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Using a Model to Investigate the Effects of SuDs in a Highly Urbanised Area

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Abstract:
With urbanisation and climate change on the rise, urban areas are becoming more prone to pluvial flooding events due to increased surface flow going into drainage systems. A significant investment is required to mitigate the increase in the risk to urban flooding which currently puts 325 thousand homes at risk. Sustainable Urban Drainage System (SuDS) has been implied to be an effective tool at mitigating flood risks but their uptake in highly urbanised areas is low due to a lack of understanding and trust in SuD projects. The aim of this study was to create and use a model to simulate the effects of different SuD applications in a highly urbanised area as well as reviewing relative literature to analyse the contamination mitigating effects SuDS hold. In this study, green roofs were found to be the best independent system for mitigating flow, but a multiple SuD system was seen most suited with both its impressive flow and contaminant mitigating capabilities. The study concluded that SuDS could be a viable option to help mitigate the damage of floods in developing urban cities but that further modelling, research and SuD development will be required to effectively combat the current and future impact of pluvial flooding.

Keywords: Urbaneisation, Climate Change, Drainage system, Flooding, Contamination

1. Introduction/ Background

Worldwide populations are increasing at a rapid rate and are predicted to continue rising until 2085 (Macrotrend, 2024). The current rate of population growth is 0.9% annually and will remain a positive figure for another 60 years. At its peak in 2085, the global population is predicted to rise to 10.43 billion. In the UK, the increase in population has also been on an upwards trend with an increase of 609 thousand in 2023 alone (Office for national statistics, 2024). The increase in population will require more infrastructure such as housing, transport and essential facilities leading to a greater loss of natural ground.

Studies on the relation between urbanisation and increased flooding events (Braud et al., 2013; Huang et al.,2008) reveal that an increase in urbanisation due to rising populations have led to more flash flood events with higher peaks and shorter duration to peak due to the reduction in naturally infiltrating ground.

Urbanisation has led to more cars, streets, homes and other aspects of regular urban areas being created. (Goonetilleke, 2016). Urban areas could hold more than 10-100 times greater contamination loads than its rural counterpart (Sonzogni et al.,1980). Increased dry spells between rainfall events are also leading to greater sedimentation build up and larger concentrations of contaminants in runoffs (Sämann et al.,2019). As a result, the number of contaminants being moved and flushed around and leaking into groundwater have increased.

Climate change has been a heavily researched topic in recent decades especially with its effect on rainfall events (Ahmad Tarmizi et al., 2019; Met Office, 2022; Hanlon et al., 2021) and urban water environments (Deng et al., 2023; Praskievicz & Chang, 2009). Rainfall events are becoming harder to predict and are of a different nature in comparison to previous years. The occurrence of short duration, high intensity storm events are on the rise (Osborn & Hulme, 2002). These Intense rainfall events are predicted to increase annually with increased flash flood events expected to increase by 3.5x by 2080 in high emission scenarios. This change in the weather cycle and rainfall characteristics cause issues for drainage systems with increased surface water run-off leading to higher risks of pluvial floods (Deng et al., 2023; Praskievicz & Chang, 2009).

2.0 Literature Review:

2.1 Surface Runoff

Surface water runoff is defined as water flow over the surface of roofs and ground surface to a drainage system (BRE Group, 2022). With increasing rates of urbanisation and climate change, there has been a stark increase in the amount of surface water runoff observed due to increased rainfall events as well as less natural ground for water to natural infiltrate into (Ahmad Tarmizi et al., 2019; Braud et al., 2013). Due to these factors, urban drainage systems are becoming more prone to pluvial flooding with increased quantities of water entering stormwater drainage systems. In drainage design, they are constructed to be able to manage a specific year return period flood depending on the country and area. This is usually known as a 1-in-T year event and correlates to the likeness of that quantity of flood to occur (Tonn & Guikema, 2020). For example, a 1-in-100-year flood is a flood which has a 1% chance of occurring. However, due to these increased rates of surface water runoff because of a reduction in pervious ground and climate change, these predictions are becoming inaccurate, and drainage systems are more frequently being overloaded and causing pluvial floods.

2.2 Sustainable Urban Drainage System

Sustainable Urban Drainage Systems (SuDS), sometimes referred to as Low Impact Developments (LID), are a progressive approach to urban drainage challenges. SuDS move away from the standard pipe-based drainage process that traditional drainage systems use which focuses on moving large volumes water away quickly and transporting them through sewers to nearby watercourses (Upaka Rathnayke & Uvini Srishantha, 2017). SuDS create a more natural approach utilising natural processes such as infiltration, evapotranspiration, filtration, and retention to reduce flow. By mimicking these natural processes, SuDS can reduce time for peak flow to occur, as well as minimising peak flow which decreases the likelihood of flooding events. They are environmentally beneficial, causing minimum or no long-term detrimental damage. This is due to their holistic approach to drainage issues which go further than just water quantity but also consider issues such as water quality and biodiversity (Stephenson, 2008).

SuD systems can be comprised of different component parts which may include green roofs, permeable pavements and swales as utilised in the present study. Each of these SuDS have distinctive effects on the flow and as such, their properties are relevant to the present study and will be reviewed below. The introduction of SuDS in a highly urbanised area is a complex process which relies on the systematic introduction of reliable information which requires a putative representation of the urban drainage system prior to running simulations utilising SuDS in the system. Both processes require modelling to accurately predict behaviour of SuD configurations (Ferrans et al 2022).

