resulting in different proportions of roof area, roads and paving, and remaining green space. This local-scale focus is also best placed to understand greenspace provision benefits for residents (Bach et al. 2013).

Building on Hargreaves' (2015) tile-based approach to urban catchment analysis, this study looks to better understand this urban design and SuDS provision relationship, through addressing the following questions:

- How do the responses of different SuDS infrastructure to a rainfall event vary under different urban density scenarios?
- How do characteristics of the urban form (e.g. antecedent soil moisture, slope, soil type) influence the SuDS response to a rainfall event?
- For a given urban design, is there a density threshold that can be identified, achieving a balance for meeting housing demand and offering space for SuDS to reduce flooding impacts?

## Methodology

In this research, one hectare urban tiles were created to visualise a range of urban conditions in order to address the identified questions. Three distinctive housing types were chosen – detached, terraced and apartments – and their minimum footprints identified from the national Technical Housing Standards (Ministry of Housing 2015). These were then each used to create three density scenarios with a homogenous housing type at 20-, 30- and 40- residences per hectare. As each dwelling typology had a different building footprint, this led to different total dwelling footprint areas between the typologies. Road networks were added to connect the houses, with figures for minimum widths and component spacing drawn from the UK Manual for Streets (Department for Transport 2007). To reduce runoff impacts from settlement layout, a uniform design approach was then applied. That is, a main central road was identified through the tile, and additional side roads added individually only when required. The resulting nine tiles can be seen in **Figure 2**, and land use footprints are listed in **Table 2**.

SuDS infrastructures (bioretention, green roofs, and permeable surfaces) were also modelled within each of these designs, and the area covered by this SuDS type varied. That is, the potential space for each type of SuDS was calculated in each scenario (total undeveloped space for bioretention, total roof area for green roofs, total road area for permeable paving), and then a simulation undertaken with the SuDS constructed on between 0–100% of this area at 10% intervals. Each infrastructure was considered independently from the others, with no scenario involving more than one type of SuDS.

All urban designs, with and without SuDS implementations, were independently simulated using the Stormwater Management Model (SWMM) under three different sized storm events. These represented a 2-hour duration 1-in-2, 1-in-5 and 1-in-10 year storm event, as calculated by the Modified Rational Method, for the Oxfordshire region – 13.65, 17.28 and 20.22 mm/hr respectively. Distribution of the rainfall during the event was considered to be uniform, both temporally and spatially. The parameters used to represent the system and SuDS design in the model are listed in Appendix 1.

### *Model design*

SWMM is a dynamic rainfall-runoff model originally developed by the US Environmental Protection Agency in 1971. It uses continuous precipitation data to model runoff, primarily in urban locations (Haowen et al. 2020). Conceptually, the model visualises the drainage network as four systems – atmosphere, land, groundwater and transport – with their own internal operations and potential interactions. **Table 3** indicates the main processes in the hydrological cycle, and the equations used by SWMM to represent these. In this study, only the atmospheric and land systems are represented – since the model is representing a new-build scenario, it is assumed there is no pre-

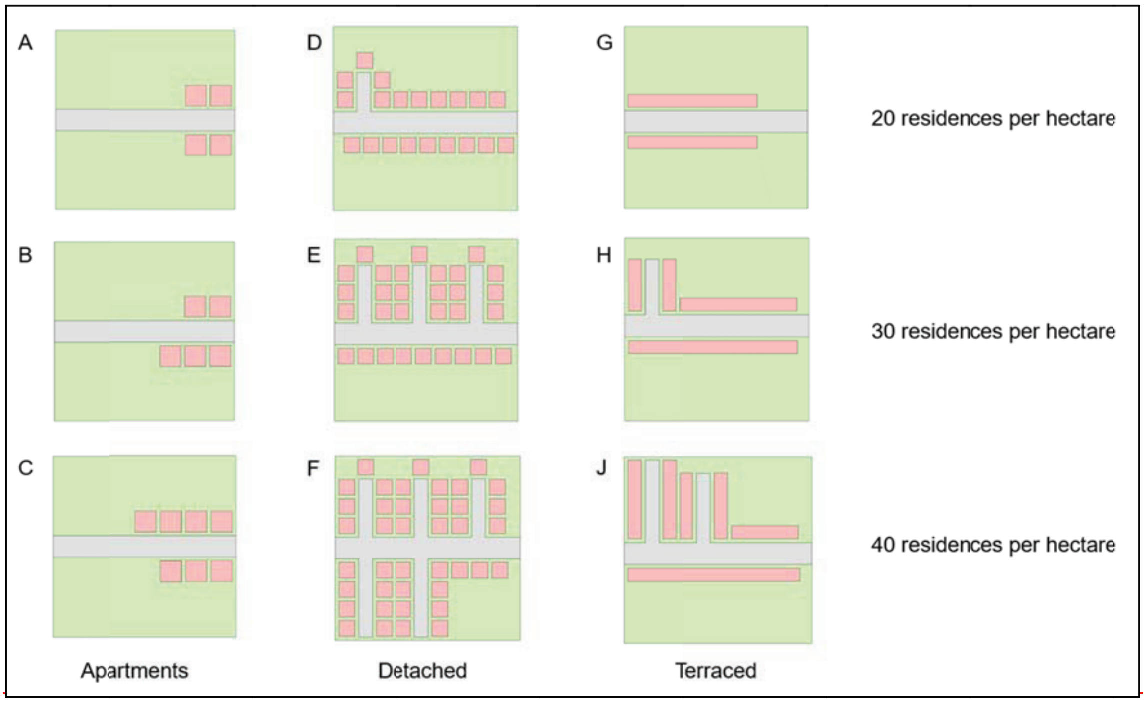


**Figure 2:** The nine 1-hectare scenarios illustrating varied housing type and development density. When slope is present, each scenario slopes from top to bottom.

