

Infiltration efficiency and subsurface water processes of a sustainable drainage system and consequences to flood management

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Abstract

With increased intensity rainfall events globally and urban expansion decreasing permeable surfaces, there is an increasing problem of urban flooding. This study aims to better understand rainfall infiltration into a Sustainable Drainage System (SuDS) permeable pavement, compared with an adjacent Green Area of made ground, in relationship to groundwater levels below both areas. Both areas were instrumented with soil water content and matric potential sensors and four shallow boreholes were instrumented with groundwater level sensors. Surface infiltration rates were measured using a double-ring infiltrometer. Results showed that average infiltration rates of the SuDS (1,925 mm/hr) were significantly higher than the Green Area (56 mm/hr). The SuDS was well designed to transfer rainfall rapidly to the aquifer below, where groundwater levels rapidly rose within 1 hr of a 1 in 30 year event (32.8 mm/hr). In comparison, soil compaction of the made ground Green Area decreased infiltration rates, but still enabled the majority of rainfall events to infiltrate. The aquifer below the Green Area responded more slowly, as lower matrix potentials facilitated water retention in the soil profile, slowing water draining to the aquifer. This work reiterates the importance of ensuring a 1 m separation depth between the base of the SuDS infiltration zone and aquifer depth.

KEYWORDS

groundwater, natural flood management, sustainable drainage systems, urban drainage

1 | INTRODUCTION

Record-breaking rainfall events have significantly increased globally (Allan & Soden, 2008; Lehmann, Coumou, & Frieler, 2015) and in combination with urban expansion and decreasing permeable cover, there is an increasing

problem of surface water urban flooding (Adelekan, 2010; Du, Van Rompaey, Shi, & Wang, 2015). In tandem, increased peak river flows, generated by smooth impermeable surfaces and straight drainage channels, are leading to increased fluvial flooding as described by Charlesworth, Harker, and Rickard (2003). However, Sustainable Drainage

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Systems (SuDS) are becoming a widespread approach to decrease and reduce peak surface runoff and pollutants, within many urban areas, using various “green” (vegetated), “grey” (engineered) and “blue” (open water) structures, such as infiltration basins, vegetated swales, bioretention systems and soakaways, as reviewed by Tedoldi, Ghassan, Pierlot, Kovacs, and Gromaire (2016). Design and construction of SuDS however, remain weakly regulated in the UK, even though the SuDS philosophy is to as closely as possible replicate catchment hydrology (Melville-Shreeve et al., 2018). In terms of improving urban resilience to climate change adaptation, Depietri and McPhearson (2017) suggest that hybrid approaches that combine both blue, green and grey structures may be the most effective strategy to adapt to increasing hazards in the urban environment.

In urban environments, a typical grey structure in SuDS design is to install permeable pavement systems, which are designed to increase rainfall infiltration, to reduce greenfield runoff rates and retain surface contaminants, such as hydrocarbons, heavy metals and nutrients. These permeable pavements allow for dual use of space and are generally low maintenance (CIRIA, 2007) but require the underlying geology to have sufficient permeability to allow water to infiltrate effectively. As described in Scholz and Grabowiecki's (2007) review of permeable pavement systems, the combination of permeable paver units, drainage cells and coarse gravel layers above a native subgrade and aquifer, promotes rainfall and surface water runoff to infiltrate into the ground.

Several studies have examined infiltration rates of permeable pavements. For example, in Auckland, New Zealand, a newly built inter-locking pavement was measured to have an infiltration rate of 1,200 mm/hr (Fassman & Blackbourn, 2007); whereas in the Netherlands newly installed permeable pavements must demonstrate minimum infiltration rate of 194 mm/hr, of which eight performing permeable pavements were measured to have infiltration rates between 29 and 342 mm/hr (Boogaard, Lucke, van de Giesen, & van de Ven, 2014).

Other studies have found that infiltration rates decrease over time due to the clogging of porous pavers and drainage slots between interlocking pavers. For example, infiltration rates of a permeable pavement in Calgary, Canada were measured to have initial surface infiltration rates about 3,200 mm/hr, but then decreased to 1,800 mm/hr after the pavement came into use (Brown, 2007). Also in Calgary, Canada, freeze/thaw and the application of sanding materials to a newly installed, open-joint inter-locking pavers, with an initial average infiltration rate of 7,547 mm/hr, was found to decrease the infiltration rate by more than one order of magnitude (Huang, Valeo, He, & Chu, 2012). For permeable interlocking concrete pavers infiltration reduced from 20,000 to 800 mm/hr and for porous concrete pavers infiltration reduced from 40,000 to 130 mm/hr (Bean, Hunt, & Bidelspach, 2007).

Considering these relatively high infiltration rates through the gravel layers of permeable pavement systems during storm rainfall, it is important to understand the response below ground in the unsaturated zone and how quickly infiltrating water will recharge the aquifer. It is known that 100% gravel content retains relatively little water. For example, Wang, Xiao, Wang, and Shao (2013) developed water retention curves for 100% pebble and shale clasts. From this, it was estimated that for 3–5 mm diameter pebbles, saturation was approximately 30% and soil water content exponentially decreased to below 5% at water potentials below –10 kPa. Therefore, it is likely that rapid infiltration of water through the permeable pavement into the gravel layers could recharge the aquifer relatively quickly. However, little research has been done to investigate the possible hydraulic connectivity between permeable pavements and underlying aquifers. We therefore aim to investigate the water retention of a permeable pavement, water contents below the permeable pavements in the unsaturated zone, and groundwater levels below the SuDS, in response to high intensity rainfall events.

In contrast to permeable pavements, the use of greenspaces (such as recreation areas, brown and green field developments) have also been suggested as areas to retain and reduce runoff alongside engineered SuDS in urban environment planning (Ellis, 2012; Jim & Chen, 2003). As described by Schwartz and Smith (2016), modern land development practices often reduce permeability and in some cases the hydrological soil structure of many open green areas. In particular, areas of made ground are routinely found to be almost impervious. To investigate the storage in made ground, plus its effectiveness in retaining rainfall and reducing overland flow to mitigate surface flooding, we study an engineered/modified Green Area adjacent to the SuDS carpark. The Green Area is typical of made ground developed from crushed building bricks mixed with local sandy loam and covered by a perennial clover/grass mix. By comparing these two sites: (a) a permeable pavement of open joint inter-locking pavers and (b) re-made ground of crushed bricks covered by a layer of sand, clay and grass, we aim to develop a better understanding of surface infiltration rates, ground water retention and groundwater level response to local rainfall events in relationship to flood mitigation of urban environments.

2 | MATERIALS AND METHODS

2.1 | Site information and experimental layout

In 2005, a Sustainable Drainage System (SuDS) was installed as part of a car park at Red Kite House in