2.2.1 Green Roofs

A green roof is a SUD technique which is becoming more utilised in urban spaces due to its ability to reduce flow and delay runoff. Previous research has shown the effectiveness of green roof to reduce peak flow and time to reach peak flow. Green roofs consist of 4 layers, vegetation on the surface that initially intercepts rainfall, substrate/soil which acts as storage as the water infiltrates and provides nutrients to the vegetation and allows for evaporation, filter membrane which prevents substrates/soil entering the drainage layer, drainage layer which acts as extra storage and is where excess water runoff occurs (Stovin et al., 2007). The thick vegetation also increases the surface roughness which in turn, reduces the flow of the runoff providing extra delaying and infiltration benefits (Ercolani et al., 2018).

Stovin et al. (2007) exposed green roofs to 9.22mm of rainfall resulting in only 3.55mm runoff, a 61% reduction. On average the green roof was able to retain 34% of rainfall and a reduction of 57% peak flow. It was also recorded that the green roof performed better after long dry weather spells as it allowed for storage in the substrate to be evaporated or drained. This research is effective in showing the potential flow mitigating qualities that green roofs can have in urban areas. However, they do not take into consideration intense rainfall events leaving answers to their applicability in intense storm events. Thus, this paper does not provide a clear insight into green roofs capability to mitigate the damage of changing weather scenarios caused by climate change. Work by Lee et al. (2015) found that green roofs could mitigate flow by 13.8- 60.8% and determined that substrate depth

had a major factor in its mitigating ability. It also found that changing the substrate also effected the delaying capabilities with less storage being available for use. Thicker substrates were found to reduce flow by 42.8-60.8% compared to only a 13.8-34.4% decrease when using thinner substrates. Moreover, the applicability in urban areas was examined, due to their location on roofs, green roofs minimise the reduction in public space. Especially in urban and heavily urban spaces, many flat roof constructions are used with large buildings such as offices, warehouses and residential blocks. Sample data from structural appraisal of a range of flat roof types suggests that retrofitting a green roof will be a feasible option in many cases. Moreover, many concrete roofs will have significant spare capacity, even allowing for the installation of intensive green roofs (i.e. deeply planted vegetation) or wetland features (Stovin et al., 2007; Locatelli et al., 2014) but some roofs may need lightweight steel- and timber-framed structures for support.

2.2.2 Permeable Pavements

Permeable pavements are a SuD method used primarily in areas with limited space for traditional drainage infrastructure due to its ability to replace traditional grey space and be accessible to the public for commuting via walking, cycling or driving if traffic is lightweight or slow moving (Xie et al., 2019). Permeable pavements refer to paving materials such as porous concrete, porous asphalt, interlocking pavements or grid systems, which allow all or part of the rainwater to infiltrate into the permeable medium. The permeable medium will either work as a reservoir or act as an infiltration system to a recipient, such as a basin or pipe system, making them effective in reducing runoff volume and peak flow (Muttuvelu et

l., 2022; Zhou et al., 2024). When the water is infiltrated into the basin or permeable medium, the water will be removed via evaporation.

A study conducted on two types of pervious pavements was conducted by Jayasuriya and Kadurupokune (2010). The experiment followed the construction of a small parking area and included a conventional asphalt surface, a pervious pavement and a turf coverage pavement type.

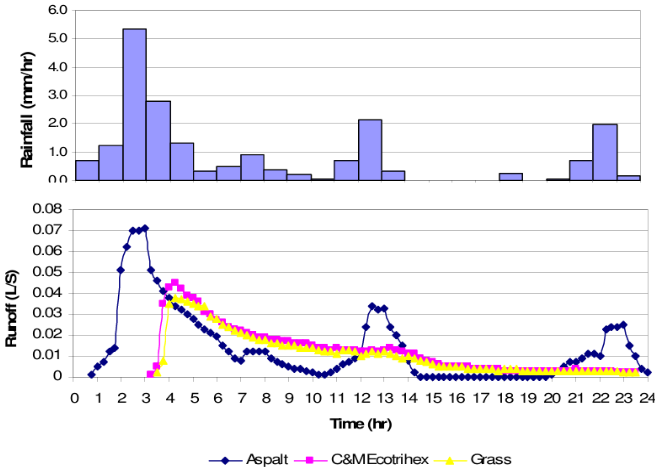


Figure 1: Runoff hydrographs produced by the Asphalt, C&M Ecotrihex and Atlantis turf cell pavements (Jayasuriya & Kadurupokune, 2010)

Figure 1 shows the hydrographs produced from the project via the different surfaces. The experiment conducted that the C&M Ecpthrihex pavement was able to reduce the peak flow by 40-55% as well as increase time to peak in ranges from 30 to 165 minutes. The maximum rainfall recorded in this study was 25mm in a 24-hour period with a max intensity of 5.3mm/hr.

2.2.3 Swales

Swales are a shallow vegetated channel with gentle sloping sides which allows for lateral flow and longitudinal flow to enter the swale. The runoff is then conveyed through the swale and flow is reduced by the thick vegetation within the swale which increases the roughness of the surface. Some of this runoff is then evapotranspirated as it is conveyed down the channel with evaporation occurring as well as infiltration into the soil (Bhat et al., 2024). With these factors in mind, swales are often seen as an effective choice near parking areas and paths due to their long length and increased lateral inflow capabilities. The goal of swales is to achieve a hydrologic landscape that is functionally equivalent that matches predevelopment conditions. This is done by ensuring they are constructed in areas with good infiltration capacity soil to encourage effective filtration. It is also essential that swales are placed in locations where there is enough area for proper channel dimensions and slopes (Davis et al., 2012).

Rujner et al. (2016) constructed a field study on a grassed swale located in a city centre in the north of Sweden looking at the effect of the relative moisture of the soil on outlet flow compared to inlet flow.