**Table 2:** Areas of each land use in the tile scenarios (m$^2$).

| Scenario | Building | Road/Pavement | Greenspace |
|---|---|---|---|
| A | 544.0 | 1200.0 | 8256.0 |
| B | 680.0 | 1200.0 | 8120.0 |
| C | 952.0 | 1200.0 | 7848.0 |
| D | 1480.0 | 1359.0 | 7161.0 |
| E | 2220.0 | 1916.0 | 5864.0 |
| F | 2960.0 | 2553.0 | 4487.0 |
| H | 1004.2 | 1200.0 | 7795.8 |
| J | 1506.3 | 1427.0 | 7066.7 |
| K | 2008.4 | 1814.0 | 6177.6 |

existing grey drainage infrastructure, whilst groundwater interactions are not considered by the research.

SWMM has been used regularly in urban hydrology studies related to surface water runoff, dynamics and water quality impacts (see Fu et al. 2019; Hamouz & Muthanna 2019; Krebs et al. 2013). These studies have been independent of the original developers (United States' Environment Protection Agency) and spanned a range of scales, climates, geologies, and urban extents. Furthermore, the introduction of new modules within the model has led to the inclusion of SuDS developments in recent simulations, too (see Arjekani et al. 2020; Peng & Stovin 2017; Rosa, Clausen & Dietz 2015). For example, Chow, Yusop & Toriman (2012) consider urban runoff quality and quantity under tropical climates, whilst Hamouz & Muthanna's (2019) analysis is focused on a cold climate, and Krebs et al. (2013) focus on high-resolution analysis in a boreal zone. Similarly, Cipolla, Maglionico & Stojkov's (2016) study is concerned with a unit-scale analysing the long-term performance of a green roof feature, whilst Fu et al. (2019) apply the model district-wide in China's Yizhuang district.

Results from these studies frequently identify the strengths of the model and take a positive outlook on its performance (see Jang et al. 2007; Krebs et al. 2013; Fu et al. 2019), including the credibility of results even without observed runoff data. Comparison with other similar modelling environments has also been optimistic, with Yazdi et al. (2019) noting SWMM's superior sensitivity to imperviousness and higher correlation coefficients during extreme events – two characteristics that are important for this study. The LID-module has seen mixed feedback from studies, in-part due to its new and relatively undeveloped nature compared to the base model and other modules. Whilst Gülbaz & Kazezyılmaz-Alhan (2017) concluded that the performance was more than satisfactory for contrasting different SuDS designs, Campisano, Catania & Modica (2017) point to overestimation in rain barrel systems smaller than 2m$^3$, and Peng & Stovin (2017) question the ability of the model to predict evapotranspiration to a sufficiently accurate degree. Nevertheless, with consideration of the identified weaknesses and comparison to other runoff models, SWMM was deemed to be an appropriate model for the aims of this study.

In this research, a single subcatchment in SWMM is used to represent each modelled, square, sloping tile, which is then sub-divided into permeable and impermeable surfaces. Surface water (standing or as runoff) can infiltrate into the soil profile in only the permeable surfaces, with a rate described by the infiltration expression.

All our simulations used the Modified Green-Ampt equation. Furthermore, each subcatchment was considered to have uniform slope and soil conditions. These are underlying assumptions of the model, since each subcatchment is conceptualised by SWMM as a single surface, orientated as a sloping plain in the direction perpendicular to the flow. This direction is determined by the location of input and output nodes (EPA 2016). To represent variation in the study area, multiple subcatchments would need to be used.

Some scenarios featured SuDS infrastructure, altering this proportional permeable-impermeable surface divide. In these scenarios, the infrastructure was represented using SWMM's separate LID module. Here, the infrastructure are treated as a third surface type, with infiltration rates defined using the same equation as the subcatchment, but separately defined soil conditions. **Figure 3** illustrates the three conceptual diagrams provided by SWMM as to the inflows/outflows of the SuDS infrastructure used in our scenarios, and their units of structure within which parameters can be independently defined.

Several types of SuDS offer a storage component, such as bioretention and permeable paving. In the model, outflow from this is treated as infiltration from the SuDS infrastructure into the underlying soil through the base of the infrastructure. When correctly designed, this infiltration rate will be lower than the infiltration into the surface of the LID, causing a build-up of water in the SuDS feature, which will continue to gradually infiltrate out after the rainfall event. Water may also be retained in the storage when soil moisture in the external environment is saturated. SWMM also has the option to add a piped drainage feature to this storage layer at a chosen height. This allows excess water to be drained from the feature and prevents a backing up and saturating of the SuDS infrastructure. The equation determining this rate is described as "outflow" in **Table 3**. This optional drainage, however, was not utilised in this research.

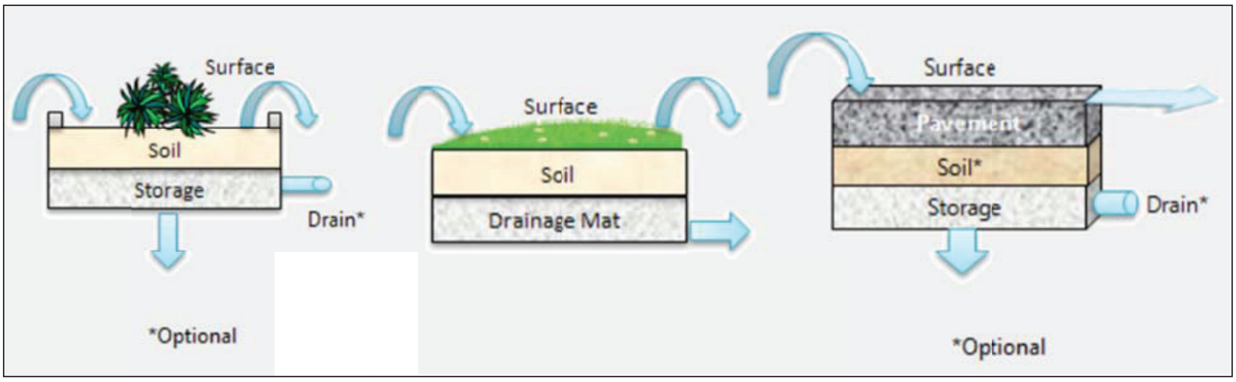


**Figure 3:** SWMM conceptualisations of flows and component layers of three SuDS infrastructures (left to right: bioretention, green roofs, permeable pavements) (EPA 2016).