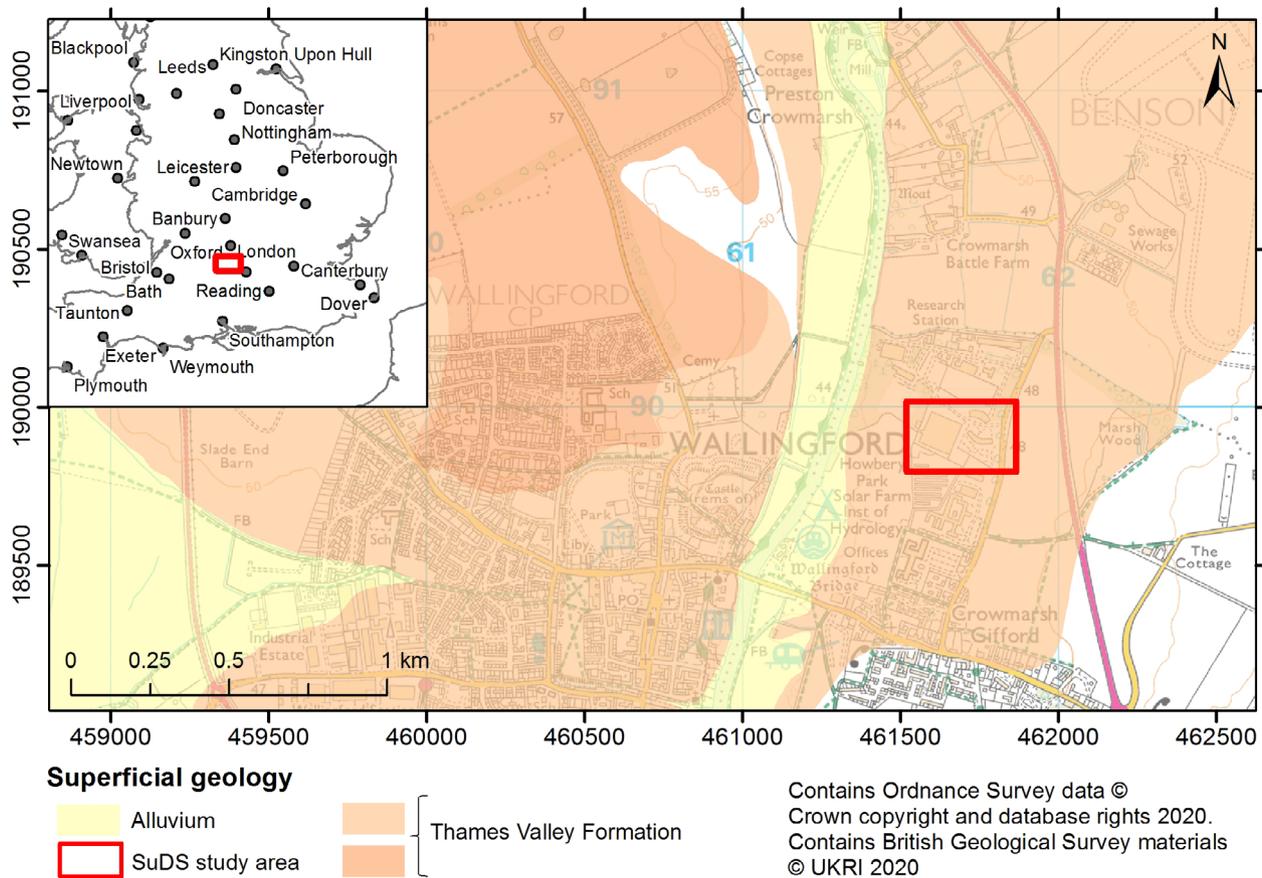


FIGURE 1 Site location and superficial geology

Wallingford, Oxfordshire, UK (Figure 1), which is representative of a moderate-use car park, where it is in relatively heavy use during the day, 5 days of the week. It was designed as a total infiltration pavement (CIRIA, 2007) where all the rainfall infiltrates into the underlying soils with no discharge from the system. The car park consists of a permeable block surface within parking bays and impermeable block surface in the aisles. The permeable paving blocks are 0.5 m thick and are laid on 60 mm single-sized aggregate, which has an approximate thickness of 80–100 mm. Below this layer is a Terram 1,000, non-woven geotextile, to ensure that the different sized aggregates cannot mix. Beneath this sub base is 0.35 m thickness of 20 mm single-sized aggregate on made ground consisting of crushed building material and clay. In some areas below the geotextile, finer 0.07–0.1 m gravel has been spread, to level out the coarse grade gravel. When removing pavers to install instrumentation, it was noted that there was no sediment accumulation on the bedding aggregate as has been found in other studies such as Lucke (2014).

Adjacent to the carpark is a grass area (as shown in Figures 2 and 3a) that was planted on made ground 15 years ago. The upper soil layer (0–0.15 m) is a loam

soil, which was spread over the coarser crushed building material below and sown with a perennial grass clover mix. Fifteen years later, this upper 0.15 m loam cover has a dense established layer of perennial grass roots. Below this is made ground containing coarse to medium sand with crushed rubble that is mainly derived from ground-up building material from a previous building that existed on site. This layer also has some cobbles 0.7–1 m and is mixed with sand and clay.

The site overlies ~5 m of the Thames Valley Formation sand and gravel (Figure 1), which is in turn, underlain by the basal Glauconitic Marl Member of the West Melbury Marly Chalk Formation (Jukes-Brown & Osborne White, 1908). Below this is the Upper Greensand (UGS), comprised of both poorly consolidated and cemented sands. The superficial sands and gravel and the UGS form two distinct aquifer units. The Marly Chalk is an argillaceous sediment and has a low permeability effectively separating the aquifers (Allen et al., 1997). Made ground covers a large part of the area and is approximately 1 m thick. The site historically held a large research building and the footprint of this lies diagonally across the car park, which has implications for the composition of the shallow subsurface. The boundary

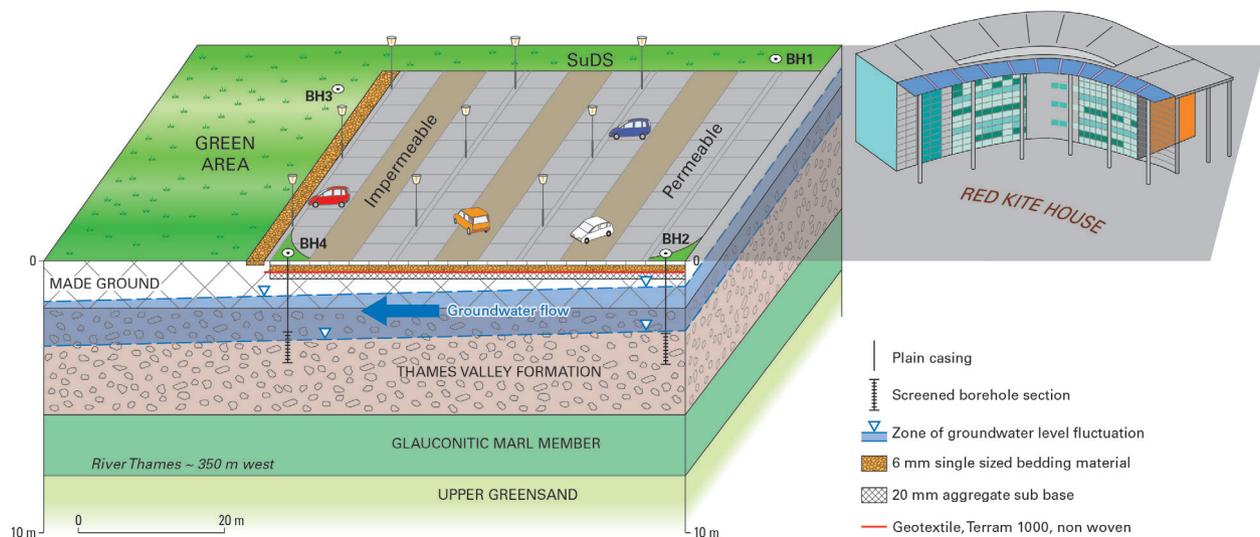


FIGURE 2 Site design and borehole (BH) construction

between the anthropogenic sediments and the Thames sand and gravels is difficult to define, forming one aquifer in the area ~ 6 m thick, although in the study area the gravels are relatively thin and the aquifer mostly comprises made ground. Both the sand and gravels and the UGS are both defined by the UK environmental regulator as being Principal Aquifers, which means they can provide a high level of water storage and have high permeability (Environment Agency, 2017). The River Thames lies approximately 350 m to the west of the study area and groundwater flow direction is towards the river. The site is classed by the British Geological Survey (BGS) Infiltration SuDS Map as likely to have significant constraints; this is due to the shallow groundwater table which can cause issues. Enhanced infiltration can result in rising groundwater levels, which in turn may compromise the functioning of the infiltration SuDS or exacerbate any local flooding issues.

2.2 | Groundwater and soil water measurements

After the permeable pavement car park was constructed in 2005, four shallow boreholes were drilled at the corners of the car park to approximately 5 m depth (Figure 2). These boreholes were then monitored by the environmental regulator for water level and quality every quarter for 5 years until 2010, with the primary function of assessing the impact of hydrocarbons on the shallow groundwater. The results of this monitoring showed that there was no evidence that hydrocarbons were migrating through the permeable pavement to the shallow aquifer (Environment Agency, 2010). For this current work, the

four boreholes were instrumented and groundwater levels were monitored and logged every 15 min, using in situ pressure transducer sensors (Solinst, Canada Ltd.). These boreholes were then sampled in 2013 for an updated assessment of water quality, and analysis was carried out for pesticides, residence time indicators, stable isotopes and a broad screen gas chromatography-mass spectrometry (GCMS), to identify any organic pollution in the shallow groundwater. These narrow diameter boreholes were purged using a peristaltic pump under a low flow rate until field parameters were stable.

Volumetric soil water sensors, SM150 probes (manufactured by Delta-T Devices, Cambridge, UK) and matric potential sensors, Watermark gypsum blocks (developed by Irrrometer Company, Riverside, CA), were installed under the SuDS car park and in the adjacent grassed area (Green Area). The layout of the gypsum blocks and Delta-T probes is shown in Figure 3a. Within the labelled squares (shown in Figure 3a), one Delta-T probe and one gypsum block were installed. These were replicated in each area at two depths, providing a total of four gypsum blocks and four Delta-T probes within each measured area. The upper depths (U1 and U2) are around 0.13 m, to measure the fine gravel layer directly below the SuDS inter-locking pavers. The lower layer (L1 and L2) measure the coarser gravel layer of the SuDS substrate at 0.33 m depth below the geotextile. The installation of the probes in the Green Area replicates the probe depths in the SuDS area to enable a comparison of the changes of volumetric water content and matric potential under the SuDS and the adjacent Green Area (Figure 3b). The loggers for the gypsum blocks and Delta-T sensors were programmed to measure every 15 min.

