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Bioretention column detention test data for percolation model evaluation

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ABSTRACT

Bioretention systems contribute to stormwater management through the detention of inflow as it percolates downwards through the growing media. Correct modelling of this process is key to the design of suitable bioretention cells. The SWMM LID module represents the flow of water downwards through the variably saturated growing media layer via a percolation model, which treats the entire growing media depth as a single homogeneous layer in which unsaturated hydraulic conductivity is estimated from moisture content and a simplified Hydraulic Conductivity Function (HCF). Controlled inflow detention tests were conducted on four bioretention columns, each with different vegetation treatments, over a 21-month period. Differences in outflow response due to vegetation treatment and system age were minimal. HCF, outflow, and media moisture content data support the adoption of a new form of HCF parameterised from routinely-characterised growing media properties. This new HCF leads to improved percolation estimates under low-flow conditions.

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Bioretention; detention; hydraulic conductivity; percolation modelling

1. Introduction

Bioretention systems are a type of green infrastructure designed for stormwater management. Most bioretention systems function in a similar way. Inflows are typically received at the system's surface, where there is ponding capacity to store stormwater volumes temporarily. The stormwater then infiltrates into the growing media and percolates through it into a drainage/storage layer. Moisture retained within the growing media either evaporates back into the atmosphere or is actively removed from the growing media by plants and subsequently released back into the atmosphere by transpiration. Stormwater that collects in the drainage/storage layer may exfiltrate into underlying soils (provided the device is unlined) or drain via an underdrain which connects to downstream stormwater controls, a receiving water course or a sewer network.

Stormwater control may be quantitatively described in terms of retention (i.e. the proportion of inflow that never becomes outflow, instead leaving the system via evapotranspiration or infiltration) and detention (i.e. the lag and attenuation of the outflow/runoff hydrograph). From an outflow detention perspective, the two most important processes are the infiltration/percolation in the growing media and the presence or absence of any outflow restriction. Here we focus specifically on the detention effects due to percolation in the growing media.

Stormwater engineers require fit-for-purpose hydrological/hydraulic modelling tools to simulate the rainfall/runoff behaviour of bioretention systems, including their performance in response to extreme events. Lisenbee et al. (2021) present a comprehensive overview of the most prevalent modelling tools for simulating the hydrological response of bioretention systems. Of the 17 bioretention models presented in Lisenbee et al. (2021), the US EPA's Storm Water Management Model, SWMM (Rossman 2015), is the most well-known of the available open-source modelling tools, accounting for $\approx 40\%$ of studies reviewed by Nazarpour, Gnecco, and Palla (2023).

To simulate the passage of stormwater through the growing media, SWMM employs a simplified depth-integrated percolation model. This approach differs from more complex tools, such as Hydrus-1D, which numerically solve the Richards equation using finite element schemes (Šimůnek, van Genuchten, and Šejna 2016).

Modelling approaches with greater complexity, e.g. Hydrus, may offer more accurate representations of unsaturated flow behaviour in bioretention growing media compared with the simplified approach used in SWMM (Liu and Fassman-Beck 2017a, 2017b). However, they do not lend themselves to integration into the drainage network modelling tools used by stormwater engineers (Lisenbee et al. 2021). Hence, this study focusses on the simplified SWMM approach (whether this be SWMM itself, or tools built on the SWMM engine) which is widely used in current stormwater management design and planning.

Equation (1) presents the percolation method used in SWMM, in which the HCF is described by a single parameter, *HCO*:

$$f_{perc}(t) = \begin{cases} K_s \times e^{(-HCO(\theta_s - \theta(t)))} & ,\theta > \theta_{fc} \\ 0 & ,\theta \leq \theta_{fc} \end{cases} \qquad (1)$$

where $f_{perc}(t)$ is the percolation rate at time t, K_s is the saturated hydraulic conductivity, *HCO* is a constant, θ_s is media porosity,

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θ_{fc} is volumetric moisture content at field capacity, and $\theta(t)$ is volumetric moisture content at time t.

Very limited data is available in practice to validate and/or refine this modelling approach. Considerable research effort has been invested in recent years to monitor the hydrological performance of installed bioretention devices in the field – see De-Ville et al. (2021) and Nazarpour, Gnecco, and Palla (2023) for reviews of relevant recent studies. The data derived from such studies provide extremely useful direct evidence of hydrological performance, but – for model development and validation purposes – they may be limited by: (i) being locally specific in terms of both system components and climate; and (ii) monitoring periods that are often too short to provide clear evidence about performance in high return period events, such as those associated with urban flooding. In practice, it can also be difficult to dissociate observed effects due to retention from those due to detention processes alone (Stovin, Vesuviano, and De-Ville 2017). There are surprisingly few data sets that permit detention processes to be quantified robustly to support model development and validation.

Laboratory studies permit a more careful exploration of the growing media's detention characteristics. The *HCO* term in Equation (1) represents the media's Hydraulic Conductivity Function (HCF). Liu and Fassman-Beck (2018) presented comprehensive new laboratory data to describe the HCFs of 14 engineered media with varying compositions, noting that media typically utilised within green roofs and bioretention cells behaves differently to a traditional soil. This is important because the recommended approach to identifying a suitable *HCO* value in the SWMM Manual (Rossman 2015) is based on existing analysis of natural soils, i.e. the Saxton and Rawls (2006) transfer function:

$$HCO = 0.48 \times (\%\text{Sand}) + 0.85 \times (\%\text{Clay}) \tag{2}$$

Peng, Smith, and Stovin (2020) reached similar conclusions regarding four different green roof growing media. Peng, Smith, and Stovin (2020) introduced controlled detention tests to characterise the media's outflow response, and also highlighted the value of simultaneously monitoring the moisture content within the media for model validation. Comparable data from a more typical bioretention media installed to a more representative depth would clearly be useful for evaluating Equation (1).

While Liu and Fassman-Beck (2018) and Peng, Smith, and Stovin (2020) highlighted that HCFs derived from natural soils (such as the Van-Genuchten Mualem or Durner Mualem HCFs) typically did not represent engineered growing media particularly well, they did not include direct comparisons with the simplified HCF presented in Equation (1). Peng, Smith, and Stovin (2020) proposed a 'three-segment curve' to characterise the typically observed HCF shape, in which the gradient (on a semi-log plot) increased as the volumetric moisture content fell towards field capacity. This observation implies that a characterisation based on a single slope parameter, Equation (1), may fail to represent these media.

These authors, among others, have also highlighted that the heterogeneous nature of engineered growing media introduces considerable uncertainty into any modelling exercise.

Liu and Fassman-Beck (2017a) and De-Ville and Stovin (2022) hypothesised that limitations to Equation (1) could be the cause of unrealistic outflow responses observed under low-flow simulations. However, the suitability (or not) of Equation 1 to characterise the unsaturated hydraulic conductivity associated with engineered growing media – as utilised in bioretention systems – has not been rigorously evaluated to date.

Several researchers report evidence that K_s characteristics associated with full-scale bioretention cells – and their associated infiltration, percolation and clogging behaviours – evolve over time in response to imposed inflow sediment loads and the presence of vegetation. In a comprehensive exploration of bioretention systems installed in the field in Australia, Le Coustumer et al. (2009) highlighted that systems with initially high saturated hydraulic conductivities may be more liable to surface clogging compared with those characterised by a lower initial K_s. Krauss and Rippy (2024) have highlighted links between vegetation type and the development of K_s over time in a range of US bioretention cells. While these studies provide valuable information about the evolution of in-field characteristics, the focus on K_s provides limited insight into unsaturated conditions, or actual outflow hydrographs, which are key to the development of percolation modelling tools.