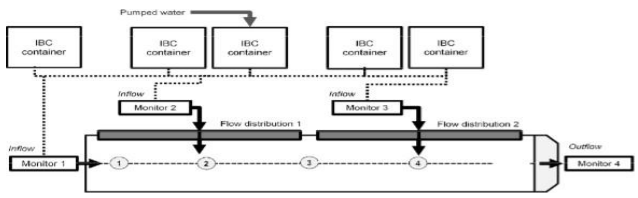


Figure.2: Schematic overview of the swale and the water supply system (Rujner et al., 2016)

Figure 2 shows the layout of the project with the circles labelled 1-4 being soil moisture probes. The swale was exposed to 3 different rain scenarios. A 0.5-, 1- and 2-year storm event equalling to 13.5mm/h, 17.6mm/h and 30.3mm/h, respectively. The results showed that peak flow and volume could be reduced by up to 40% in smaller flow events as well as reducing time to peak flow. Moreover, a correlation was observed between the swales soil moisture level and its effectiveness, with dry conditions improving performance. During the high flow event, the effectiveness of the swale greatly decreased to only 8%. In addition, a rapid baseflow was observed after 9-10 minutes, which shows that the swale had lost its flow delay due to saturation.

2.2.4 SUD Trains

SuD trains (sometimes referred to as management trains) are becoming more frequently used in new projects compared to the traditional single purpose drainage systems. SuD trains utilise a sequence of different stormwater practices and technologies that work and complement each other. The primary aim of SuD trains is to keep water within the SuD systems for as long as possible to maximise flow reduction and delaying flow being released into a watercourse or drainage network and thus reducing stress on them (Maqbool & Wood, 2022). SuD trains are broken down into three main stages. Source control where water is managed immediately after rainfall to reduce flow and generate catchment lag. Site control which entails managing runoff from multiple source control devices which has not been absorbed or evaporated. Finally, there is regional control which manages large volumes of runoff.

Table.1: The peak flow (L/s) of each designed drainage system and the percentage difference of each SuDS system compared to conventional drainage (Lashford et al., 2014)

Drainage system	Peak at outflow (L/s)	% Reduction in outflow comparison to conventional drainage	Time to peak (min)	Time to base flow (min)
(A) 1 in 100 years 30 min winter storm scenario				
Conventional	1100.3		21	63
Swale	778.1	29.3	28	235
Green roof & swale	699.3	36.4	28	255
PPS & swale	569	48.3	26	199
Green roof, PPS & swale	550.3	50	26	218
Swale & det. pond	137	87.5	25	399
Green roof, swale & det. pond	133.1	87.9	25	394
PPS, swale & det. pond	126.1	88.5	25	281
Green roof, PPS, swale & det. pond	124.8	88.7	25	283
(B) 1 in 100 years 360 min winter storm scenario				
Conventional	285.6		188	384
Swale	282.7	1	191	542
Green roof & swale	278	2.7	194	553
PPS & swale	165.1	42.2	190	507
Green roof, PPS & swale	164.1	42.5	191	514
Swale & det. pond	110.4	61.3	220	675
Green roof, swale & det. pond	109.6	61.6	222	679
PPS, swale & det. pond	91.1	68.1	203	508
Green roof, PPS, swale & det. pond	90.9	68.2	205	519
(C) 1 in 100 years 720 min winter storm scenario				
Conventional	173.2		369	741
Swale	171.9	0.8	373	891
Green roof & swale	171.2	1.2	374	899
PPS & swale	100.3	42.1	370	856
Green roof, PPS & swale	100.6	41.9	372	862
Swale & det. pond	101.4	41.5	437	904
Green roof, swale & det. pond	101.3	41.5	445	911
PPS, swale & det. pond	78.9	54.4	388	856
Green roof, PPS, swale & det. pond	79.1	54.3	398	864

The findings of the research are displayed in Table 1, showing that the use of a combination of green roof, permeable pavements, swale and detention ponds are the most effective. A total flow decrease of 88.7% in a flash flood event was observed as well as an increase in the time to reach

peak flow.

Table 2: Total volume of each SuDS device modelled at Prior Deram Park (Lashford et al., 2014)

SUDS device	Total volume (m^3)
Swales	728.7
PPS	760.68
Detention ponds	6890
Green roofs	2024

As shown in Table 2, detention ponds take up a large amount of area especially in consideration of other SuD devices. This makes them hard to use in heavily urban areas, as explored in the current study, due to the lack of available open space (U.S Environmental Protection Agency, 2022).

2.4 Similar Framework

Research conducted on heavily urbanised areas are very limited but, Jato-Espino et al. (2016) evaluated the effectiveness of SuDS in mitigating flooding in highly urbanised catchments using Geographic Information Systems (GIS) and SWMM in Donostia, Spain. The research simulated rainfall-runoff scenarios on the current drainage system and with urban friendly SuDS. The SuDS utilised were green roofs and permeable pavements due to them being easy to integrate in cities as they can be used in areas such as parking areas and buildings.

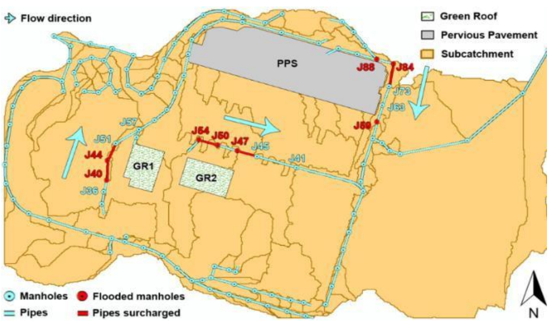


Figure 3 Layout of sub catchment areas, flooded nodes, pipes surcharged and SuDs (Jato-Espino et al., 2016)

Figure 3 shows the layout of the drainage system including the SuD devices. The nodes which surcharged in the current drainage system were analysed and the change in flow was measured as well as volume reduction throughout the system. Each SuD was individually analysed as they were in different areas of the drainage network.