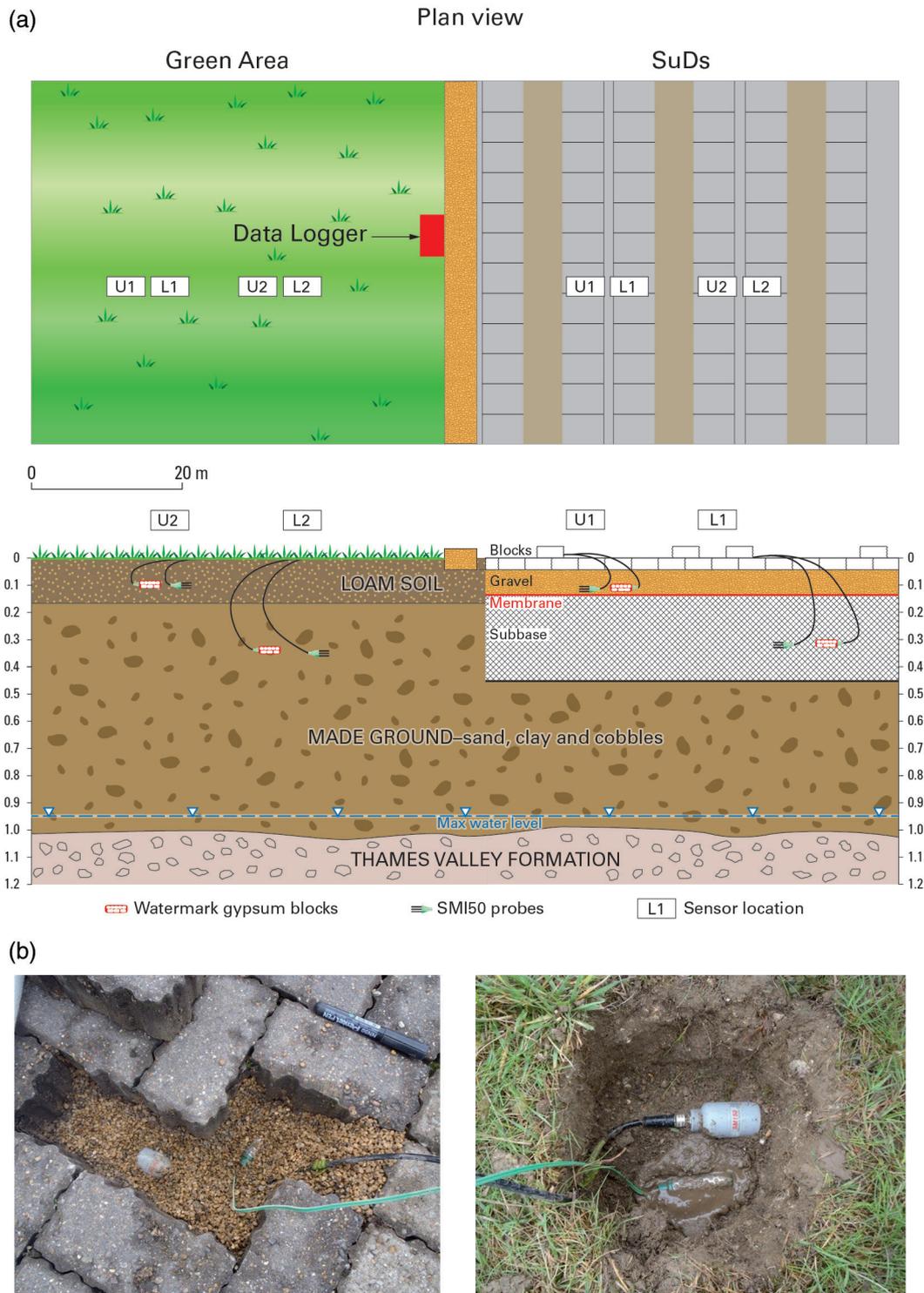


FIGURE 3 (a) Sensor installation (upper and lower soil layers—U and L) and car park design. (b) An example of a gypsum block and Delta-T probe installed in the upper layer within the SuDS Area (left photo) and the Green Area (right)

2.3 | Rainfall measurements

Rainfall was measured at the Wallingford Centre of Ecology and Hydrology Meteorological Station (51.602477°, -1.112422°), located approximately 250 m from the SuDS and Green Area site. The Wallingford station measures

rainfall using two 5 inch diameter weighing rain gauges. One rain gauge is mounted 1 inch above ground and the other is mounted below ground, enabling the rim of the rain gauge to be at ground level. This set-up enables an assessment of the undercatch of gauges mounted above the ground surface. Rainfall was calculated as an average of the two rain gauges.



FIGURE 4 Infiltrometer installed in the a) Green Area and b) the permeable pavement area

2.4 | Water infiltration rates

A Double-Ring Infiltrometer was used to estimate field hydraulic conductivity (K_{fs}) of the SuDS and Green Area. The diameters of the outer and inner steel rings were 0.55 m and 0.3 m respectively. Both rings were inserted into the Green Area to 0.03 m depth (Figure 4a), whereas the hard surface of the SuDS prevented the infiltrometer rings from being inserted into the ground. Therefore, in the SuDS area, the infiltrometer rings were sealed to the SuDS surface using bentonite (Figure 4b), successfully preventing water from flowing out from below the ring edges.

K_{fs} was calculated using a simple one-dimensional approach method, which assumes that steady-state infiltration rate (qs) approaches K_{fs} , therefore:

$$K_{fs} = qs \quad (1)$$

This approach overestimates K_{fs} as it neglects flow due to capillary suction and hydrostatic pressure and reduces the driving force of infiltration to its gravitational component. In terms of the SuDS area however, this method was considered more appropriate to estimate K_{fs} , as flow due to capillary suction and hydrostatic pressure in gravels is close to zero and the ring insertion depth was 0. However, in the Green Area, flow was more likely to be affected by capillary suction and hydrostatic pressure, because of the presence of fine soil material. Therefore, for the Green Area, the Reynolds & Elrick, 1990 method was also used to estimate K_{fs} :

$$K_{fs} = \frac{qs}{\pi R_s^2 \left\{ \left[\frac{H}{(C_1 d + C_2 R_s)} \right] + \left[\frac{1}{\alpha^* (C_1 d + C_2 R_s)} \right] + 1 \right\}} \quad (2)$$

$qs(L^3 T^{-1})$ is the steady-state flow rate, $R_s(L)$ is the inner ring radius, H is the average depth of ponded water in the inner ring, $\alpha^*(L)$ is the soil capillary length and $d(L)$ is depth of ring insertion into the soil. Following Reynolds and Elrick (1990) the dimensionless quasi-empirical constants C_1 and C_2 were chosen to be 0.316π and 0.184π , respectively, as ring insertion depth was ≥ 0.03 m and the ponded water in the inner ring was ≥ 0.05 m.

2.5 | Rainfall intensity–duration–frequency analysis and inferring dominant hydrological pathways during storms

The vertical distribution of K_{fs} and rainfall intensities are factors that determine the stormflow pathways (as defined by Chappell et al., 2007) during and shortly after a rainfall event and have been considered in research studies to understand dominant stormflow pathways predominantly in natural landscapes, such as forests and grassland (Bonell, 2005; Ghimire et al., 2014; Gilmour, Bonell, & Cassells, 1987; Hassler, Zimmermann, van Breugel, Hall, & Elsenbeer, 2011; Ziegler, Negishi, Sidle, Noguchi, & Nik, 2006; Zimmermann & Elsenbeer, 2008). Stormflow pathways include infiltration—vertical percolation, infiltration—excess (IOF, Horton, 1933) or saturation-excess overland flow (SOF), subsurface stormflow, (SSF) (Chorley, 1978) and are inferred by selecting percentiles of maximum rainfall intensities (I_{max}), which are then superimposed on measured datasets of K_{fs} values, as described by Archer et al. (2013).

In this study, we chose a maximum rainfall of 1-in-10 year return period to compare measured K_{fs} values for

SuDS and Green Area sites, because previous analysis of surface water flooding in the UK were associated with rainfall intensities of less than 1-in-10 year return periods (Hurford, Parker, Priest, & Lumbroso, 2012). However, we also considered rainfall-intensity thresholds of an average of 1-in-30-year storms, which the Extreme Rainfall Alert (ERA) service for the UK use to represent rainfall that is likely to cause severe surface water flooding. The ERA thresholds for the UK are 30 mm in 1 hr, 40 mm in 3 hr and 50 mm in 6 hr (Hurford et al., 2012).