Laboratory characterisations of unsaturated hydraulic conductivity and detention have to date largely been conducted on virgin, unplanted, growing media. Understanding how the presence/absence and type of vegetation affects these key detention processes is also important.

As part of the 'Urban Green DaMS' research project, two sets of experiments were established to fill that need: pilot-scale lysimeters located at the National Green Infrastructure Facility (NGIF) at Newcastle University; and column tests at The University of Sheffield. Both experiments utilised the same growing media and vegetation treatments described by De-Ville et al. (2021, 2024). This paper focuses on the column detention tests.

The objectives of this paper are to:

- Present new laboratory data acquired to characterise: (i) the detention behaviour of bioretention columns over time and as a function of alternative vegetation treatments; and (ii) the HCF associated with a representative bioretention growing media;
- Review the validity and robustness of the HCF used within the SWMM percolation model, proposing an alternative functional form if appropriate;
- Determine whether the detention behaviour observed in bioretention columns is affected by ageing or vegetation treatment.

2. Materials and methods

2.1. Detention column tests

2.1.1. Experimental setup

Experiments were conducted over a period of 21 months from September 2020 to June 2022. The tests were undertaken using the same columns that were used for evapotranspiration (ET) tests which were fully reported in De-Ville, Peng, and Stovin (2024), with detention and retention tests (ET tests) being alternated over time. Testing took place within a climate-regulated greenhouse exposed to ambient lighting conditions at The University of Sheffield's Arthur Willis Environment Centre (Sheffield, UK). Temperature and relative humidity were controlled within the growth chamber, while solar radiation levels were restricted (via semi-transparent blinds) only when extreme sunlight levels affected temperature control performance.

It should be noted that Autumn 2020 corresponded to the easing of COVID lockdown conditions in the UK, and the need to establish the columns rapidly ahead of the following year's growing season, combined with significant problems sourcing equipment from suppliers, placed restrictions on the planning and execution of the detention experiments. A pragmatic decision was taken to ensure that all columns were tested under an identical inflow regime for each trial, but the specific inflow profile evolved as the trials progressed. Whilst this prohibits direct comparisons between the outflow profiles over time, it does not prohibit comparisons between different treatments within each trial.

In the context of green roof test beds exposed to ambient rainfall patterns, Stovin et al. (2015); Stovin, Vesuviano, and De-Ville (2017) and De-Ville, Menon, and Stovin (2018) argued that the fitting of a suitable hydrological model may be utilised to understand whether/how any underlying hydrological properties of the system have changed over time. The original intention was to apply a similar approach here.

Twelve Bioretention Columns were constructed to explore the effect of vegetation treatment and water stress on both evapotranspiration (ET) and outflow detention. These 12 columns replicate the full depth profile of pilot-scale bioretention lysimeters located at the National Green Infrastructure Facility (NGIF), Newcastle-Upon-Tyne, UK. Each column was 152 mm in internal diameter and 1100 mm tall. They comprised (from bottom-to-top): a 180 mm drainage layer of 4/40 mm aggregate, a 120 mm transition layer of 2/6 mm aggregate, a 700 mm layer of growing media, and a 100 mm ponding zone (Figure 1(a)).

The growing media for this study was sourced locally within Sheffield, UK, and comprised 100% recycled waste components. The waste components were (by weight): 50% Quarry Waste Material (5–20 mm); 25% Crushed Recycled Glass; 15% Green Waste Compost; and 10% Sugar-beet Washings (topsoil). The physical characteristics of this media are presented fully in De-Ville et al. (2021). The media has a lab-derived saturated hydraulic conductivity of 101 mm/hour, porosity of 0.443 m^3/

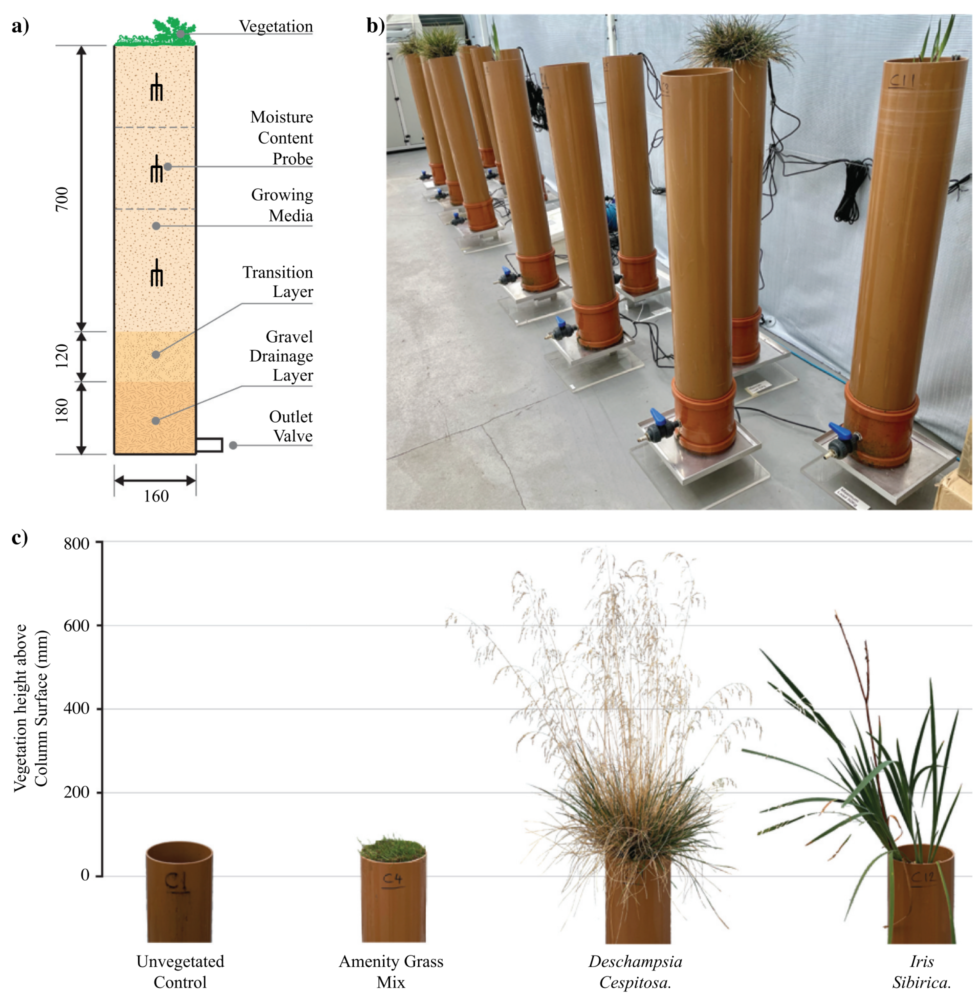

Figure 1. The bioretention columns: (a) Schematic cross-section that indicates moisture probe locations and soil volumes associated with each probe. All dimensions in mm. (b) Assembled columns on load cells inside the growth chamber (April 2021). (c) Examples of the four vegetation treatments (September 2021).

m^3, and field capacity of 0.149 m^3/m^3. Field capacity is at the lower end of the range of values reported in the literature due to the higher than usual gravel content. The media is 43.7% fines and sand, and 56.3% gravel. The growing media is used extensively throughout Sheffield in the City Council's Grey-to-Green retrofit bioretention systems (Susdrain 2016).