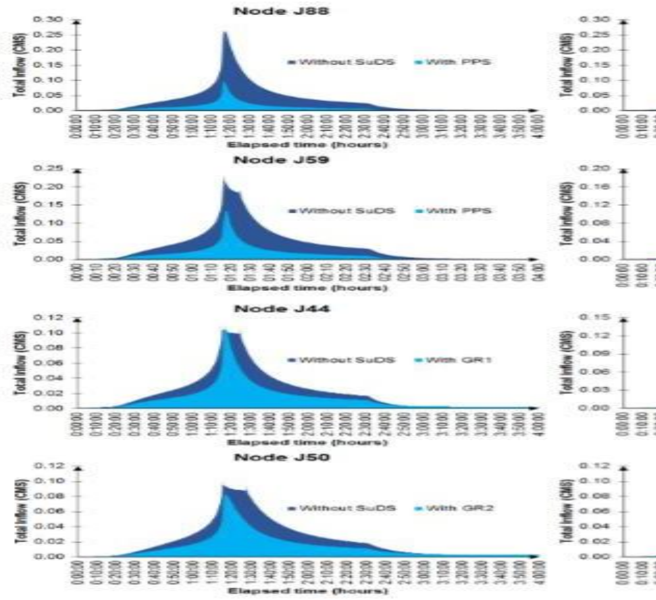


Figure 4 Inflow hydrographs of the originally flooded nodes, before and after installing SuDS (Jato-Espino et al., 2016)

Figure 4 shows the influence each SuD had on flow with permeable pavements being shown to be the most effective with a peak flow reduction of 65% while the green roofs largest reduction was 47%.

This study shows how SuDs can be effective in a highly urbanised area but there are significant limitations. They do not consider the effect each of the SUDs have on the overall system instead only focusing on its effectiveness on nearby nodes. They also do

not consider the use of the SuD systems working collaboratively and instead focus on individual performances of the SuDS. Finally, they do not take into consideration the effect the SuDS may have had on mitigating the contaminants found in urban settings. However, this research still holds valuable information in creating increased understanding of the potential effectiveness of SuDs in high urban area.

3. Research Methodology

A mixed method deductive approach has been chosen for this project using primary and secondary data. The quantitative data consisted of the creation of a drainage system model using SWMM software to analyse the change in flow through the system with different SuD applications. The qualitive data entailed a scoping secondary data review which will be analysed to build an understanding of the possible contaminant mitigating properties of SuD systems. These results will then be combined and compared to determine what SuD methods are suitable for the scenario.

3.1 Quantitative Study Methodology:

3.1.1 Site

Figure 5 Study cite in reference to London (left) and Study Site (right) (Google Maps, 2019)

The study focused on the 0.11km^2 area around Queen Anne's Street in Marylebone, Central London (528633, 181527 National Grid). This location was chosen as London is the most densely populated and fastest growing cities in the UK with 40.6% developed land use as well as the population of Inner London seeing an increase of 27% between 2001 and 2019 (Government Office for Science, 2021). In 2021, London suffered 3 pluvial flooding events on the 13th, 17th, and 25th of July (Greater London Authority, 2022). The floods left major infrastructure such as the underground lines and stations flooded and unusable causing major disruption and economic costs. Aggregate insurance claims were estimated to have totalled around £100 million (JBA Risk Management, 2024). Queen Anne's Street has specifically been chosen due to its heavily urban nature with minimum

green space. A heavily urban region has been chosen as an extreme case scenario of an impervious populated area.

3.1.2 Model Application

Modelling was the chosen method to analyse the effectiveness of flow mitigation due to it being a more cost effective and more material effective approach then lab testing. Also, it is impossible to flood a city to obtain experimental data thus modelling is the best way to test the system. Modelling also allows for large networks to be tested and adjusted quickly and efficiently to find the best configuration for flood mitigation. For the study, EPA Storm Water Management Model (SWMM) 524 was chosen due to its wide range of LID development tools which allows for more accurate and precise SuD applications. It is also the most used drainage software for SuD modelling research (46%) making it the dominant software in its field (Ferrans et al., 2022). Digimaps was partnered with the SWMM software to determine pipe lengths, catchment areas and changes in depths

3.1.3 Model Design

Figure 6 Drainage Network Layout

A new dual drainage system was constructed due to its common use in London and in urban areas. Dual drainage systems consist of two sections, the major network and minor network. The major network is the surface network including roads and streets and the minor system is the subsurface network mainly made up by pipes. These systems are connected via inlets which allows water to move from the major network to the minor network. The dual drainage system was constructed using The Building Regulations 2010: Drainage and Waste Disposal Approved Document H (HM GOVERNMENT, 2010). The main segments followed was the max length between manholes being 90m and 0.425m concrete pipes. The dual drainage model is made up of roads as the major network and pipes as the minor network. Roads were designed using Manual on Streets (Department for Transport, 2007). Inlets were placed automatically by SWMM in ideal locations. The system was treated as a single system and did not incorporate flows from other drainage systems. Two outfalls are located at the end of the project, one for the major flow and one for the minor flow. The outfalls have been assumed to discharge into the greater London sewer network due to the lack of proximity to rivers or water storages. The site holds 6

sub catchments which have been placed over residential areas and are assumed to be heavily impervious due to a lack of any green space in the area.

3.1.4 SUD Applications

Three SuDS have been selected for use in this study. Green roofs, swales and permeable pavements. Green roofs and permeable pavement were chosen as they are easier to apply in urban areas due to them utilising already urban areas (roads, roofs) (Jato-Espino et al.,2016). Swales were chosen as they can be utilised in urban areas but require more research in their use in heavily urban areas due to their increased size needs.