3 | RESULTS

3.1 | Groundwater, soil water content and matric potential between SuDS and green area sites

Figure 5 compares rainfall, volumetric soil water content for the SuDS (Figure 5a) and Green Area sites (Figure 5b) and the water levels of the two nearby boreholes BH3 in the Green Area and BH4 in the SuDS

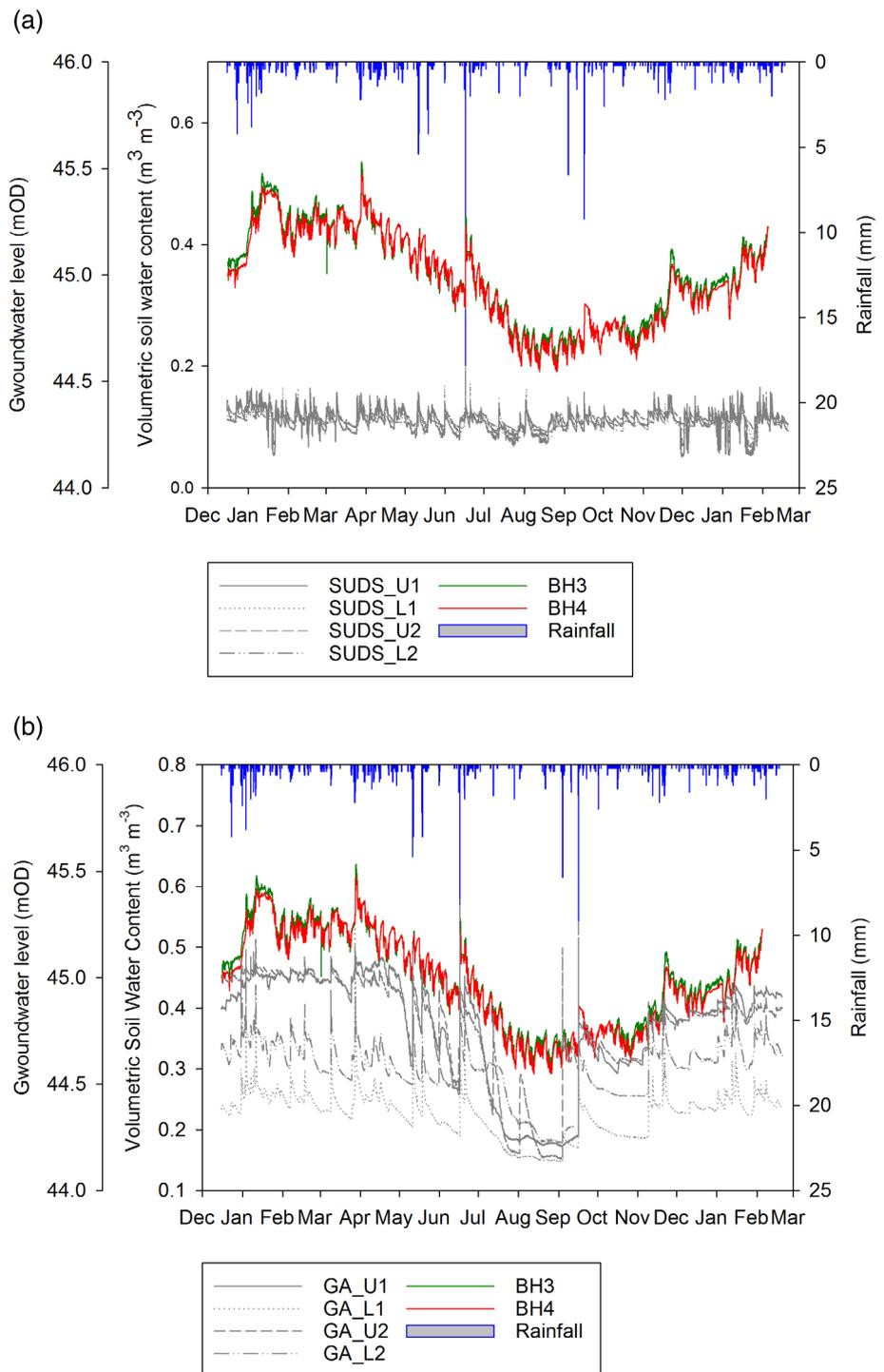


FIGURE 5 Comparison of rainfall, groundwater levels (BH3 and BH4), and soil water content for upper and lower soil layers (U and L respectively) for two soil groups (1 and 2) in the (a) SuDS area and (b) Green area

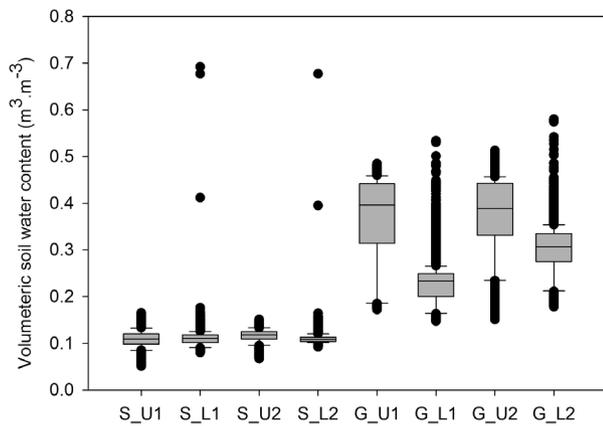


FIGURE 6 Boxplots show how the soil water content data is spread during the measurement period. The lower 25 percentile and the upper 75 percentile of the data are shown within the grey boxes and the black dots show outliers (data points lying outside 10th and 90th percentiles) of soil water content during the measurement period. S denotes the SuDS Area and G denotes the Green Area. U1 and U2 are the upper soil layers and L1 and L2 and the lower soil soils as described in Figure 3a

(locations shown in Figure 2) for the complete measurement period from December 16, 2015 to February 20, 2017. Overall groundwater levels for boreholes BH3 and BH4 show very similar water levels and responses in relation to rainfall. Figure 5a shows that soil water content in the SuDS site remains below $0.2 \text{ m}^3/\text{m}^3$ at all times, except during a storm event, which recorded 30 mm of rainfall within 30 min during June 16, 2016, when maximum soil water content peaked at $0.7 \text{ m}^3/\text{m}^3$ in the SuDS site. On the other hand, soil water content in the Green Area had consistently higher water content ranges throughout the measurement period, with a maximum volumetric soil water content recorded at $0.58 \text{ m}^3/\text{m}^3$ (Figure 5b).

To investigate soil water content ranges between the two sites, box plots graph the spread of soil water content data for the two sites (Figure 6). The larger spread of data within the 25 and 75% interquartile ranges in the upper and lower soil layers of Green Area shows that the soil in the Green Area stores a greater amount of water than the SuDS Area. Taking the range of these values (from the 25 to 75% interquartile) over the measurement period, soils retained $0.05\text{--}0.5 \text{ m}^3/\text{m}^3$ water content in the upper layers and $0.05\text{--}0.45 \text{ m}^3/\text{m}^3$ in the lower layers of the Green Area. This is a significantly higher water content ($p > .0001$) than the $0.05\text{--}0.15 \text{ m}^3/\text{m}^3$ soil water content in the SuDS gravel layers.

To investigate the range of matric potentials in the two sites, the matric potential data were grouped into six categories (Table 1) adapted from Orloff et al. (2002) and then graphed as histograms (Figure 7).

TABLE 1 Matric potential categories adapted from Orloff, Hanson, and Putnam (2002), Watermark Soil Moisture Sensors, The Irrometer Company, Riverside, CA

Matric potential range (kPa)	Approximate soil water content for different soil categories
0 to -10	Saturated soil
-10 to -30	Field capacity for most soils
-30 to -60	Sandy or loamy sand or sandy loam approximately 50% water content
-60 to -100	Loam and clay loam approximately 50% water content
-100 to -250	Crop stress for most soils
< -250	Very dry soil conditions for most soils.

As shown in Figure 7, the SuDS site matric potentials remained at field capacity to saturated, for both upper and lower layers, which follows typical van Genuchten water retention curves for coarse sand and gravel material, where saturated gravels retain only $0.15 \text{ m}^3/\text{m}^3$ water content (Dan, Xin, Li, Li, & Lockington, 2012) and therefore rapidly drain when water content is above $0.15 \text{ m}^3/\text{m}^3$. In comparison the matric potentials for the Green Area for both upper and lower layers, were mainly at field capacity to saturated and at times their water contents decreased to less than $0.5 \text{ m}^3/\text{m}^3$, which is typical of a clay loam.