Four vegetation treatments were trialled (in triplicate) across the 12 columns: an unvegetated control, an amenity grass mix, a tufted hair-grass (*Deschampsia cespitosa* 'Goldtau') and an iris (*Iris sibirica* 'Ruffled Velvet'). Moisture content probes were located in one sample column from each vegetation treatment. The moisture content probes (METER 5TMs) were positioned vertically at depths of 100, 300 and 500 mm below the surface (Figure 1(a)).

2.1.2. Description of detention tests

Five detention trials were conducted, each taking place directly before or after an ET trial. Detention trial data were collected from unvegetated control column C2, amenity grass column C5, *D. cespitosa* column C8 and *I. sibirica* column C11 (denoted herein as C, AG, DC and IS respectively).

Prior to all detention trials, the bioretention columns were saturated by closing the column's outlet valve (blue lever in Figure 1b) and applying water until a constant ponded head of at least 50 mm was maintained. Columns were saturated to minimise the effects of any retention processes on the detention trials. Columns were left in a saturated condition for 24 hours. The outlet control valve was then opened and the columns allowed to drain freely under gravity for a period of 2 hours, with the intention that they would drain down to field capacity. Columns were then subjected to the specific target inflow applications detailed in Table 1. The outlet control valves remained open during detention testing to permit outflow rate monitoring.

Trial I was conducted on columns prior to the establishment of any of the vegetation treatments, i.e. all columns were unvegetated. Inflow was applied to the surface of each column via a network of 11 0.5 l/hr Netafim drippers supplied with water via a mains connection. Application of inflow was controlled by a solenoid valve connected to a Campbell Scientific CR800 data logger to provide automated repeat applications of inflow. Each of the four bioretention columns was subjected to three flow applications, each of a 5 mm/min constant intensity (approximately equal to the mean intensity for an M30–60 design storm in Newcastle-Upon-Tyne with a 10:1 loading ratio) for a 10-minute duration with an inter-application period of 20-minutes. Outflow from the column's outlet was directed to an Aercus Instruments WS2083 tipping bucket gauge with a calibrated tip-depth of 0.085 mm, recording at a 1 s temporal resolution. Moisture content data was not collected during this trial.

Trial II was conducted at the end of the first ET trial in May 2021. Vegetation had been allowed to establish since planting in October 2020. Inflow was applied to the surface of each column via a network of 11 infinite rate drippers (i.e. non limiting) with flow rates controlled by a peristaltic pump drawing from a constant head reservoir. The pump was controlled by a Campbell Scientific CR800 data logger to provide automated repeat applications of inflow. The flow application regime was the same as Trial I, with outflow monitored using the same tipping bucket gauge. Volumetric water content data was collected from the 3-probe vertical array as dielectric permittivity. METER suggest that their factory calibration 'may not be applicable to all soil types', and so a media specific calibration was undertaken – a detailed description of this is provided in the accompanying dataset (De-Ville and Stovin 2024). Pump control and data collection operated at a 5 s temporal resolution. The DC column was not tested during this trial due to timing and access limitations associated with the COVID-19 pandemic.

Trial III was conducted prior to the second ET trial in August 2021. Vegetation was considered to be fully established during this trial (Figure 1(c)). Inflow application used the same techniques as Trial II but with a higher target intensity of 9.2 mm/min (approximately equal to the mean inflow intensity for an M30–60 minute design storm in Newcastle-Upon-Tyne with a 19:1 loading ratio) applied for a 20 minute period separated by a 40 minute inter-application period. The application period was lengthened to achieve a period of equilibrium between inflow and outflow rates which had not been observed during the shorter 10-minute flow applications. Column outflow and volumetric water content data were collected at a 5 s resolution for all column configurations.

Trial IV was conducted after the second ET trial in September 2021. Vegetation was in approximately the same condition as during Trial III. Inflow application used the same techniques as Trial II but three variable intensity 60-minute duration design storm profiles were applied separated by a 120 minute inter-application period. The applied design storms were all derived for Newcastle-Upon-Tyne, and represented the M10–60, M30–60 and M100–60 design rainfalls for the column area only (a 1:1 loading ratio). Column outflow and volumetric water content data were collected at a 5 s resolution for all column configurations.

Table 1. Summary of trial target conditions.

Trial	Date	Inflow Type	Inflow Intensity (mm/min)	Inflow Depth (mm)	Application Duration (min)	Inter-test Duration (min)	No. of Applications
I	09/2020	Constant	5.1	50.5	10	20	3
II	05/2021	Constant	4.9	48.7	10	20	3
III	08/2021	Constant	9.2	184	20	40	3
IV	09/2021	Design Storm	1.4*	22.7	60	120	1
		Design Storm	1.8*	29.1	60	120	1
		Design Storm	2.4*	38.2	60	120	1
V	06/2022	Design Storm	1.8*	29.1	60	120	1
		Design Storm	5.5*	87.3	60	120	1
		Design Storm	11.0*	174.6	60	120	1

*Peak Intensity.

Trial V was conducted after the third ET trial in June 2022. Vegetation was observed to be similar in appearance and density to that during Trial II. Inflow application used the same techniques as Trial IV but inflows were scaled to represent a 5:1 loading ratio. Higher peak inflows were not possible due to the limited maximum capacity of the peristaltic pump. The DC column was not tested during this trial due to timing and access limitations associated with the COVID-19 pandemic.

The different inflow rates and profiles support the assessment of detention performance (and model performance) across a comprehensive range of conditions.

The topmost moisture content probe failed for both the Amenity Grass and *Iris sibirica* columns in Trials IV and V.

All the detention test data is available in a fully documented open-access database: De-Ville and Stovin (2024). This dataset also includes a mass-balance analysis where the majority of mass balance errors were observed to be less than 5% (Dataset Section D5).

2.1.3. Column data analysis and interpretation

The detention data were recorded at a temporal resolution of either 1 (Trial I) or 5 (Trials II-V) seconds. All data were converted to a 1-minute time step, starting from the onset of applied inflow. Outflow data was cumulated over 1-minute intervals, whereas the moisture content data was averaged over the preceding minute.

The results for all trials were plotted to permit qualitative assessment of both the outflow and moisture content temporal profiles. In addition, Peak Attenuation was determined for each of the three flow peaks per trial to permit a quantitative evaluation of differences between vegetation treatments within each trial. Peak Attenuation is defined as $(\text{max inflow} - \text{max outflow})/\text{max inflow}$ based on a 5-minute moving mean of the 1-minute data.

Non-parametric inferential statistical tests (Kruskal-Wallis and Dunn's pairwise comparisons) were conducted to identify any statistical independence between grouped data at the .05 significance level (α). These tests were only conducted to identify differences between the mean Peak Attenuation ($N = 3$) associated with the four different vegetation treatments within each of the five trials. For trials II and V, only three different vegetation treatments were considered. Caution should be exercised when interpreting the *P* values derived from these statistical tests given the low sample sizes.

Due to the variation in inflow profiles, direct Trial by Trial comparisons cannot be used to infer whether any differences in Peak Attenuation over time are a result of ageing effects (real physical changes) or simply a reflection of variations in the applied inflow profile. Instead, an attempt was made to comment on this as part of the model evaluation exercise, see Section 2.2.

2.2. Model evaluation

SWMM employs a simplified depth-integrated percolation model, Equation (1), in which the HCF is described by a single parameter, *HCO* (Rossman 2015). Equation (1) will be referred to as the 'Kslope HCF' henceforth.