Each SuD system was created using SWMM's LID Editor and used the LID Editor guidelines for dimension specification (U.S Environmental Protection Agency, 2022) in partnership with relevant design codes and standards The green roofs have been located upon the top of the residential areas and are assumed to take up 50% of each subcatchment

due to the extensive area of roofs available. There are no specific regulations for constructing green roofs in the UK, so design was based on specifications in the Gro Green Roof Code produced by the Green Roof Organisation (2021). The permeable pavements used was a porous concrete pavement and are in the grey space within the residential areas (parking areas, through roads) and are assumed to take up 20% of each subcatchment and were designed under the BS 7533-13:2009 (The British Standards Institution, 2025) regulations. Swales have been chosen to take up available pavement space on the model. There are no British Standards for the design of swales so the S104 SUDS Guidance Document (United Utilities, 2022) was utilised for the designing of the swales. Despite the proposed location of the swales being outside the subcatchments, for simulations it will be assumed to be inside the subcatchments and take up 10% of the total area. (See Appendix B for SuD design values)

3.1.5 Data Collection

5 different configurations of drainage methods will be simulated

- Baseline
- Green Roofs
- Permeable Pavements
- Swales
- Green Roofs, Permeable Pavements, Swales (Multiple SuDs)

The network was designed to not surcharge in the flash storm event to ensure flow reduction can be accurately recorded. Conduit 25 is connected to the outfall of the minor system and will be used to measure the change in flow of each configuration. This conduct has been chosen as it is the final pipe in the network so it will provide a good oversight of the effects of the SuDS through the entire system. Each simulation will run for 24 hours with the first rainfall occurring two hours into the simulation. The data obtained from the simulation will be placed in an excel sheet and the flow hydrographs will be produced. The peak flow of each SuD configuration will be compared to the peak flow of the baseline

simulation. Percentage decrease compared to the peak flow of the baseline simulation will be used to determine effectiveness of flow mitigation of each configuration. The calculation used for this will be:

$$\frac{Peak\ Baseline\ Flow - Peak\ Scenario\ Flow}{Peak\ Baseline\ Flow} \times 100 = Flow\ reduction(\%)$$

The shape of the hydrographs will also be analysed to discuss flow characteristics such as flow delay. Time steps of one minute were selected for this project to ensure increased data accuracy. This was chosen as when using long time steps, key events (such as peaks) may not be recorded or analysed (Chiwater, 2009). The downside of small-time steps is increased analysis time and file size however due to the short analysis duration and the size of the model; these factors have minimal influence. Dynamic Wave was also chosen over Kinematic Wave due to its ability to effectively analyse factors using one-dimensional Saint Venant flow equations, which consist of the continuity and momentum equations. This method produces the most theoretically accurate results for flow in closed conduits (Autodesk, 2024).

3.2 Qualitative Study Methodology

SWMM software can conduct analysis of contaminants within a drainage system. However, build up and wash up algorithms utilised by the model are gross simplifications of the real heterogeneous physiochemical processes at play (Niazi et al., 2017). On top of this, the location and movement of contamination is heavily dependent on-site conditions and topography meaning accurate analysis can only be conducted when constant site monitoring is taking place, and a suitable GIS is produced. As there was a lack of site data and GIS unavailable, secondary research was chosen to be better suited for this study.

A scoping review of different case studies and laboratory studies published after the year 2000 will be reviewed. Key words such as "physical contaminants", "chemical contaminants" and "contamination mitigation" was used to find relative literature. Values and trends in data will be reviewed and correlations discovered to determine if each SuD has a positive or negative effect on contamination loads. The contaminants will be split into physical and chemical contaminants. When looking for physical contaminants, TSS and turbidity will be the focus and for chemical contaminants, Total Nitrogen (TN) and Total Phosphorus (TP) will be the main factors reviewed. This has been done to provide a better comparison compared to listing all the possible contaminants which can affect urban runoff.

4. Results and Discussion

4.1 BASELINE

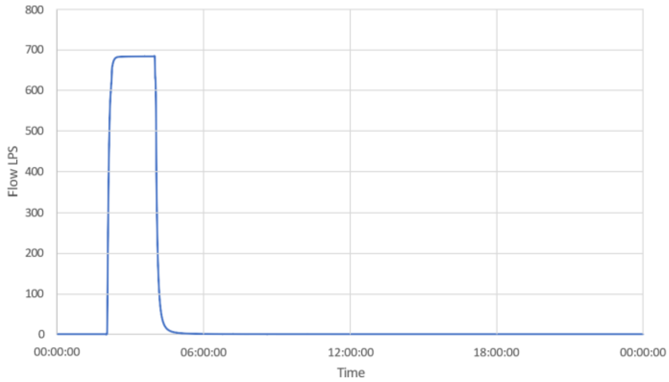


Figure 7: Hydrograph for baseline simulation

The baseline simulation with no SuD solutions showed a very steep spike at the start of the rain event. The system saw a peak flow of 683.04 LPS which is extremely high for an urban drainage system. Flows of this quantity can cause pluvial flooding events due to drainage systems overflowing as well as potentially leading to damaging drainage infrastructure. Figure 4.1 shows a constant flow after the initial spike highlighting the lack of delay features in urban drainage systems which further increases their risk of overflowing. This baseline simulation will be used as a comparison to the other drainage systems.