Comparing soil water contents with adjacent gypsum blocks when they were at field capacity (i.e., around -33 kPa), soils stopped draining in the Green Area when soil water contents were around $0.36 \text{ m}^3/\text{m}^3$ in the upper soil layers and around $0.19\text{--}0.33 \text{ m}^3/\text{m}^3$ in the lower soil layers (Figure 6). In the SuDS Area the lower layers remained constantly saturated and therefore additional water entering during rainfall events drained rapidly. There was only a short period during the summer time when the gravels began to dry towards $0.05 \text{ m}^3/\text{m}^3$ soil water content, which would allow a relatively limited amount of rainfall storage, during this time.

3.2 | Rainfall events, infiltration and rainfall response times

To analyse the response times and correlation between groundwater and soil water content, to the rainfall during the whole measurement period, the software package R (version 3.0.2) was used to identify cross-correlation coefficients for the groundwater level, and soil moisture data for the whole measurement period December 16, 2015 to February 20, 2017. The data were first log-transformed to ensure a normal distribution, and cross-correlation was calculated on the transformed data (Chatfield, 2004). The

FIGURE 7 Frequency of soil matric potentials for the SuDS and Green Area (GA) sites, categories follow Table 2. The x-axis represents negative matric potentials (kPa). U1 and U2 indicate upper soil layers, L1 and L2 indicate lower soil layers

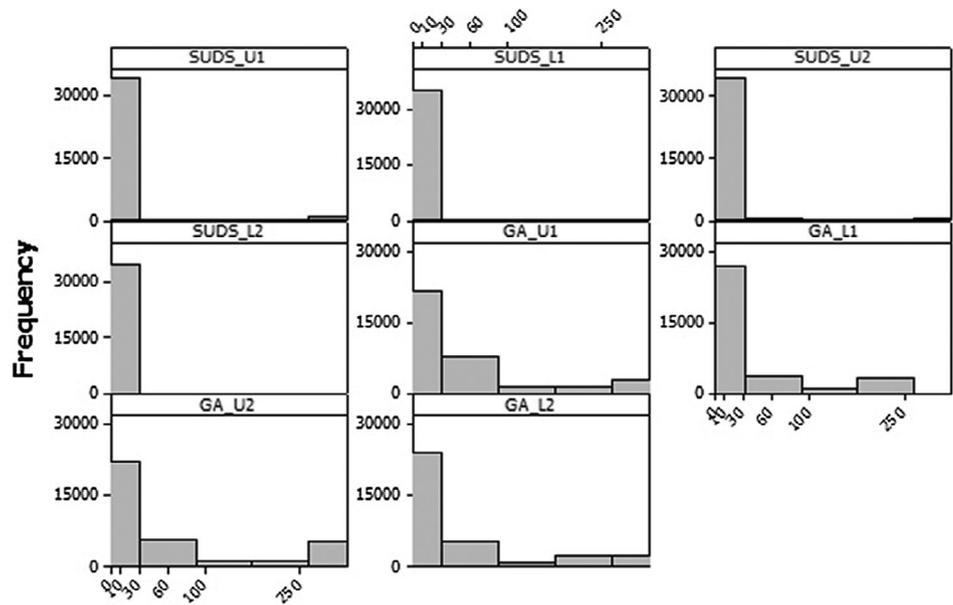


TABLE 2 Soil water content and groundwater level response times to rainfall events

Site	Layer (m)	Time lag to rainfall (minutes)	ACF
SuDS area 1	0.13	<15	0.120
SuDS area 1	0.33	<15	0.101
SuDS area 2	0.13	<15	0.119
SuDS area 2	0.33	<15	0.156
Green area 1	0.13	135 ^a	0.041
Green area 1	0.33	15	0.119
Green area 2	0.13	35 ^a	0.052
Green area 2	0.33	15	0.093
Groundwater (BH4)		75	0.038

Note: ACF is the autocorrelation coefficient, where 0.01 is the confidence interval for the whole dataset.
^aShow values in error, explained in text.

cross-correlation coefficients were then plotted with lower and upper 95% confidence intervals ($2/\sqrt{n}$; n = sample size) to show significant correlations, and response times (lags) were determined as the highest correlated points from each plot (Table 2).

Table 2 shows that overall soil water content responded within 15 min of rainfall events in upper and lower layers of the SuDS Area, however in the Green Area soil water content responded after 15 min for the lower layers. The response times calculated by cross-correlation for upper layers of these values are not correct. Both upper layers in the Green Area responded to rainfall within 15 min, but soil water content gradually increased in many cases over a number of hours. As cross-correlation uses maximum values as response times, longer lag times for these layers indicates greater storage potential.

Fifteen-minute duration rainfall were graphed for the whole measurement period and four individual rainfall events greater than 5 mm/15 min were selected (Figure 8) to investigate the response to rainfall, groundwater and soil water content. Figure 9a shows the first event as a series of low rainfall events with a peak event at 5.4 mm/15 min and the second event (Figure 9b) is an extreme event of 32.8 mm within 1 hr (8.2 mm/15 min), which caused localised flooding during June 16, 2016. The second set of rainfall events (Figure 10) occurred within 12 days of each other. The first (Figure 10a) shows low rainfall <1 mm and then a sudden high rainfall event of 7 mm/15 min. The second event (Figure 10b) has much higher rainfall within 2 hr, where the highest rainfall is 9 mm/15 min followed 15 min later by another event of 5 mm/15 min.

Consistently across all rainfall events, the soil water contents within the permeable pavement do not increase above $0.15 \text{ m}^3/\text{m}^3$ for both upper and lower layers except

during the very high intensity rainfall (Figure 9b), where both the lower soil water sensors recorded an almost instant response to the extreme rainstorm where 32.8 mm of rainfall fell during 1 hr. This value was compared to a 1-in-10-year rainfall event modelled using the Flood Estimation Handbook 13 model (FEH13; Centre of Ecology and Hydrology, 2018) for the field site, which modelled hourly rainfall of 25.5 mm, showing that this rainstorm was recorded to be greater than a 1-in-10-year rainfall event and reached just over the ERA threshold of 30 mm in 1 hr for a 1-in-30-year flood.

Investigating the four rainfall events (Figures 9 and 10), the SuDS site shows higher peaks of water content in response to lower rainfall events in the upper layer under the inter-locking pavers in comparison to the lower coarse gravel layer (Figures 9a and 10a). However, during the very high intensity rainfall (Figure 9b), the upper sensors recorded only a slight water content increase. This could be because the rainfall passed so rapidly through the upper layer, that the 15-min logging duration was too coarse to record a sudden peak in soil water content,

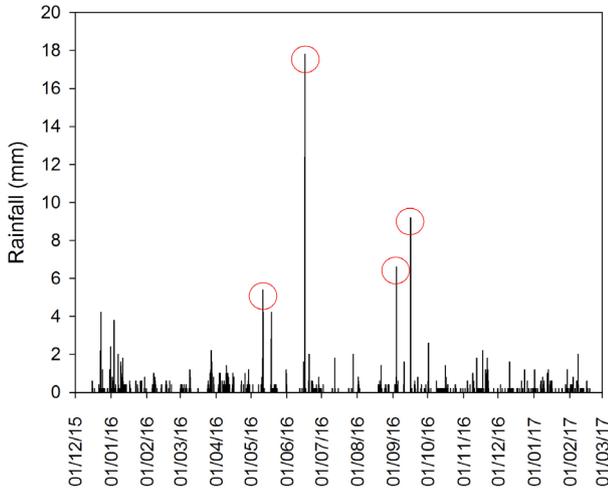


FIGURE 8 Rainfall events during the measurement period. Red circles note rainfall events above 5 mm/15 min