Supplementary Material A provides a detailed comparison between HCF data collected in a laboratory infiltration column and the simplified Kslope HCF function for five different engineered growing media, including the media used here. The comparisons consistently highlight limitations to the exponential Kslope HCF, which lead to hydraulic conductivity (or percolation rates) being over-estimated when the moisture content is close to field capacity. These observations led to the proposal of an alternative HCF, termed 'New HCF', Equation (3). The proposed HCF takes the form of a power function, which is 'pinned' to the media's K_s, θ_s, and θ_{fc} values:

$$f_{perc}(t) = \left(\begin{array}{ll} K_s \times {S_{act}}^n & ,\theta > \theta_{fc} \\ 0 & ,\theta \le \theta_{fc} \end{array} \right. \quad (3)$$

$$S_{act} = \frac{\theta - \theta_{fc}}{\theta_s - \theta_{fc}} \quad (4)$$

Note that S_{act} as defined here differs from the normal definition of effective saturation as it adopts θ_{fc} as the lower bound in place of residual moisture content. The power *n* in Equation (3) was assigned the value 5/2, following initial calibration. A comparison between the HCFs of Equation (1) and Equation (3) is presented in Figure 2.

The SWMM percolation model has been replicated in-house using MATLAB, using both equation (1) and equation (3). Percolation rates were modelled using both HCFs based on input rainfall and physical characteristics of the media only. Moisture contents and effective saturations were determined entirely within the model based on these inputs. Surface infiltration was assumed to happen instantaneously, and the initial moisture content was set to θ_{fc}. The code included checks to ensure that percolation rates could not exceed K_s and that moisture in excess of θ_s was temporarily retained as ponding.

2.2.1. Lysimeter data model comparison

De-Ville and Stovin (2022) compared SWMM simulation results against observed outflow data from a storm event monitored at

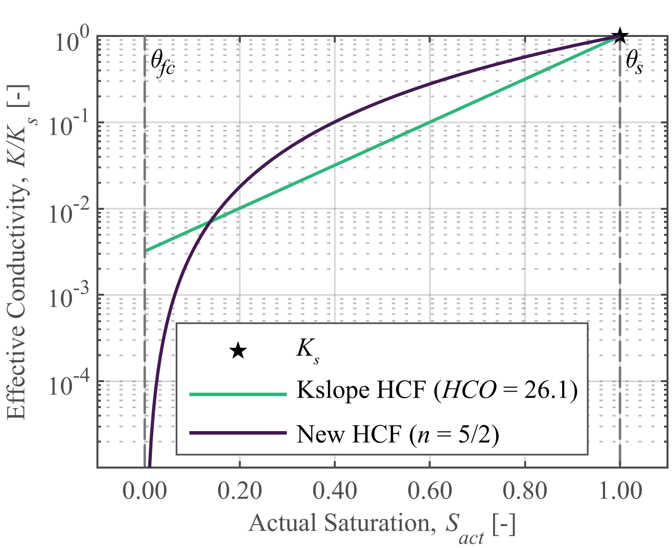

Figure 2. Comparison of the Kslope HCF (equation (1)) and new HCF (equation (3)).

NGIF. This data was collected in July 2021 from a lysimeter with an identical vertical profile to the columns considered here. The lysimeters only received incident rainfall as inflow. A more complete overview of the lysimeter set-up is presented in Green, Goddard, and Stirling (2022). The comparisons highlighted a limitation of the Kslope HCF, in that percolation rates close to field capacity appeared to be significantly overestimated, and the outflow was prematurely terminated. The modelling exercise is repeated here to establish whether or not the New HCF (equation (3)) results in an improved outflow simulation. In this case, for comparability with De-Ville and Stovin (2022), the model was applied using 5-minute time steps and the following parameter values were adopted: K_s = 579 mm/hr; $HCO = 26.1$; $\theta_{fc} = 0.15\ \mathrm{m^3/m^3}$; and $\theta_s = 0.44\ \mathrm{m^3/m^3}$. Visual comparison between simulated and measured outflow was used to qualitatively evaluate the two alternative HCF functions. The modelled outflow series were compared with the measured data using R_t^2 (Young, Jakeman, and McMurtrie 1980) to assess the goodness-of-fit.

2.2.2. Column detention test model comparison

In the final section we consider how well the two percolation models represent our detention column data, which were obtained under controlled conditions and represent a far greater range of inflow rates compared with the lysimeter data.

The model input parameters values for θ_s and HCO again correspond to the media characterisation originally reported in De-Ville et al. (2021) and applied in Green, Goddard, and Stirling (), i.e. $HCO = 26.1$ and $\theta_s = 0.44\ \mathrm{m^3/m^3}$. However θ_{fc} and K_s were revised based on the following considerations.

For θ_{fc}, $0.2\ \mathrm{m^3/m^3}$ was used, as this value was most commonly observed at the mid-depth of the detention columns at the start of each experimental run.

The K_s value of 101 mm/hr (1.68 mm/min) reported in De-Ville et al. (2021) falls well below the peak outflow rates observed in the detention tests reported here, i.e. approximately 8.5 mm/minute ($\approx$ 510 mm/hr) (Trials III and V). The model simulations reported in De-Ville and Stovin (2022) used a value of 579 mm/hr, based on in-situ Saturo testing of the same growing media in installed systems in Sheffield, while Green, Goddard, and Stirling () reported values of up to 648 mm/hr from the NGIF lysimeters. In this case K_s was measured using a Soil Moisture Equipment Corporation Guelph Constant Head Field Permeameter.

The original laboratory characterisation (De-Ville et al. 2021) of K_s was reported as (101$\pm$82 mm/hr) based on three repeat tests. The high standard deviation reflects the heterogeneity of the media samples. It is also noted here that the tests were done using a compacted sample. Smith et al. (2021) note that the effects of spatial heterogeneity of soil typically increase with scale. Thus, small-scale laboratory tests, which may not capture preferential flow pathways, are often reported to result in K_s values which are lower than field measurements by as much as an order of magnitude (Ebrahimian et al. 2020; Smith et al. 2021). For these reasons it is considered that the lower and upper limits for K_s are of the order of 510 and 1000 mm/hr (8.5–16.7 mm/hr). Models were run for both of these K_s values to generate a 'window' of expected outflow profiles for comparison with the new column detention data. The modelled outflow series were compared with the measured data using R_t^2 (Young, Jakeman, and McMurtrie 1980) to assess the goodness-of-fit.

Changes in the qualitative model performance and model performance metrics between trials were explored to understand whether any systematic changes in the columns' physical properties had occurred over time.

3. Results

3.1. Detention column tests

3.1.1. Qualitative assessment of outflow profiles

Figure 3 presents the inflow and outflow profiles for all five Trials. In most cases, differences in the responses due to vegetation treatment appear to be relatively minimal. None of the columns in Trial I were vegetated, but the differences between the outflow responses from the columns in this trial (Figure 3(a)) are comparable to the differences observed in later trials (Figure 3(b-e)). In Trials III and IV there is some evidence that the outflow from the *D. cespitosa* occurs later and with a lower peak compared with the other treatments (Figure 3(c-d)). Note that results for Trials II and V are not available for this vegetation treatment. Similarly, the Control (unvegetated) treatment detention performance appears to deteriorate over time compared with the vegetated treatments, although any differences appear to be relatively minor.

While the experiments were designed to ensure that columns were drained down to field capacity at the start of each trial, Trials I and II both indicate higher outflow volumes and peaks for the later applications of inflow (Figure 3(a-b)). This is because outflow did not return to zero between each application of inflow, such that the column remained above field capacity at the start of the subsequent applications.