**Table 3:** The equations used by SWMM to represent various processes of the hydrological cycle.

| Process | Equation |
|---|---|
| Evapotranspiration, *ET* | $ET = 0.0023\,(T_{max} - T_{min})^{0.5}\,(T_{mean} + 17.8)R_a$<br>where $T_{max}$ = maximum temperature, $T_{min}$ = minimum temperature, $T_{mean}$ = daily mean temperature, $R_a$ = extraterrestrial radiation |
| Infiltration, *I* | $I = k(\frac{1+(\Psi(\Phi-\theta))}{F})$<br>where $k$ = hydraulic conductivity, $\Psi$ = suction head, $(\Phi - \vartheta)$ = change in moisture content, $F$ = cumulative infiltration |
| Outflow, *O* | $O = j\,(d^{\eta})$<br>where $j$ = coefficient, $d$ = water depth, $\eta$ = coefficient |
| Percolation, *P* | $P = K(\theta)\left(1+\frac{\Psi(\theta)}{D}\right)$<br>where $K$ = hydraulic conductivity, $\Psi$ = capillary tension, $D$ = depth of soil layer |
| Runoff, *Q* | $Q = B\frac{1}{n}S^{\frac{1}{2}}\,(y-y_d)^{\frac{5}{3}}$<br>where $B$ = catchment breadth, $n$ = Manning's roughness coefficient, $S$ = catchment slope, $y$ = surface water height, $y_d$ = surface depression storage |

## Results

The resultant hydrograph responses of the different urban designs were analysed to ascertain the impact of different soils and topographies, housing design and SuDS design in the tile.

### *Urban hydrology*

Irrespective of building or SuDS design, alterations to the urban hydrology illustrated the same patterns across the scenarios. Lower antecedent moisture conditions led to an increased lag time and reduced peak runoff rate as soils had a greater capacity to infiltrate and store more water before saturation occurred. Post-saturation, additional water to the system became surface runoff, which was then directly discharged. An increase in slope led to a reduction in lag time and an increase in peak runoff, as water on the surface is transported downslope faster by gravity, reducing the opportunities for infiltration and evapotranspiration, and thus decreasing overall transport times through the urban tile. Different soil types result in different runoff rates, too, due to their varied textures and consequent hydrologic properties. The sandy soil type resulted in the lowest peak runoff and longest lag time, which is likely due to its increased pore volume, whilst the clay soil led to the opposite.

### *Housing design*

Both housing density and housing type present impacts on the hydrograph response to the design rainfall events. With increased housing density, we see an increase in both total and peak runoff, as illustrated in **Figure 4**. This occurs across all three housing types, albeit to varying magnitudes, with apartments seeing the smallest difference and detached housing the greatest. This is a result of increased surface sealing as the variation between housing types comes from the different impermeable surface areas for the typologies under the different densities.

Nevertheless, the hydrograph for all nine scenarios without SuDS interventions show a similar shape, as seen in **Figure 4**. With limited greenspace to promote infiltration and evapotranspiration into subsurface soils (and thus slowing the movement of runoff through the urban tile), and without infrastructure to store runoff, runoff occurs from the beginning of the storm event, with a greater increase in runoff rates in those with less greenspace. After a period of time, a plateau is reached, indicating that the ground has become saturated. Finally, following the end of the storm event, runoff rates decline rapidly before returning to pre-event levels, as no additional water is being added to the system.

A higher density of certain housing types can show lower total and peak runoff than lower density scenarios of other housing types. An example would be the terraced houses at 40 houses per hectare, which offer a lower peak runoff than 30 houses per hectare in the detached form. This is partly a result of the reduced footprint of a terraced house compared to a detached house, meaning less surface sealing occurs per terraced house than per detached house. It is also, in part, due to the additional infrastructure required in the scenarios. In order to be defined as detached houses, space is required between dwellings, meaning that properties are more dispersed across the