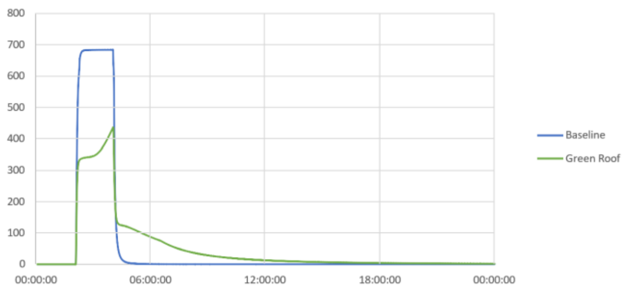
4.2 SUDS

4.2.1 Green Roofs

In comparison to the baseline, the peak flow has been reduced by 36.27% as well as the time to reach the peak flow being increased. From the hydrograph (Figure 4.2) a significant reduction can be seen at the initial flow compared to the baseline scenario. This has occurred due to the green roofs ability to infiltrate water though their system and keep it as storage. Green roofs do this by having multiple permeable layers which allows for water infiltration through the system (Stovin et al., 2007). Firstly, they have a thick growth of vegetation which increases the roughness coefficient of the surface compared to a conventional concrete roof (Ercolani et al., 2018). The increase in roughness coefficient creates a reduced velocity/flow and allows for the system to have an increased contact time and allows for more opportunity to infiltrate into the system. The substrate below has voids/pores which allow the water to infiltrate into it and be stored in the system. The water in the substrate is then either evaporated out and back into the atmosphere, gets absorbed by the vegetation as nutrients to allow for continued growth, or seeps out the bottom of the substrate through the drainage mat and into the drainage pipe below.

These factors allow for the green roof to reduce the flow in the system and to reduce surface flow that can cause flooding risks in the urban drainage system (Tonn & Guikema, 2020).

After the original spike, a gentle curve can be analyses as it reaches the peak flow of the event. This highlights the green roof’s ability to attenuate and delay flow. Once infiltration has been completed, all the water that is not evaporated or absorbed by the vegetation seeps out the bottom of the substrate and into the drainage system which then disposes the water back into the greater urban drainage system (Lee et al., 2015). After this, a second spike is noticed as the water leaves the system. However, after this spike a small gradual curve can be further noticed which further confirms the green roofs flow delaying capabilities.



4.2.2 Permeable Pavements

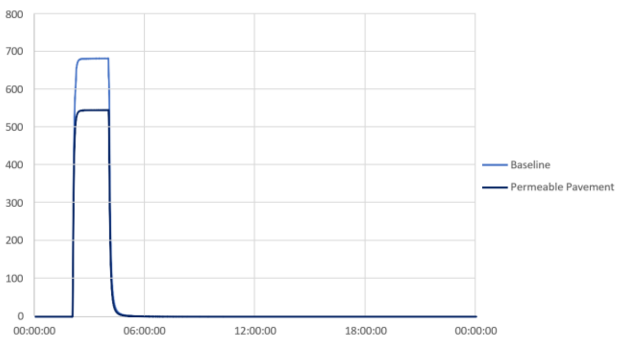


Figure 8 Hydrograph for permeable pavement simulation

Compared to the baseline scenario, the peak flow can be seen to have taken a considerable amount of flow away from the peak with an overall reduction of 20%. Permeable pavements reduce flow by promoting infiltration into their system using the porous concrete surface. Compared to conventional concrete, the porous concrete has been designed to have pores and voids. This allows for the water to be infiltrated into the substrate though the voids/pores into the concrete (Zhou et al., 2024). The water is then

stored in the substrate/medium where it may have vegetation which absorbs it. If not, the system will remove the water via evaporation or allow it to seep into a basin below. When the water is in the basin it is stored until it evaporates away (Muttuvelu et al., 2022). As no drain was chosen, the system may reach max capacity and become oversaturated and reduce its infiltration quality in higher intensity events (Hu et al., 2018).

After the original spike (shown in figure 8), the flow is seen to level out showing that the permeable pavement system did not hold peak flow delaying capability in this simulation. The permeable pavement used in the model was designed without a pipe to relieve flow from the system. However, due to the flow staying constant after the original peak, it can be determined that max storage was not achieved and thus the permeable pavement could still effectively infiltrate water into the basin (Hu et al., 2018). This shows that even if a drain were applied to the design, a delay in flow would not be noted.

4.2.3 Swales

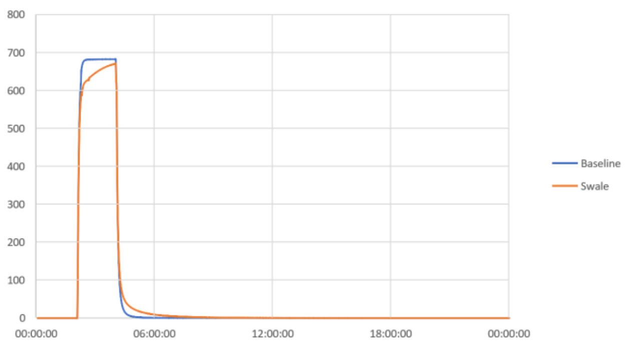


figure 9: Hydrograph for swales simulation

Swales were seen to only have a marginal effect on the urban runoff with a reduction of only 1.7% being noted. As seen in Figure 9, the initial flow is reduced slightly compared to the baseline scenario. This is due to the infiltration qualities found in swales. They have thick vegetations to increase their roughness to reduce the velocity/flow of the water travelling down it (Bhat et al., 2024). They have gentle longitudinal and lateral slopes to further encourage flow mitigation as water is conveyed down the channel (Davis et al., 2012). The substrate (soil) has pores/void space which the water infiltrates into as it runs down the channel. When the water gets infiltrated into the soil, it either gets taken in by the vegetation as nutrients to help them grow, gets released into the surrounding soil, is absorbed into local ground water or is evaporated out of the soil and into the atmosphere.

After the initial peak, a gentle curve can be noticed in the hydrograph as the water begins to leave the drainage system at which it hits the peak flow. This occurs since swales benefit from long contact with the water to maximise its infiltration capabilities.