It may be seen that – for all vegetation treatments – the ability of the bioretention column to attenuate the inflow peak is much more strongly influenced by the inflow profile than the vegetation treatment. Attenuation is consistently low for Trial III, which was characterised by relatively long duration, high intensity, applications and the highest overall inflow volume. Conversely, Trial IV, characterised by relatively small inflows, demonstrated the best Peak Attenuation performance.

For Trial III, where inflows of 9.2 mm/min were sustained for 20-minute periods, there is evidence of a plateau in outflow at $\approx$ 8.5 mm/min. This plateau may represent the growing media's approximate K_s value as the hydraulic gradient within each column was close to 1.0 during this time.

3.1.2. Quantitative assessment of peak attenuation performance

The mean Peak Attenuation values per treatment and Trial are presented in Figure 4. Visual inspection of the data does not reveal any evidence of systematic differences between vegetation treatments developing over time. This is confirmed by statistical analyses (Kruskall-Wallis and Dunn's pairwise comparisons) which indicate statistical independence between some of the vegetation types in Trial III only ($P = 0.0984$).

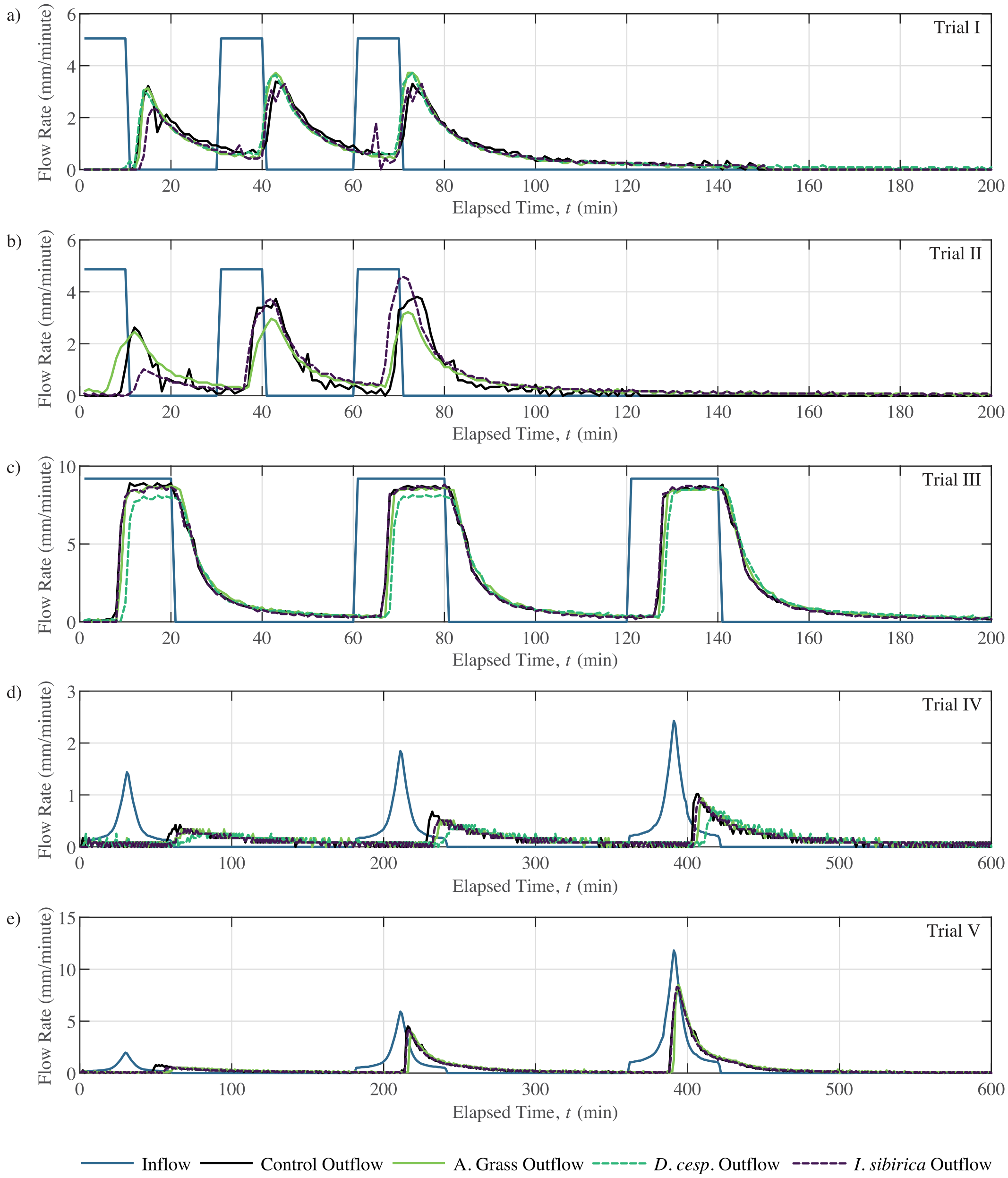

Figure 3. Raw inflow and outflow data from the column detention tests for all five trials..

Owing to the limited statistical independence between vegetation types, all peak attenuation data was compared across the five trials. This analysis indicates that peak attenuation in Trial III is statistically independent from all other trials ($P = 0.01$) due to this trial's sustained high intensity of inflow. The final application in the Trial V set had a similar total depth compared with the three repeated applications in Trial III, but the Peak Attenuation was notably better in the former (mean 0.272 for Trial V versus 0.064 for Trial III over $3\times$ vegetation treatments). This reflects the fact that the average inflow intensity in the Trial V event was approximately one-third of the intensity associated with the Trial III events, such that the column had greater capacity to moderate the peak. Qualitative and quantitative analysis confirms that – for all vegetation treatments – the ability of the bioretention column to attenuate the inflow peak is much more strongly influenced by the inflow profile than the vegetation treatment.

3.1.3. Moisture content profiles

Figure 5 presents the moisture content profiles for Trials II-V. No moisture content data was collected for Trial I. Figure 5(a) highlights the vertical variation in moisture content that was typically observed in all Trials and all treatments. This example is the Trial II Amenity Grass; all other vertical profile data sets are presented in Supplementary Material B. These profiles clearly show the time delay associated with the inflow moving down through the layers of the growing media, with the Top probe's reading increasing sooner and more rapidly compared with the Middle and Bottom probes. Similarly, the gradient in profile, from lowest moisture content at the Top to highest at the Bottom, is consistently observed. The only exceptions were the Control column, Trial II, and the *D. cespitosa* column (Trials III and IV).

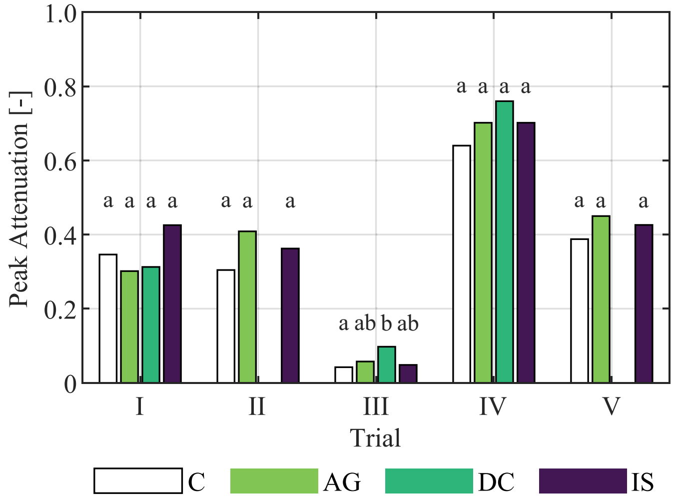

Figure 4. Mean peak attenuation as a function of vegetation treatment and trial number. Statistical groupings indicated by a, b, c etc.