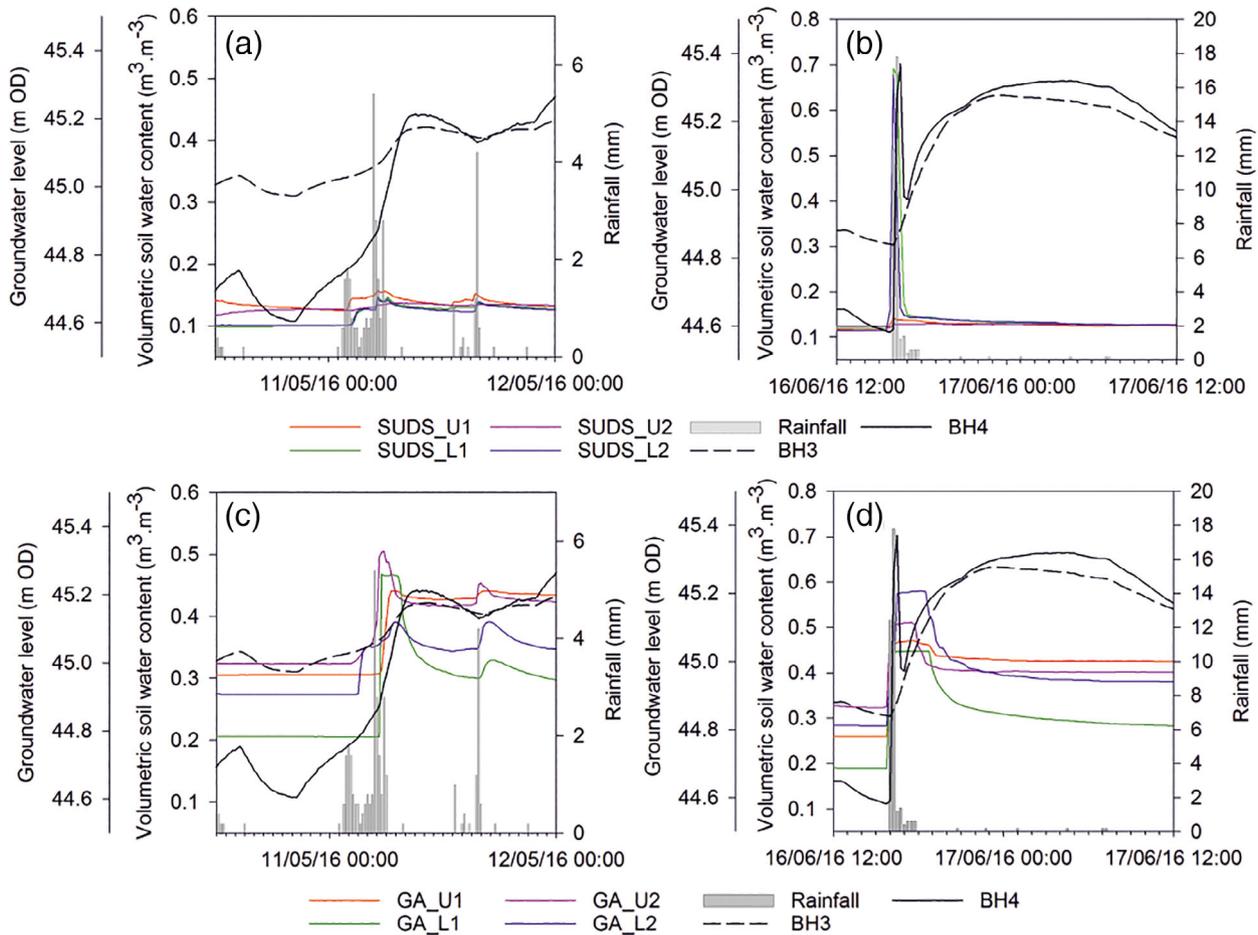


FIGURE 9 Soil water content and groundwater level response to (a, c) relatively low intensity rainfall and (b, d) very high rainfall intensity in the SuDS a and b and Green Area (c, d). GA denotes Green Area, U is upper soil layer, and L is lower soil layer, BH3 and BH4 are boreholes showing groundwater levels

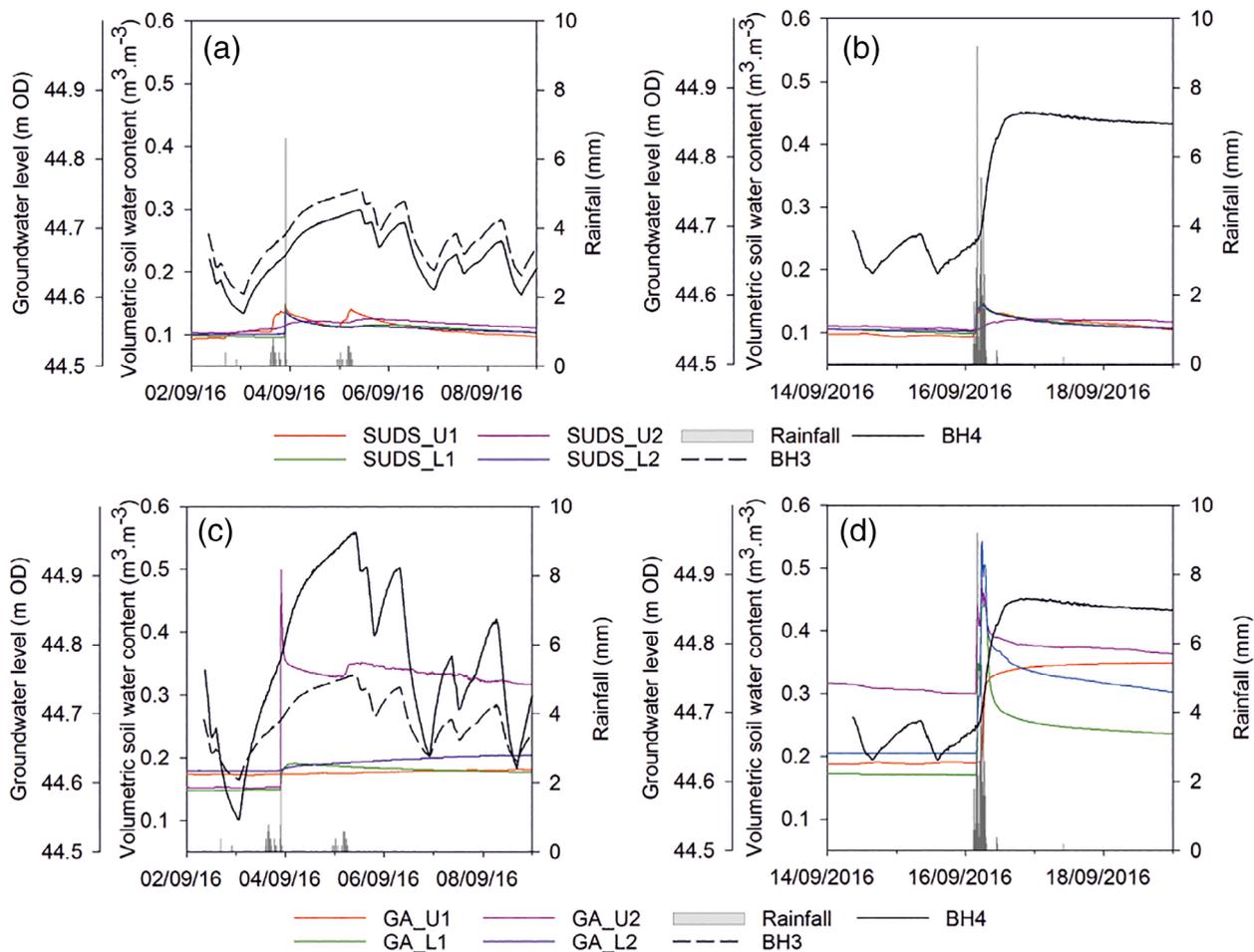


FIGURE 10 Soil water content and groundwater level response (a) in the SuDS after a relatively dry period, (b) in the SuDS 12 days after heavy rainfall, (c) in the Green Area after a relatively dry period, and (d) in the Green Area 12 days after heavy rainfall. *Note:* BH3 groundwater levels are missing for (b, d), due to a sensor failure. U denotes upper soil layer and L denotes lower soil layer, BH3 and BH4 are boreholes showing groundwater levels

which may have had a duration of less than 15 min. To test this possibility, infiltration tests were undertaken on both sites (explained in following section). In all rainfall events in the SuDS site, the upper and lower layers show a rapid response to rainfall, but also a rapid decrease of soil water content, once the rainfall decreases.

The Grass Area site has a greater range of soil water contents compared to the SuDS site. Following the heavy rainfall shown in Figure 10b, soil water content increased from the previous heavy rainfall (Figure 10a) for all layers by at least $0.05 \text{ m}^3/\text{m}^3$. Soil water content of the upper layer (GA U2) remain relatively high, and again increase after the second heavy rainfall (Figure 10b). This shows that upper and lower layers in the Green Area store water, which is expected due to the lower soil matric potentials (Figure 7). Soil water content increased and plateaued in the Green Area after the heavier rainfall events shown in Figure 9a,b, illustrating that all layers reached saturation for a number of hours.