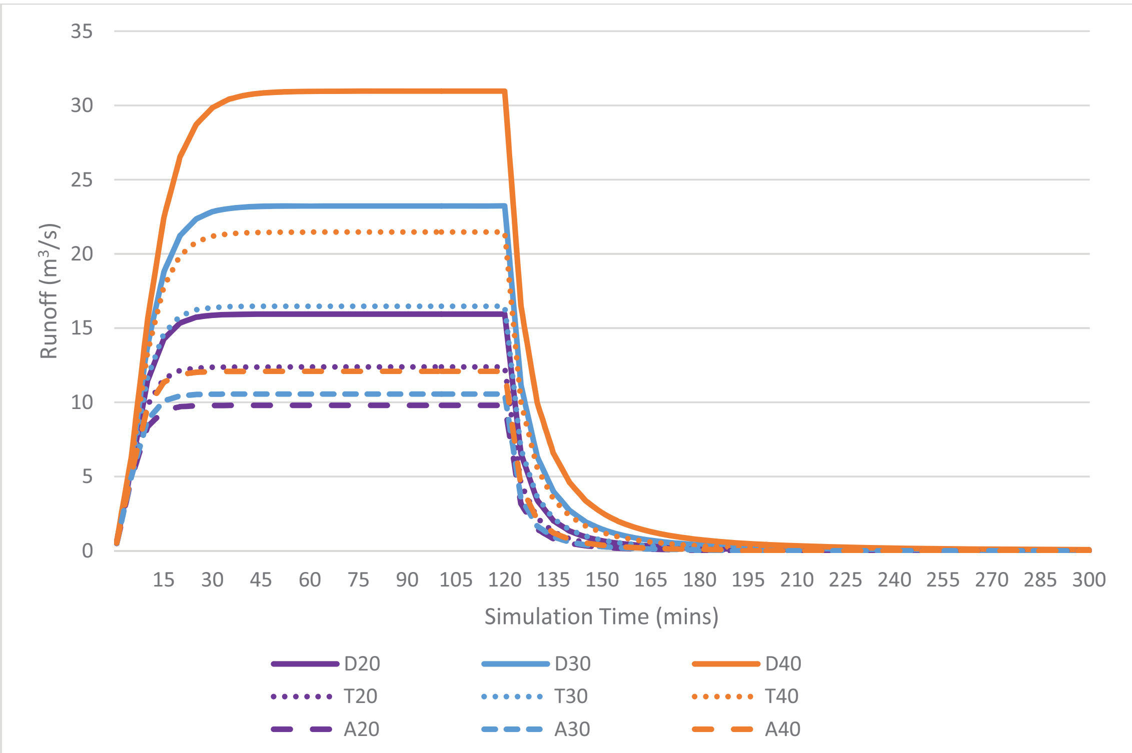


**Figure 4:** Influence of residence type (detached, terraced, apartments) and residence density (20-, 30-, 40-houses per hectare) on the hydrograph of a one hectare site during a 2-hour duration, 1-in-5 year rainfall event.

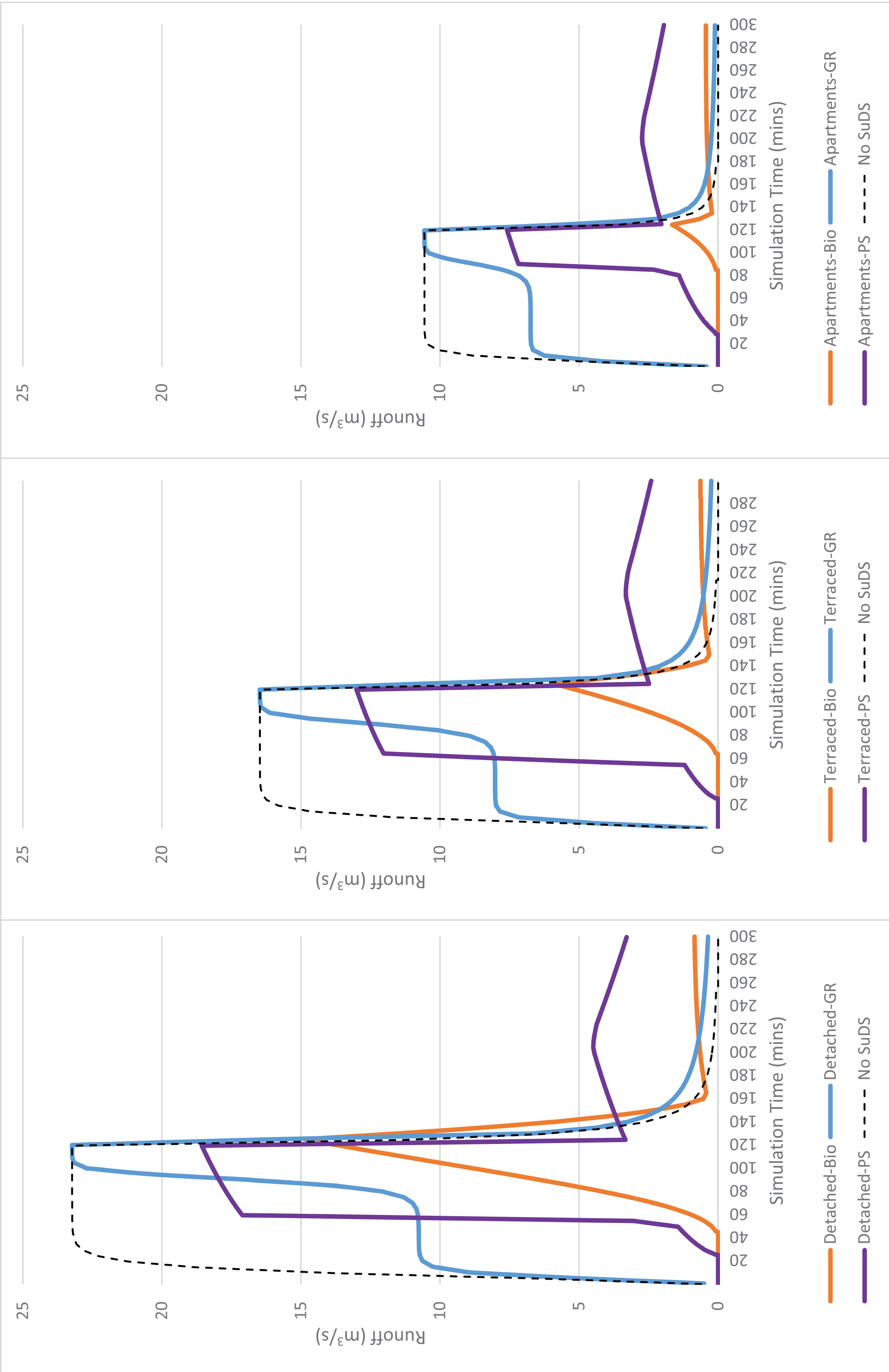


**Figure 5:** Influence of different SuDS infrastructure (bioretention, green roofs, permeable surfaces) on the hydrograph of a 1-hectare tile, under a 2-hour duration 1-in-5 year rainfall event, for each of the housing typologies (left-to-right: detached, terraced, apartments).

tile and so require greater road surface to connect all the houses than in a terraced setting.