Figures 5(b-e) show the data from the middle probe only for Trials II-V for all vegetation treatments. The Middle probe is taken to best represent the temporal variation in 'bulk' moisture content of each column. Note that the middle probe for the *I. sibirica* column shows indications of probe failure/partial performance in Trials IV and V, with erratic measurements and some data exceeding the growing media's nominal porosity ($0.44\ m^3/m^3$). As expected, the moisture content profiles rise and fall in response to the inflows and correlate with the outflow behaviour shown in Figure 3. None of the upper moisture content probes indicated values in excess of the media's nominal porosity ($0.44\ m^3/m^3$) and surface ponding was not observed in any trials.

Some of the Middle and Bottom probes recorded moisture contents close to θ_s during Trial III and the final application of Trial V. This provides further evidence that the plateau in flowrates corresponds to the system reaching $K_s \approx 8.5$ mm/min, as observed in Section 3.1.1.

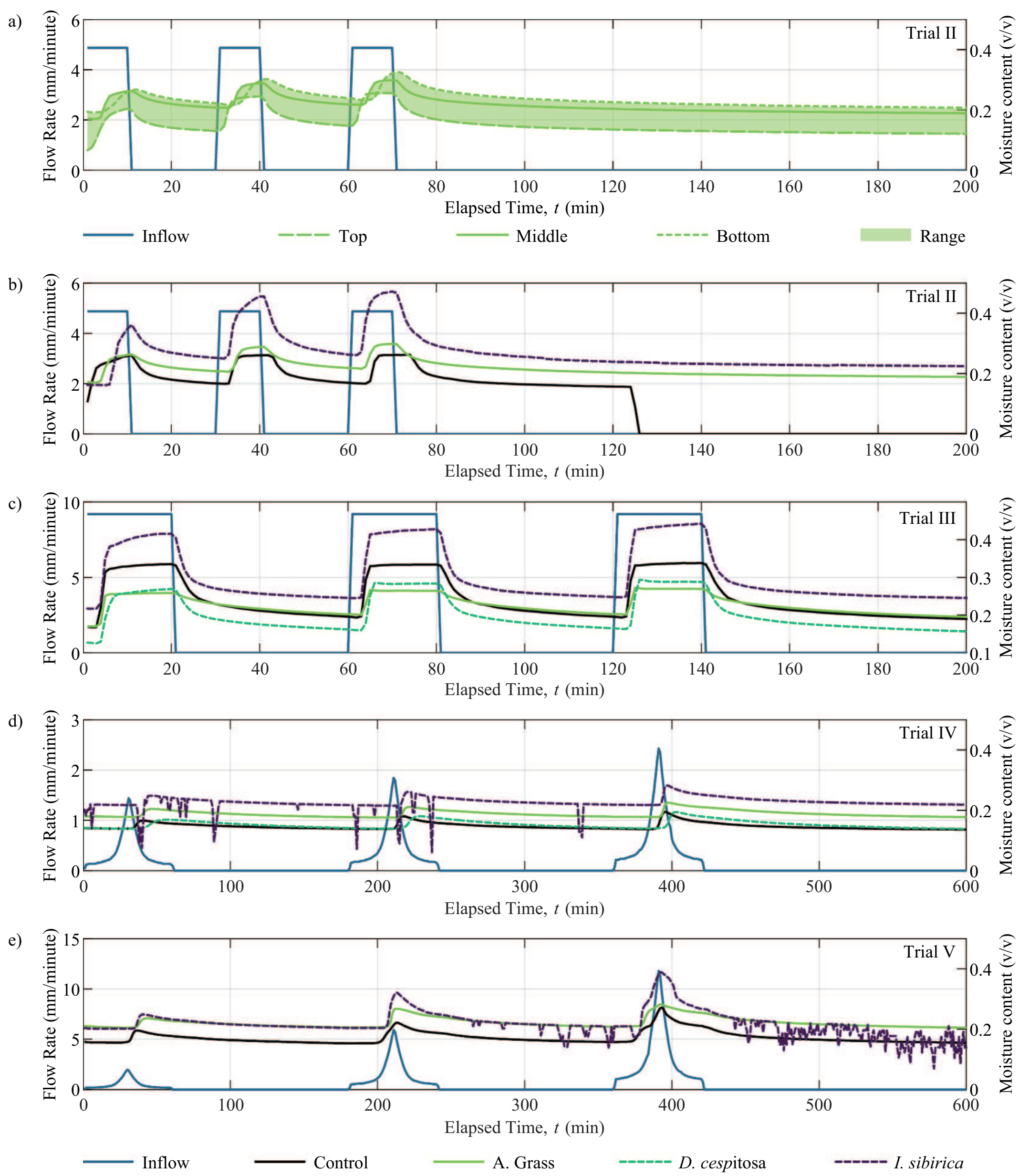

Figure 5. Moisture content profiles from the column detention tests. (a) vertical variation in moisture content for trial II amenity grass. (b-e) comparison of middle moisture probe readings for all column configurations from trial II to trial V.

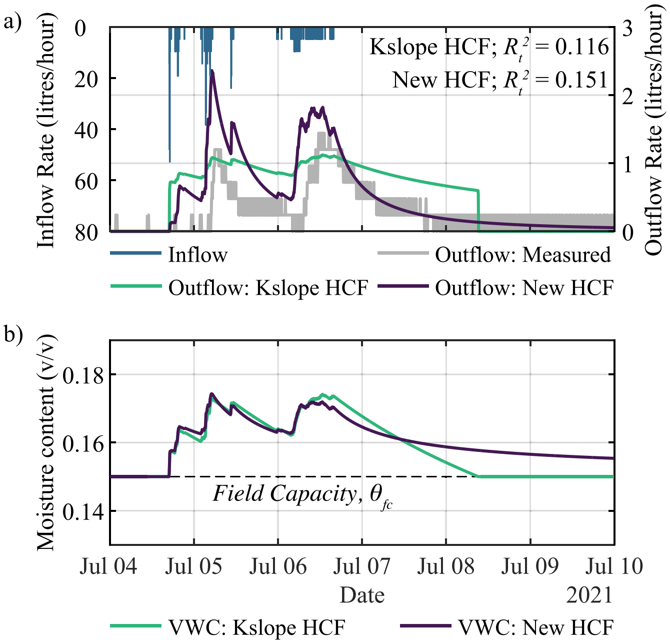

Figure 6. Modelled outflow responses compared against monitored lysimeter data. (a) Inflow and outflow data; (b) Simulated moisture content.

3.2. Model evaluation

3.2.1. Lysimeter data model comparison

Figure 6a presents the lysimeter data for a real event monitored at the NGIF lysimeter in July 2021. Figure 6a clearly reproduces the problematic outflow profile associated with the Kslope HCF form of percolation model originally highlighted by De-Ville and Stovin (2022), and also demonstrates that the New HCF function leads to a far more realistic profile under these low flow conditions. There is some evidence that the New HCF leads to overestimation of the peak flows which results in a low R_t^2 value, but this may reflect the omission of any infiltration or drainage component in the model. The recession limbs following each peak are particularly well reproduced by the New HCF (Kslope HCF $R_t^2 = 0.297$, New HCF $R_t^2 = 0.902$). It is interesting to note how minor the differences in moisture content are compared with the resulting differences in outflow rate (Figure 6(b)).