Groundwater levels increased with all rainfall events (Figures 9 and 10), however, the rise of groundwater level did not always coincide with locally measured rainfall, but continued to rise after rainfall events. Where there was sustained rainfall, not just one isolated peak, the groundwater levels continued to increase, although the response was also influenced by antecedent soil moisture conditions and water levels. Zhang, Singh, Migliaccio, and Kisekka (2017) highlighted that differing water levels before rainfall events could correspond to different aquifer properties (porosity, specific yield), which in turn leads to variable water level responses. In addition, saturated soils before a rainfall event could also lead to longer recharge to the aquifer. The wider catchment rainfall and regional groundwater flow are also likely to be influencing the groundwater levels under the permeable pavement. Results from the residence time indicators (Table 3) showed that the modern fraction of groundwater below the permeable pavement is between 0.251 and

TABLE 3 Isotope and residence time indicator results for the SuDS boreholes

Units	$\delta^{18}\text{O}$ ‰	$\delta^2\text{H}$ ‰	SF_6 Modern fraction
BH1	-6.97	-47	0.913
BH2	-6.94	-46.7	0.616
BH3	-6.91	-46.5	0.251
BH4	-7.13	-48.8	0.527

TABLE 4 Mean estimated Kfs for the SuDS and Green areas

	SuDS area	Green Area
Kfs method 1 (mm/h)	1,925 (776)	196 (100)
Kfs method 2 (mm/h)	-	56 (29)

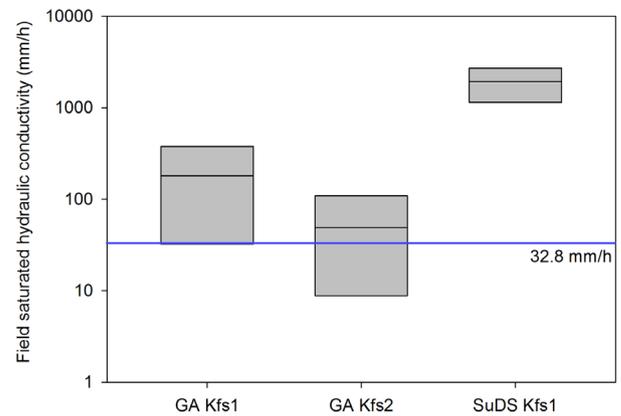
Note: The values within brackets are mean standard areas of the three infiltration experiments measured for each site. Method 1 calculates Kfs using Equation (1) and Method 2 calculates Kfs using Equation (2).

0.913. As the aquifer is unconfined, these waters would be anticipated to be young due to active circulation at these shallow depths. The SF_6 data suggest that the residence time for the groundwater is between 30 and 8 years, typical for shallow aquifers (Shand, Edmunds, Lawrence, Smedley, & Burke, 2007). This highlights that there is some storage within the aquifer and the isotope data (when compared to data in Darling and Talbot (2003)) would indicate recharge coming predominately from winter periods. The water levels in this shallow aquifer may also be influenced by the proximity of the River Thames which is ~ 350 m to the west of the permeable pavement.

The very high rainfall event (Figure 9b), however does have a relatively fast response in the groundwater. At this point, groundwater levels in BH4 increased by 0.8 m, 30 min after the peak rainfall and then rapidly decreased by 0.4 m and then gradually rose again and remained relatively high for several hours. On the other hand BH3, which was situated in the Green Area did not peak in the same way, but the water level rose slowly approximately 6 hr after the peak rainfall.

3.3 | Hydraulic conductivity (K_{fs})

The double ring infiltrometer measurements reflected the very porous nature of the SuDS gravels, where average K_{fs} was estimated to be up to 10 times higher than the average K_{fs} measured in the Green Area, using method 1 to calculate K_{fs} (Table 4). Considering the less porous

**FIGURE 11** Boxplots show the range of Kfs for the Green Area (GA) and SuDS Area Kfs1 was calculated using Equation (1) and Kfs2 was calculated using Equation (2). The blue line shows the maximum rainfall measured during the measurement period (32.8 mm/hr), relating to a 1 in 30-year return period

nature, which creates greater capillary tension and hydrostatic pressure of the Green Area soils, Method 1 is likely to overestimate K_{fs} . Considering that Method 2 provides a closer estimate of K_{fs} , the SuDS gravel matrix has an average K_{fs} of 34 times higher than in the Green Area.

Combining the highest rainfall storm (32.8 mm/hr), which occurred during the measurement period, and the K_{fs} estimates of the two site areas, shows that the open joint inter-locking pavement and coarse gravel layers of the SuDS enables very significant high rainfall intensities to enter the ground surface. On the other hand the storm event would have caused some overland excess flow in the Green Area, because not all points, that is, values below the blue line in Figure 11 in the Green Area, had sufficiently high enough K_{fs} values to allow such high rainfall intensities to infiltrate without causing surface ponding (infiltration overland flow excess).

3.4 | Groundwater quality

The results of the recent groundwater quality sampling show that little has changed since the groundwater monitoring programme carried out by the Environment Agency. No gross contamination of hydrocarbons was detected and the broad screen GCMS detected mostly plasticisers and insecticides at low (<0.01 $\mu\text{g/L}$) concentrations (Table 5). In three of the boreholes trichloroethylene was detected, again at low (<0.06 $\mu\text{g/L}$) concentrations, most likely as a legacy contaminant from previous land use. A pesticides screen detected up to 0.03 $\mu\text{g/L}$ of mecoprop, a general use herbicide sprayed on the car park to kill broadleaf weeds. This was picked up in all the boreholes with the exception of BH2, which is up

TABLE 5 GCMS screen and pesticide results for the SuDS boreholes

Units	Solvent	Plastic production	Insecticides		Pesticides
	Trichloroethylene µg/L	Cyclohexanone µg/L	DEET µg/L	Sulfur µg/L	Mecoprop µg/L
BH1	0.06	–	–	–	0.0267
BH2	0.05	–	–	0.01	<0.005
BH3	0.05	0.1	0.01	–	0.0131
BH4	–	–	–	–	0.0124

gradient and furthest away from the area where the herbicide was applied. Mecoprop is a relatively mobile, water soluble chemical and now no longer used on the SuDS car park. These water quality data suggest that the geotextile is working adequately to stop hydrocarbons migrating down into the shallow groundwater and the groundwater quality is not being adversely affected by the enhanced infiltration.

4 | DISCUSSION

4.1 | Water retention and infiltration rates of SuDS and Green Area

The combination of 6 and 20 mm aggregate layers of the permeable pavement ensures very little water retention within the SuDS. This is shown by the high frequency of high matric potential within the SuDS (Figure 7) even though there were dry events during the measurement period. This is typical of a gravel water retention curve, when large macropores cannot maintain low matric suction to retain water (Wang et al., 2013). On the other hand the mix of crushed building bricks mixed with loam and clay in the Green Area had a greater distribution of low matric potentials (Figure 7), showing that voids between the soil matrix in the Green Area can retain infiltrating rainfall and runoff up to 50% water content (as shown in Table 1). It is therefore not surprising, that the range of soil water contents between the two sites is significantly lower in the SuDS, than the Green Area (Figure 5a,b) showing that stored soil water content is up to 35% less in the SuDS in comparison to the adjacent Green Area.

Even though the SuDS site was 11 years old since installation, the average K_{fs} of 1,925 mm/hr measured by the double ring infiltrometer method was relatively high (Table 3) and compared to other studies where open joint inter-locking pavements have low sediment accumulation in the top gravel layer, as described by Fassman and Blackburn (2007), Bean et al. (2007), Brown (2007) and Huang et al. (2012). The average infiltration rate

(196 mm/hr) measured in the Green Area cacluated by Method 1 can be compared to other grassland studies using a double ring infiltrometer. Average double ring infiltrometer rates of 420 mm/hr of a heavily grazed pasture on a loam soil were measured in the Czech Republic (Sochorec et al., 2015), suggesting that perhaps the loam soil of the Green Area is even more compacted than a heavily grazed pasture. Other studies have investigated infiltration rates of similar made ground in urban locations, including an example by Schwartz and Smith (2016), who investigated improving compaction of re-made urban green areas using deep ripping of the upper soil layer and compost amendment. Using a single ring falling head method, average K_{fs} values of 50, 6 and 83 mm/hr were measured for a control site which had been left to recover as meadow land, a grass playfield prepared with topsoiling and another area with deep ripping respectively. As the single ring falling head method takes into account capillary suction and hydrostatic pressure, as does the calculation of Method 2 in our study, the K_{fs} results of our study can be compared, showing that the urban area left to mature as meadow land compares well to the average measured K_{fs} of 56 mm/hr in the Green Area.