However, in flash flooding events, they are exposed to high flows minimising their effectiveness (Bhat et al., 2024). They also become more saturated the longer they infiltrate water which makes them less effective at infiltrating water as there is no more

available storage. Increased flows also mean that the water rises above the vegetation making their roughness qualities less effective. Another consideration for why the peak flow was minimally affected is due to design constraints in an urban area which increases the slope gradients which in turn, increases the flow and further reduces contact time Rujner et al. (2016). None the less, the hydrograph still shows the swales ability to delay peak flow as after the large decrease in flow at the end of the simulation, a small curve can be seen showing that the swale is still conveying water down its length.

4.3 Multiple SUDS

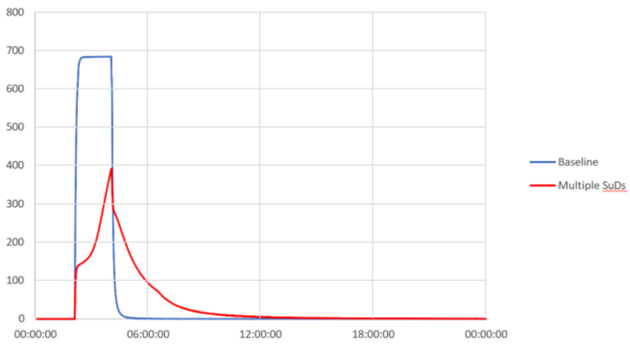


Figure 10 Hydrograph for multiple SuDs simulation

The multiple SuD system produced a significantly smaller flow compared to the baseline scenario with a substantial reduction of 42.84% of the peak flow. The hydrograph in Figure

4.5 shows a significant reduction in the original peak compared to the base line scenario. This is due to all the infiltration and storage qualities of the individual SuD systems working together. After the original peak, there is a significantly steep curve towards the peak of the flow as the delaying properties of the green roof and swales are put into effect. During this simulation, it can be inferred that the swales and permeable pavements are becoming more effective thanks to the flow delaying qualities of the green roof at the start of the SuD train (Fletcher et al., 2014). The reduced flow from the green roof allows extra contact time between the runoff water and the SuD systems which encourages increased infiltration. This also supports the swales flow delaying qualities as with reduced flow, the thick growth vegetation can have a bigger effect on slowing down the flow. In turn, this provides evidence that the swale is an effective tool when utilised in a SuD train system compared to implemented on their own.

4.4 Contamination

4.4.1 Physical Contaminants

4.4.1.1 Green Roofs - Physical Contaminants

Reports conducted by Zhang et al. (2015) showed green roofs potential to reduce the concentration of TSS with reductions from 67.04mg/L from an asphalt roof being reduced to 20.42mg/L (70%). Further studies by Hashemi et al. (2015) found green roofs were more effective at TSS removal during initial rainfall but becomes less effective with longer rain periods. However, studies by Morgan et al. (2011) reported that green roofs can be a source of TSS after initial planting during first flush events due to the type of media growth used in construction. Despite this, they found after the first flush, green roofs no longer become a source. Moreover, the use of vegetation could reduce the TSS and turbidity in the initial flush by 63% and 53% respectively. Trends across research shows that green roofs are more commonly seen as effective physical contamination mitigating tool. However, considerations still need to be made during initial construction to reduce physical contaminant release during first flush events.

4.4.1.2 Permeable Pavements – Physical Contaminants

Eck et al. (2012) found TSS to have a reduction of up to a 96% when permeable pavements are compared to conventional pavement surfaces. This is an extremely large reduction implying that permeable pavement can be an effective contaminant tool. Studies conducted by (Sansalone et al., 2012) also showed that turbidity rates could be reduced by ranges of 42-95% depending on design considerations furthering support that pavements can be an effective physical contaminant mitigator. However, due to the reduction of contamination being from the pavement's infiltration qualities, they are susceptible to clogging when exposed to contaminants for extended periods of time.Contaminant reduction was found to be reduced by 40-90% when maintenance was not undertaken. A correlation between findings show that permeable pavements have high physical contamination mitigating capability with most contaminants being removed.

However, clogging concerns can reduce their effectiveness bringing attention to the need for regular maintenance.

4.4.1.3 Swales – Physical Contaminants

According to research by Lucke et al. (2014), 50-80% of TSS was removed from urban runoff after travelling down the first 10m of the swale. It was also noted that after 30m, a further 10-20% was removed by the swale. Further research by Nara (2005), supported these claims with 56% reduction of TSS being found 0.6m down the channel and a further 76% at 1.6m. An overall reduction of 40% turbidity was also noted during observations.

Moreover, work by Shammizi and Razali (2018) reported TSS and turbidity removal rates of 91.2% and 78.9% respectively. These trends show that swales are an effective tool for physical contamination removal with their filtration qualities being highlighted.

4.4.2 Chemical Contaminants

4.4.2.1 Green Roof - Chemical Contaminants

There have been conflicting accounts over green roofs' sink or source relation to nitrogen with some studies, like Teemusk and Mander (2011), finding low nitrogen concentrations in green roof runoff, while others, such as Li and Babcock (2014) reported a higher nitrogen runoff compared to precipitation, providing evidence of it being a source.

Furthermore, the study highlights that green roofs can influence nitrogen concentrations in runoff, showing a decrease of approximately 15% compared to conventional roofs.

However, Hathaway et al. (2008) observed that green roofs could increase rates of phosphorus and nitrates due to compost and substrate considerations and could produce more nutrient runoff compared to conventional roofs. Research by Karczmarczyk et al. (2018) found that substrates of newly placed green roofs have high levels of phosphorus in them leading them to become a source of potential contamination in rainfall events.