3.2.2. Column detention test model comparison

Figure 7 presents a sample comparison between the measured and modelled outflow data, in this case for the Amenity Grass column. Data from all four tested columns is presented in the Supplementary Material, Appendix C.

Whilst neither model performs perfectly, both give a reasonable outflow response, and there is some evidence that the New HCF reproduces the moisture content profiles more consistently than the Kslope HCF.

There is no strong evidence that model performance improves or worsens with respect to time (Trials I to V), although it is acknowledged that minor systematic variations may be masked by the different inflow profiles used in the five respective trials.

Both models show a tendency to generate outflow ahead of the observed outflow at the start of the event; this reflects the limitation inherent in any bulk moisture content-based model. In the physical system, the moisture content at the bottom of the column will remain unchanged for a period of time after the start of inflow, as the wetting front gradually moves downwards. More sophisticated finite element modelling approaches (such as Hydrus-1D) are able to reproduce this phenomenon through the representation of the media as multiple layers. However, in the bulk approach adopted in SWMM, any inflow leads to a change in the entire bulk moisture content, leading to the early generation of a percolation flux at the bottom of the column.

The model fits shown here may be improved in practice, as the inclusion of a surface infiltration function may delay the onset of outflow to some extent.

Given these limitations, fitting/optimisation of model parameters in an attempt to detect differences in the underlying physical characteristics of the growing media was not judged to be appropriate.

While Figure 7 does not show any significant benefit associated with the New HCF, the comparisons presented in Figure 6 and Supplementary Material C tend to confirm that the New HCF leads to improved model fits under low-flow conditions (Trials I, II and IV).

Figure 8 presents data from the Amenity Grass column across all Trials. R_t^2 values are similar for the two HCFs for the high-flow trials (III and V), but clearly better for the New HCF in the lower flow trials (I, II and V). Supplementary Material D confirms that this is also the case for the Control, *D. cespitosa* and *I. sibirica* columns. The comparisons do not suggest any systematic differences over time or as a result of the different vegetation treatments.

4. Discussion

Given the small number of monitored tests, just four columns and five inflow Trials, it was not possible to obtain rigorous statistical analysis to fully support all of the observations. Therefore, further work, with a more comprehensive and consistent test programme would clearly be of value. Nonetheless, important lessons can be learnt from this preliminary study.

The data presented here did not provide any systematic evidence that the detention characteristics of a bioretention column changed as a result of different vegetation treatments, or of ageing over a period of 21 months. Additional work (not presented here) was done to explore the recession rates (as an indicator of internal drainage behaviour). The extracted recession limbs showed remarkable consistency, both over time and across different vegetation treatments. These observations imply that the complete dataset, comprising four vegetation treatments and five detention Trials, can be considered to be representative of virgin media, for the purpose of model development and validation.

However, the data should not be interpreted as suggesting that changes will not occur in full-scale bioretention systems subjected to more representative inflow conditions over longer periods of time. Only clean water was applied in this study, and therefore the potential risks associated with clogging due to

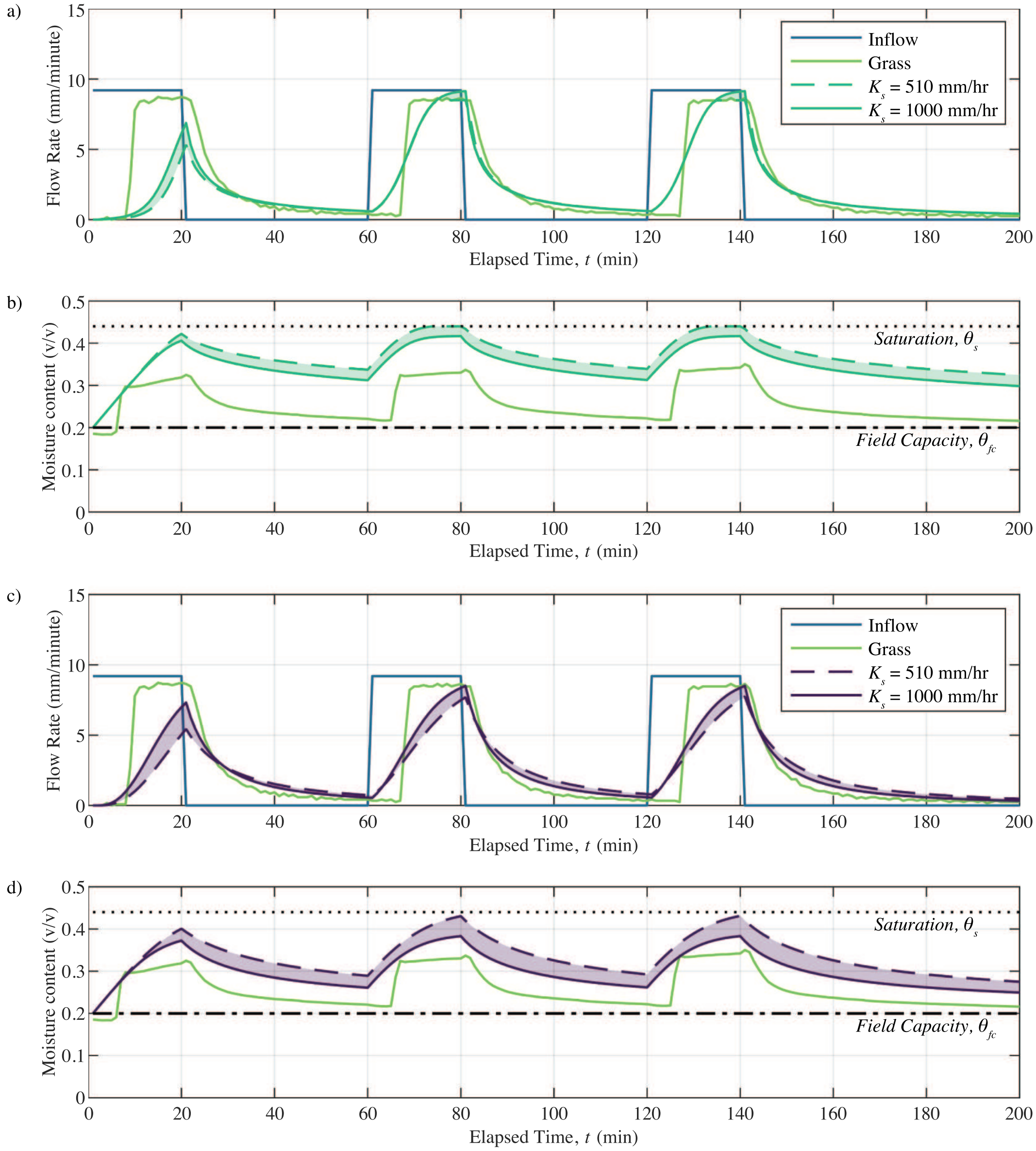

Figure 7. Model comparisons for trial III assuming K_s = 510–1000 mm/hr and θ_{fc} = 0.2 v/v. Monitored data corresponds to the amenity grass column. (a) and (b) Kslope HCF; (c) and (d) New HCF. (a) and (c) Outflow profiles; (b) and (d) Moisture content profiles.

suspended solids in urban road runoff have not been considered here. The columns were also normally (between detention tests) only subjected to incident rainfall, so the long-term inflow hydraulic loading was also much less than would be expected to occur in reality. The effects of increased hydraulic and sediment loadings on ageing should therefore be the topic of further research.