The apartments show a much lower peak runoff than the other two housing types. Whilst apartments have the greatest floor area per dwelling, these by nature are constructed vertically in the tile as well as horizontally, considerably reducing the overall footprint of a collection of apartments in the urban tile.

These patterns are also seen across all three design storm sizes, with peak runoffs increasing and lag times decreasing with an increased storm magnitude. This is to be expected from the increased intensities, and consequent volumes of water, that the scenarios must manage. However, some of the denser scenarios show less peak runoff in more frequent storm events than less dense scenarios under less frequent events. For example, the 40 houses per hectare density in a 1-in-2 year event has a lower peak runoff rate than the 30 houses per hectare in a 1-in-10 year event. This highlights the importance in appreciating a range of storm return periods for a development, which is an integral factor in current approaches to green and grey drainage design (Yazdanfar & Sharma 2015).

### *SuDS design*

The implementation of SuDS can affect the scenario hydrographs, regardless of the other features. **Figure 5** represents three urban tiles, and illustrates the impact of the different SuDS infrastructures in each. Compared to the baseline (non-SuDS) scenario, all SuDS implementations led to an increase in the lag time and, excluding green roofs, a reduction in the peak runoff. Post-rainfall, there are typically greater runoff rates in the SuDS scenarios than the baseline, due to the slowed rate at which the water passes through the tile with increased infiltration, percolation and throughflow processes. These slowed rates, and consequent low runoff periods, have important biodiversity and soil/groundwater recharge properties (Martin-Mikkle et al. 2015). Green roofs are the exception to this, not offering a reduction in the peak runoff rate, but increased lag time and a longer low flow period post-event can still be seen.

The specific type of SuDS deployed also shows a notable difference in the overall hydrograph shape, both in terms of peak runoff and lag time, as well as the runoff rates at other points during the event. This variation acts as an indication of the effects of different storage, drainage and infiltration properties of the different SuDS infrastructures. In all of the scenarios, however, the peak runoff rate is achieved by 120 minutes, which marks the end of the rainfall event. As with the baseline scenarios, the green roofs see a plateau at this peak rate due to a saturation of the tile. This response is due to the design of the rainfall events in the simulation, which see rainfall distribution across the 2-hour duration of the storm as uniform. This rainfall then ceases abruptly after the $120^{th}$ minute of simulation, and without additional water being added to the system, runoff volumes decrease.

Bioretention responses see a simple curve, much as with a basic hydrograph, featuring a rising limb to the peak runoff and then a falling limb. After this sharp fall in the runoff rates, there continues to be a low runoff from the tile with a much smaller second peak, as runoff slowed by the LID continues to drain from the tile post-event. As the implementation of bioretention is increased, as seen in **Figure 6**, the peak runoff rate is reduced and the lag time increased – a response seen across the housing types and densities. This is because bioretention promotes infiltration, and so with more bioretention area, more water can be infiltrated, reducing surface water runoff. In the low extent implementations, a peak runoff plateau is created, much as with the baseline scenario, and the peak runoff rate (caused by saturated ground and SuDS infrastructure, and the consequent surface runoff) persists until the rainfall event finishes.

In the green roofs response, there is an initial rise in runoff rates before a plateau is reached. This is as not all rain in the scenario will land on green roofs (and is not channeled from non-green roofs to the green roofs), and so this initial rate represents runoff from the non-green roof areas. From the first plateau, this is followed by a second increase in runoff rate to a second plateau. As the green roof LIDs become saturated, runoff is generated from these too, which causes the second increase in runoff rates, before levelling out at the second plateau – the peak runoff rate which represents saturated conditions and surface runoff.

Permeable surfaces also see a two-stage increase in runoff rates, with a dramatic increase between the first and the second. Then, following the rainfall event, runoff rates decrease sharply, followed by a secondary peak in the runoff. Whilst peak runoff rates decrease and lag times increase with increased permeable surface coverage, this secondary peak increases and occurs at a sooner period.

### *SuDS & housing design*

When we consider the influence of housing type and density, bioretention consistently offers the greatest peak runoff reduction, followed by permeable surfaces and green roofs. Between the apartment scenarios, bioretention in particular offers a noticeable difference between its peak runoff reduction and those of the other SuDS. This is a result of the significantly larger area bioretention can occupy in the urban tile, as the roof and road areas (the base areas for green roofs and permeable surfaces) are much smaller than the undeveloped land area (the base area for bioretention). However, bioretention also makes a noticeable peak runoff reduction in terraced scenarios and, to a much lesser extent, in the detached scenarios, also as a result of the relative areas of "undeveloped" land to roads/buildings.