Comparing the greater than 1 in 30 return period storm event (32.8 mm/hr) during September 16, 2018, which caused localised flooding with surface soil K_{fs} values (Figure 11), suggests that such an extreme high rainfall intensity will easily infiltrate into the open joint inter-locking pavement, into the coarse gravel layers of the SuDS site. In the Green Area, on average, the surface soil K_{fs} is also high enough to allow such a high rainfall event. However, as some K_{fs} values were lower than this rainfall intensity (Figure 11), runoff will be generated in some areas of the Green Area during such high intensity rainfall.

4.2 | Response to rainfall events

The very fast response times (<15 min, as shown in Table 2) of soil water content in upper and lower layers

of the SuDS site (Figures 9 and 10) in response to the rainfall events, shown in Figure 8, are expected when considering the high infiltration rates in the SuDS site. Also the rapid decrease of soil water peaks during the high rainfall event (Figures 9b and 10b), illustrates that rainfall rapidly drains through the coarse gravel of the SuDS, which correlates to the low water retention capacity in the upper and lower layers of the SuDS observed by the frequency of high matric potentials in both layers (Figure 7). This suggests that the SuDS design could tolerate a 1-in-30-year flood event (following the ERA threshold) of longer duration, that is, greater than 1 hr.

The results clearly show that when monitoring high intensity rainfall events, that is, the 32.8 mm/hr rainfall event infiltrating, 15-min monitoring duration was too coarse to capture the fast moving wetting curve in the upper SuDS layer. With increasing rainfall intensity, caused by climate change, monitoring of SuDS will need higher resolution to capture the true nature of SuDS designs, or infiltration measurements should be undertaken of the SuDS area, as exemplified in this study.

During the high intensity rainstorm, even though soil water content in the Green Area responded rapidly, within 15 min of rainfall infiltration (Figure 9c), soil water content in all layers plateaued between 0.45 and 0.58 m³/m³ volumetric water content for 2 hr before decreasing. This indicates that all layers had reached saturation and remained saturated for 2 hr before draining. This suggests that the construction of the Green Area can infiltrate and store a 1-in-30-year flood of 1 hr duration (following the ERA threshold). However, if the storm continued for a longer duration, surface water flooding would be highly likely.

In terms of consecutive rainfall events, the soil layers stored water in the Green Area during the first heavy rainfall (Figure 10c) and then during the following second heavy rainfall (Figure 10d) soil water content continued to rise in the lower soil layers towards saturation (Figure 10d). This suggests that further rainfall may cause the soil to become totally saturated, increasing the probability of surface water flooding, even if rainfall intensity is relatively low. On the other hand, the SuDS site, continues to allow rainfall to infiltrate and drain (Figure 10a, b) to deeper layers, even when heavy rainfall events occur within 12 days of each other. The design of the SuDS is such that it is highly permeable and recharge bypasses the gravel zone. However, groundwater levels during the following heavy rainfall (Figure 10b) rise very quickly and remain at relatively high levels for a period of time, suggesting that the transference of rainfall from the SuDS through the unsaturated zone recharges the aquifer. Unfortunately, there is no groundwater data in the Green Area to compare to Figure 10b,d, but during

all other rainfall events (Figures 9 and 10), the groundwater level below the Green Area, does not rise as high or as quickly in comparison to the groundwater level under the SuDS site.

4.3 | Implications of SuDS and urban green areas to flood risk

Even though the SuDS site has been operational for 11 years, it is still very efficient, in terms of facilitating high intensity rainfall to infiltrate into deeper gravel layers. Little clogging found between the SuDS pavers may be due to the car park being surrounded by vegetated surfaces, which has a low potential for supplying fine sediments that could be transported by surface runoff onto the car park surface. This, however, needs to be further researched to provide evidence of such processes, as this could be an important way to increase the temporal efficiency of SuDS.

Because of the rapid flow between the SuDS to the aquifer, it is important to know not only the unsaturated zone thickness, permeability and groundwater vulnerability, but also the connectivity of the aquifer to the local river. This work suggests that although a large SuDS area in a floodplain setting reduces surface runoff, this enhanced recharge through the SuDS infiltrates rapidly though the unsaturated zone, recharging the local aquifer. If this aquifer is connected directly to the nearby river, the sudden increase in aquifer level could cause additional input to the river. In addition, if the river level is already high, this can reduce the storage capacity of the system. In our specific example, the water table is already relatively shallow (<1 m below the base of the SuDS), therefore any additional inputs from the River Thames could cause flooding of the SuDS. Groundwater flooding (more specifically, clearwater flooding) occurs when antecedent conditions (high water levels and soil moisture content) combine with extreme rainfall volumes (Macdonald, Bloomfield, Hughes, MacDonald, & Adams, 2008). Further research is needed to understand the complete connectivity of water flows from SuDS to rivers to ensure that SuDS designs do not aggravate river flooding, which is important for SuDS implementation and regulation (Melville-Shreeve et al., 2018). This study reiterates the importance of having at least a 1-m separation depth between the base of the SuDS infiltration zone and ground water level all year round and this suggests that groundwater level monitoring is essential when developing SuDS into urban developments before and after SuDS implementation. Also if SuDS are near rivers, the river level should also be monitored.

The groundwater chemistry data highlights that there is no issue of hydrocarbons migrating down into the shallow groundwater and the groundwater quality is not being adversely affected by the enhanced infiltration. The geotextile was installed as an interceptor and appears to be functioning as designed. The results do however highlight that where the SuDS overlies a shallow unconfined (and therefore more vulnerable) aquifer with high water levels, chemicals used to maintain the SuDS (such as mecoprop) can have an impact.

In comparison, the Green Area is relatively permeable, which is typical of made ground, having infiltration rates of compacted urban green areas, as studied by Schwartz and Smith (2016). The majority of rainfall events will infiltrate this area, although some overland excess flows will occur for an 1-hr duration 1-in-30-year rainfall return period events, unlike the SuDS Area. Rainfall infiltrating through the mix of soil and crushed building material is retained, showing that the Green Area can store water, creating a longer lag time before it enters the aquifer. This water storage maybe of importance for countries that have seasons of drought, where water storage could be maintained for a mix of urban plant species. In these conditions, a combination of green areas with SuDS designs could be complementary.

Below the SuDS, it is the aquifer that provides water storage rather than the SuDS gravel zone. Understanding the zones of water storage and connectivity to local water bodies, such as lakes and rivers, is important and suggests that hybrid combinations of SuDS and green areas in urban settings may be preferable, depending on sub-surface characteristics.

This study shows the importance of thinking beyond the surface of the urban environment and understanding how the below ground matrix retains and facilitates water to flow to deeper aquifers that may connect to nearby rivers and drains. Large scale SuDS similar to the design tested in this study will reduce runoff, but this runoff is then transferred rapidly to an unsaturated zone that connects to an aquifer (and potentially surface water features). On the other hand, green areas are able to infiltrate heavy rainfall and can retain rainfall within the unsaturated matrix, slowing down water to nearby rivers. Because of compaction problems of green areas, perhaps a combination of SuDS and green area would benefit urban environments, particularly if there are rivers nearby. The design of SuDS is therefore a trade-off between infiltration and storage; SuDS allow infiltration of high rainfall intensities, where green areas do not have the capacity for such high infiltration flows, however, this is at the expense of reducing the rate of infiltration to allow greater storage, which may be important in areas with a hydraulic continuity to surface water features

exists. Green and grey urban infrastructure have been discussed as a sustainable option for resilient cities (Bricker, Banks, Galik, Tapete, & Jones, 2017; Depietri & McPhearson, 2017; Tedoldi et al., 2016), but there is still little understanding about how urban aquifers will respond to high discharges of surface runoff, particularly in highly urbanised estuaries.

ACKNOWLEDGEMENTS

We are grateful for the continued input from Craig Hampton (Environment Agency, UK) in helping us gain access to the permeable pavement and scientific input. From BGS, we are grateful to Barry Townsend, Debbie White, Dan Lapworth and Rachel Dearden for help with setting up the SuDS Observatory and fieldwork. Daren Goody, NERC Isotope Geosciences Laboratories and the British Geology Survey, (Keyworth, UK) Labs are also thanked for their analysis of the groundwater samples. Henry Holbrook from BGS is acknowledged for compiling the figures. Simon Price is thanked for his work in the initial stages of the project and HR Wallingford Estates Management for allowing us access to the site. From Centre of Ecology and Hydrology, Wallingford, UK (CEH), we are grateful to Katie Muchan for providing rainfall data and information on the Wallingford metrological station and to Ragab Ragab for discussions on soil moisture and infiltrometer measurements. We also thank two anonymous reviewers for helping to improve the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Archer NAL, Bell RA, Butcher AS, Bricker SH. Infiltration efficiency and subsurface water processes of a sustainable drainage system and consequences to flood management. *J Flood Risk Management*. 2020; e12629. <https://doi.org/10.1111/jfr3.12629>