Further research by Karczmarczyk et al. (2020) showed common aggregates and construction methods in green roofs lead to increased concentrations of phosphorus in urban runoff. Previous research shows either increases or decreases in nitrogen and phosphorus in urban areas making it unclear if they are a contaminant mitigator or source.

4.4.2.2 Permeable pavements – Chemical Contaminants

Drake et al. (2014) investigated the effects permeable pavements had on reducing contaminants and found that they can reduce the concentration of TN by 47% and reduce the total loading of TN by 75%. Further research conducted by Ostrom and Davis (2019) found adding internal water storage to a permeable pavement allowed for an increased 33% TN reduction. On the other hand, Tota-Maharaj and Scholz (2010) found that nitrate levels slightly increased when passing over permeable pavements however, they did note that these levels were still lower than those found when conventional pavement were used. Moreover, they found that the level of total phosphorus was reduced by 78%. Selbig et al. (2019) found lower levels of removal with 20% total phosphorus reduction found in porous asphalt and interlocking pavements and a 43% reduction in porous concrete. The studies above show the potential of permeable pavements to reduce chemical contaminants found frequently in urban runoff. Despite a variation in results for nitrogen and phosphorus reduction, it can be deduced that permeable pavements are significantly better for the removal of contaminants compared to conventional pavements.

4.4.2.3 Swales – Chemical Contaminants

Lucke et al. (2014) evaluated four grass swales and found no evidence of total nitrogen removal in any of the tested grass swales. However, reductions of TP were observed to be within the range of 20-23%. Work conducted by Shammizi and Razali (2018) found similar findings reporting minimum reduction of nutrients by swales. On the other hand, work by Yuan et al. (2019) reported that grassy swales were effective at reducing values of TN and TP. It was reported that the TN was reduced by 57% which agrees with work done by Koch et al. (2014) which noted levels of nitrogen reduction did not exceed 60%. Similar range was noted by Wu & Allan (2018) which saw reductions of 67% for nitrogen but found swales ability to reduce phosphorus not as effective with levels of 33% reduction notices.

Despite some disagreement in swales ability to remove chemical contaminants, most studies find that swales can reduce significant amounts of nitrogen and phosphorus.

Table 4 Data obtained from quantitative and qualitive research

Scenario	Peak Flow (LPS)	Percentage Decrease (%)	Subcatchment Are Used (%)	Physical Contaminant	Chemical Contaminant
Baseline	683.04			x	x
Green Roofs	435.30	36.27	50.00	Good	Variable
Permeable Pavements	546.45	20.00	20.00	Good	Good
Swales	671.45	1.70	10.00	Good	Good
Multiple SuDS	390.41	42.84	80.00	Good	Good

From Table 4, it can be observed that the majority of SuD systems provided an effective flow mitigation effect with green roofs proving to have the largest impact of the individual system. The green roofs also showed the largest response in flow delay compared to the individual systems (

5. Conclusion

The UK is currently in a pluvial flooding crisis due to increased levels of urbanisation and climate change. This issue is expected to continue to become more severe in the future and thus significant investment in drainage solutions is required in highly urbanised areas. SuDS have been suggested to be a flow and contaminant mitigating method suitable to help reduce the likeliness of pluvial flooding events and reduce the amount of physical and chemical contaminants in urban areas. However, due to a lack of understanding and trust in SuD projects, their application in highly urban areas have been low. Using the model, we could show that SuDS could potentially reduce flow within highly urban areas, especially green roofs or SuD trains. Furthermore, using a review of current literature, it can be suggested that most SuDS hold contamination mitigating qualities against common pollutants in urban runoff. Together, it can be perceived that SuDS can be an appropriate tool in rising drainage challenges in urban settings.

A drainage model was developed in a highly urbanised area in London to analyse flow in a high intensity rainfall event. In the current study used, geographical data was used from Digimaps as well as a brand-new system constructed without knowledge of the real drainage network. These limited the accuracy of the model due to a lack of GIS data available to create a realistic topographical model to determine lengths, gradients, and slopes for e.g. pipes and subcatchments. Furthermore, the simulation can be assumed to reflect the real drainage system, but it cannot be confirmed to be fully accurate. Different SuD systems were placed into the model to analyse the effects they had on flow in the system. Different results were found when different SuDS were placed into the system under high intensity rainfall. However, there is a limitation to the general applicability of the data as different rainfall events, SuD design considerations and subcatchment area usage were parameter which were not considered in this study. The contamination relationship between the SuDS were analysed and compared using past literature to establish the putative contaminant mitigation in the SuD system. The literature review indicated that SuDs could have significant effects on physical and chemical contaminant mitigation.

Limited amounts of contaminants were chosen to be analysed to allow for a clear comparison thus the study focussed on TSS, turbidity, total nitrogen and phosphorus. However, this means that the effects of SuDS on other contaminants like, for instance,

heavy metals, chlorine and biological contaminants remains to be explored. SuDS are a relatively new concept and have a wide range of applications and as such limited data was available that provided information directly relevant to the current study. Thus, more data is needed to provide a clearer insight into their use in heavily urbanised areas when exposed to intense rainfall scenarios. Furthermore, due to the research being secondary, results must be taking at face value so observations of variations cannot be fully understood to determine reasons for different results. Finally, the flow of the system was validated against current literature to ensure the values obtained from the model was an effective reflection of the way SuDS can work in a highly urban environment. The model was deemed to be valid as the present studies experimental flow values corresponded with the range of values observed in literature. Despite this, we still cannot say this model is an accurate representation of every urban environment as each city, location and situation will require different specifications and require for different SuDS or combinations to be used. However, we can still say that the model provides a good insight into the possible effects that SuDS can have in future urban settings which will help guide future experimental studies and the possible implementation of SuDS in more highly urbanised areas.

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