Similarly, as the area of bioretention (at a given extent implementation) is decreased as housing density increases (see **Figure 7**), peak runoff rates are increased and lag times reduced due to the relative decrease in available SuDS infrastructure for infiltration, percolation and storage. Less water is also lost through evapotranspiration and interception by the vegetation. The same can be seen in the first plateau for the green roof scenarios. However, the second plateau remains unaffected, because it represents a saturated environment, with the roofs generating surface

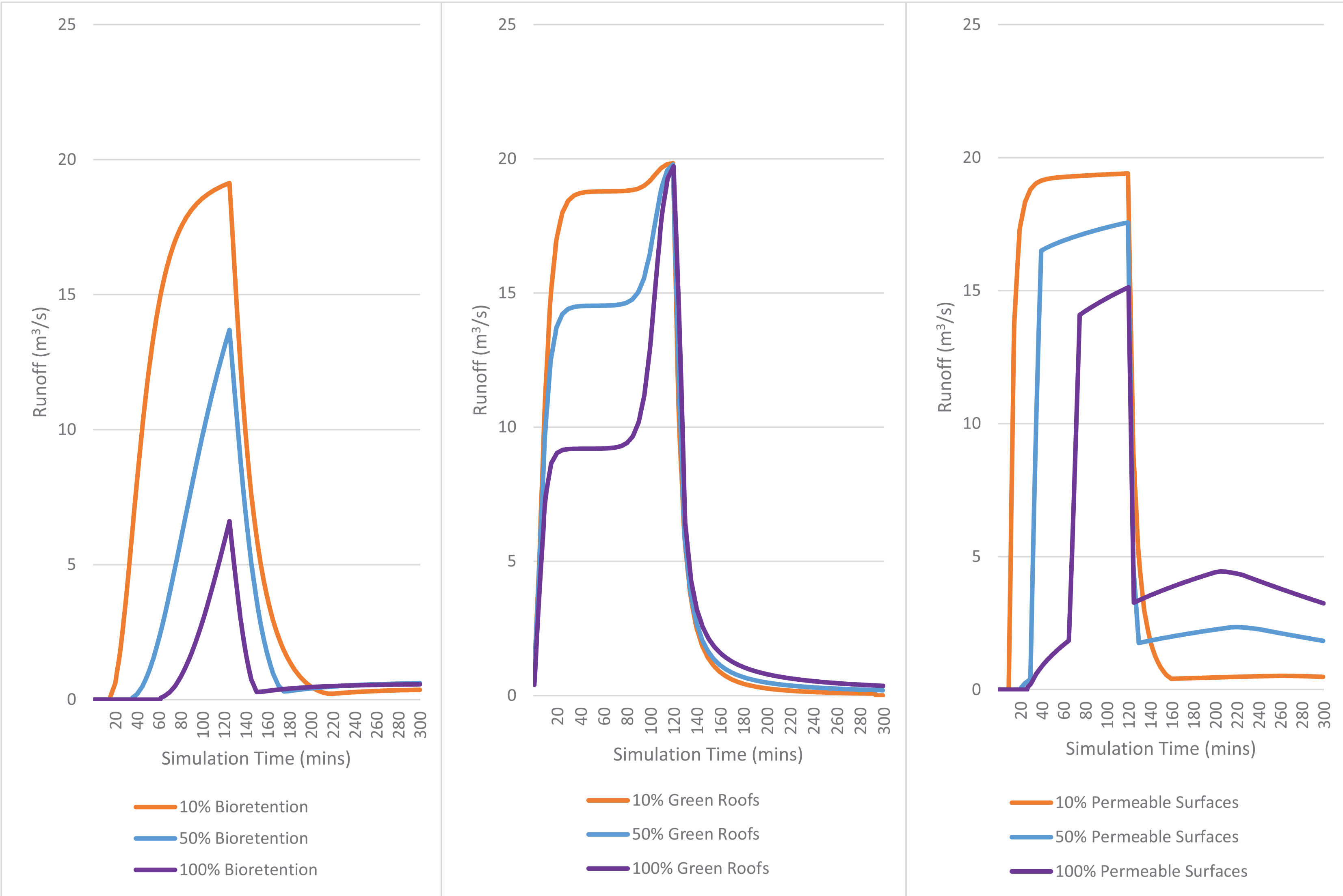


**Figure 6:** Influence on the runoff hydrograph of the extent coverage of a SuDS infrastructure (i.e. the proportion of maximum potential area covered) on the runoff hydrograph of a 1-in-5 year, 2-hour duration rainfall event on a 1-hecatre tile at 30-detached-houses-per-hectare.

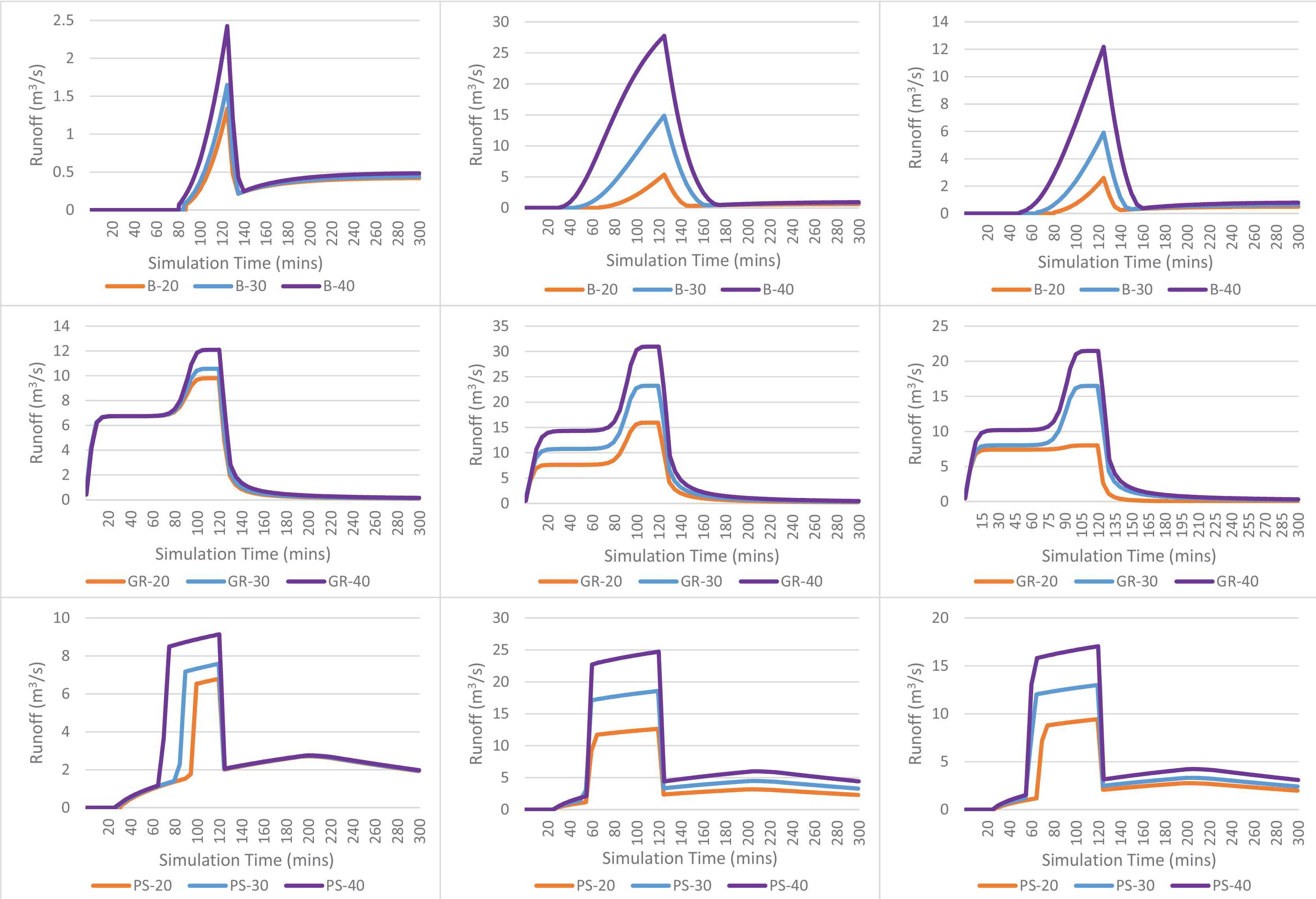


**Figure 7:** The impact of housing density (20-,30-,40-houses-per-hectare) and type (left to right: apartments, detached, terraced) on the hydrographs of a 1-hectare tile under a 2-hour duration, 1-in-5 year storm event with the maximum potential implementation of different SuDS infrastructure (top to bottom: bioretention, green roofs, permeable surfaces).

runoff, and so the same total runoff rate will be reached as this is dependent on the magnitude of the rainfall event.

Additionally, with permeable surfaces, we also see differences in lag time between the different densities. Whilst across the permeable surface scenarios runoff rates begin to increase around the 20-minute mark (the point at which non-SuDS scenarios begin their peak runoff plateau), the start of the peak runoff plateau in all densities and housing types occurs later when permeable surfaces are present, ranging between 55 and 96 minutes duration. This is due to the greater proportion of permeable surfaces in the scenario (whether natural or SuDS) that encourage infiltration (and resultant percolation), throughflow and groundwater recharge. These processes slow the transport of water through the tile, increasing the time taken for significant volumes of runoff from the tile to occur.

The two-stage response of green roofs and permeable surfaces raises a point of note in some scenarios. In both the terraced and detached housing types, the permeable surfaces reach their second peak plateau before that of the green roofs, which could create challenges on the ground. Undesired build-up or runoff of surface water could occur at an earlier timeframe in the permeable surface scenario than the green roofs, despite the absolute peak runoff rate being reduced to a greater extent in the former.

Equally, we find that in some scenario designs, a lower implementation of one SuDS has a greater impact on reducing peak runoff than a higher implementation of another. This can be seen, for example, with the 50% bioretention extent, which boasts a lower peak runoff than the 100% extent of both permeable surfaces and green roofs in the same scenario. Whilst this is to be expected, given that the area covered by 50% bioretention is greater than that of 100% green roofs, this can have important implications for the design and planning of green infrastructure interventions, where less can actually do more. It is unrealistic to assume that all building- or land-owners will be willing, or able, to adopt green technology on their property. Therefore, identifying scenarios with a more realistic coverage (such as 50%) that outperform those with a greater extent can be useful in considering how such developments can realistically be achieved in the real-world.

## Discussion & Conclusion

The management of stormwater in cities is becoming increasingly important as dual pressures from urbanisation and climate change look to exacerbate existing issues (Yazdanfar & Sharma 2015). Whilst several significant stormwater flooding events worldwide have raised formal calls for increased appreciation of the urban water nexus, such as the UK's Pitt Review (2008), there has been little research into how features and design of the urban environment impact upon the potentials for, and responses of, SuDS elements. Using an urban-tile approach, different urban designs were simulated using SWMM to identify the impacts of different features on the hydrograph response. These included changes to urban design, housing design and the design of the SuDS.

It was found that runoff from the tiles was affected by both the type and the extent implementation of SuDS elements, which were in turn influenced by the type of development and its density. That is to say that in denser scenarios, infrastructure-based SuDS resulted in a greater reduction in peak runoff rates and increased extension of the lag time, as the maximum areal extent for the implementation was increased. It is also the case that the inverse is true for freespace SuDS, which see a decreased maximum potential extent with increased density. This supports the findings of Jia et al. (2019), who identified changes in runoff dynamics due to varying spatial layouts of urban neighbourhoods attributed to changing proportional requirements of road, greenspace and other infrastructure.

All three SuDS elements led to an increase in the lag time compared to a baseline (non-SuDS) scenario, and this increased with increased extent implementation. Bioretention and permeable surfaces also led to an overall reduction in the peak runoff rate, but due to tile saturation, this was not achieved with the green roofs intervention. Bioretention consistently offered the greatest reduction in peak runoff for a given scenario, with the greatest magnitudes in peak runoff reduction seen in the terraced and detached scenarios as the differing densities resulted in a larger change in the permeable-impermeable surface ratio.

With the type and footprint area of both houses and SuDS elements influencing the shape and magnitude of the response to rainfall events, it is clear that how we build our urban environments is as important a consideration as what we build when we consider the influence on urban hydrology. This goes to reinforce the findings of Sörensen et al. (2016), who argue that the dynamics of a catchment response need to be considered when designing flood management responses, not just overall figures of peak and total runoffs from large-scale events.

Understanding the impacts of urban design on SuDS performance can support the increased role and efficiency of these infrastructure in developments where they occur. Just as design components of the infrastructure themselves can determine relative performance in flood mitigation, the design of the urban environment in which they are located has an influence, too. Thus, acknowledgement of this relationship in policy guidance and standards, alongside resultant good practices, is important for communicating such information to the planners and developers ultimately responsible for implementing the systems. In England, and formerly Wales, large-scale developments that can prove SuDS to be disproportionately expensive when compared to traditional drainage are exempt from the SuDS requirements of the NFWMA (Ellis & Lundy 2016). Findings from this study, such as the improved performance of low SuDS extents in higher densities over higher deployment in lower densities, however, could alter design approaches, leading to lower proportional SuDS requirements, creating less of an economic burden – whether perceived or real.

Whilst a 100% implementation of a SuDS infrastructure was modelled in the study, it is not realistic to make such an assumption for the uptake in reality. Realistic potentials would vary on a case-by-case basis for both the type of

SuDS and the catchment itself, and therefore are development-specific. It is also probable that developments involving SuDS will use more than one type of SuDS element – it is how they are currently designed – and so future modelling studies should look to understand how multiple SuDS may interact under differing urban conditions. The investigation of post-event dynamics are important too, as illustrated in this work, and should therefore also feature as an important part of drainage system modelling.

Furthermore, as has already been illustrated through a vast range of work (see Fletcher, Andrieu & Hamel 2013; Liao, Deng & Tan 2017; Weiss et al. 2017), the design of specific SuDS elements has a significant impact on their ability to infiltrate, evapotranspirate, store, and filter rainfall events. Whilst figures for this research were drawn from recommendations and best practice guidelines, such as CIRIA (2015) and Department for Transport (2007), altering element design will have its own impacts on catchment response that will be important to consider in the drainage network design. The scenarios presented in the research are also idealised in relation to soil permeability and SuDS design. The natural permeability of the local soil profiles, as explored by Bach et al. (2013) and Kanso et al. (2019), significantly influence the performance of SuDS infrastructure, and as such local soil conditions contribute to the choice of SuDS infrastructure in developments. SuDS that rely on the infiltration rates of local soils, such as bioswales, are thus not employed in areas with poor soil permeability, such as clay soils, where they would be unsuitable (Kanso et al. 2019).

There is also the need for future work to consider greater storm sizes. A range of design storms were chosen in this study up to the 1-in-10 year magnitude, since this is typically the size used to design greywater systems in order to avoid huge infrastructure dimensions and potential system overbuild. However, an appreciation of how a system may react to larger events, or multiple events in quick succession, is important for additional response and planning considerations (Sörensen et al. 2016), especially under current climatic change predictions.

Developing this approach further, there is a need to identify what proportion of the runoff is surface, and what is subsurface, as this divide will have important consequences for flood management. From this, greater spatial analysis could also help identify whether the surface runoff is uniform across the catchment, or whether particular design approaches cause concentrated areas of surface water flooding.

**Appendix 1:** Summary of SuDS parameters used in the SWMM simulations. Design factors were based upon guidance in the CIRIA SuDS Manual (2015) and default values used for other parameters based upon the model manual (EPA 2016).

| Parameter | | Bioretention | Green Roof | Permeable Paving |
|---|---|---|---|---|
| Surface Layer | Berm height (mm) | 45.00 | 20.00 | – |
| | Vegetation volume fraction | 0.05 | 0.05 | – |
| | Roughness (Manning's n) | 0.14 | 0.24 | 0.012 |
| | Surface slope (%) | 0 | 0 | 0 |
| Soil Layer | Thickness (mm) | 300.00 | 80.00 | 50.00 |
| | Porosity (volume fraction) | 0.412 | 0.464 | 0.26 |
| | Field capacity (volume fraction) | 0.20 | 0.20 | 0.20 |
| | Wilting point (volume fraction) | 0.10 | 0.10 | 0.02 |
| | Conductivity (mm/hr) | 119.40 | 119.40 | 118.00 |
| | Conductivity slope | 45.05 | 45.05 | 27.00 |
| | Suction head (mm) | 49.80 | 49.80 | 3.50 |
| Pavement Layer | Thickness (mm) | – | – | 80.00 |
| | Void ratio | – | – | 0.26 |
| | Impervious surface fraction | – | – | 0.10 |
| | Permeability (mm/hr) | – | – | 400.00 |
| Drainage Mat | Thickness (mm) | – | 25.00 | – |
| | Void fraction | – | 0.50 | – |
| | Roughness (Manning's n) | – | 0.30 | – |
| Storage Layer | Thickness (mm) | 150.00 | – | 350.00 |
| | Void ratio | 1.00 | – | 1.00 |
| | Seepage factor (mm/hr) | 4.00 | – | – |

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The authors have no competing interests to declare.

## Author Contributions
C. Chapman designed the presented study, performed the modelling and analysis, and wrote the paper. J. Hall supervised the work, providing critical feedback and helping to shape the research, analysis and manuscript.

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