While the original intention was to apply model parameterisation to explore changes in system characteristics over time, the limitations of the bulk percolation model were judged to be too great to proceed. However, it was interesting to note that model goodness-of-fit – using either the Kslope HCF or the New HCF with parameters defined from basic soil characterisation – did not change markedly as a result of time or vegetation treatment.

There are limitations inherent in a bulk percolation modelling approach, such as the one implemented in SWMM. Nonetheless, the data presented here provides confidence that the model can reproduce the key performance quantities of interest for stormwater management planning, including accurately capturing peak flow rates under conditions of high inflow. The New HCF appears to better represent the unsaturated hydraulic conductivities near field capacity compared with the Kslope HCF (Figure 2 and Supplementary Material Figure S1.2), and has been shown here to lead to improved estimates of outflow profiles, particularly at low flows. It is recommended that this alternative function is included as an option within SWMM.

The New HCF function is arguably more robust in this specific modelling context because it is pinned to both the growing media's field capacity and its saturation/porosity; these parameters are readily obtainable from standard soil characterisation tests. Our experience suggests that $n = 5/2$ fits a broad range of engineered growing media. This may

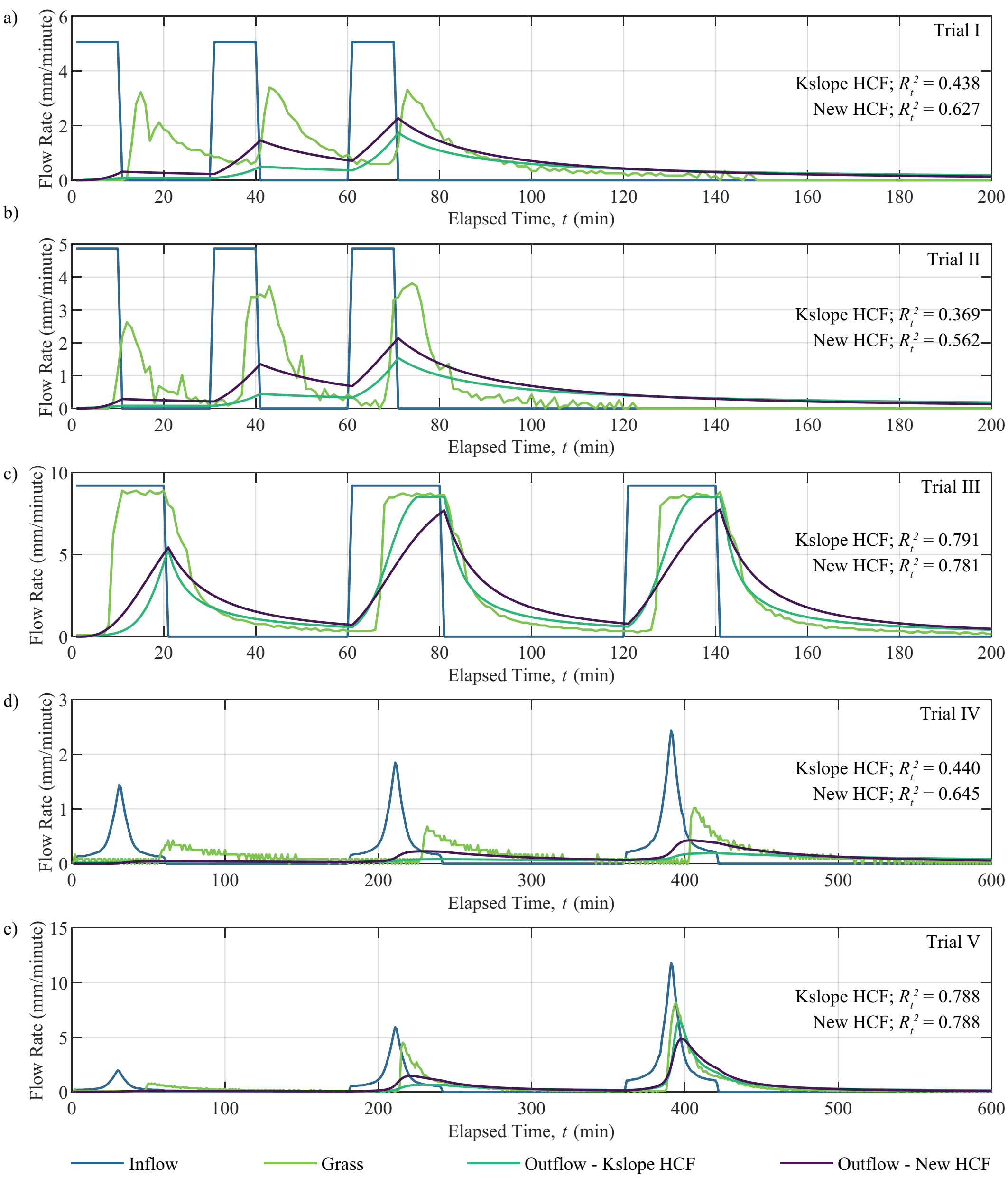

Figure 8. Comparison between modelled and measured outflow profiles for the amenity grass column across all trials. Note that overall model performance could be improved by calibration (increasing K_s), but that is not presented here as the point of the present exercise is to evaluate model performance using best estimates of the model parameters based on measurable physical properties.

benefit from further exploration. However, it should be noted that model estimates will have relatively limited sensitivity to the choice of *n*, because the curve is pinned, by definition, to the value of zero for field capacity and K_s at saturation. *n* only controls the degree of curvature between these two points. The Kslope HCF, in contrast, risks estimating values of unsaturated hydraulic conductivity that differ markedly from zero at field capacity, leading to unrealistic on-off outflow profiles (De-Ville and Stovin 2022; Liu and Fassman-Beck 2017a). The form of the New HCF removes any potential inconsistencies between the Kslope HCF-derived values of hydraulic conductivity at field capacity and the SWMM model's assumption that the value will be zero at field capacity.

5. Conclusions

The key conclusions from this study are:

- The HCF for the media of this study, and similar growing media, is better characterised by a power function (New HCF) than an exponential (Kslope HCF) function, particularly under low flow conditions. The proposed New HCF is pinned to the media's field capacity, ensuring that the function's estimate of hydraulic conductivity approaches zero at field capacity; this is consistent with the SWMM percolation model's assumptions.
- Detention characteristics monitored in four bioretention columns over 21 months did not show strong evidence of

any systematic differences, either as a result of vegetation treatment or ageing.

These findings lead to several practical recommendations:

- It has been demonstrated that the New HCF provides a more robust characterisation of unsaturated hydraulic conductivity in bioretention cell media compared with the Kslope HCF. It is therefore recommended that the New HCF be implemented within the SWMM model. It should be noted that the new function does not require any new parameterisation in addition to what is already required within SWMM.
- The results of this study suggest that detention performance due to percolation in bioretention cells is unlikely to differ significantly between vegetated and unvegetated systems. This implies that, for modelling purposes, good characterisation of the virgin (new, unvegetated) media should be sufficient to parameterise the percolation model.
- By acknowledging the limited impact on detention performance associated with vegetation treatment in bioretention systems, stormwater planners can provide landscape architects with more agency to maximise the amenity and ecological benefits of bioretention planting schemes.
- • However, the data should not be interpreted as suggesting that changes will not occur in full-scale bioretention systems subjected to more representative inflow conditions over longer periods of time. Only clean water was applied in this study, and therefore the potential risks associated with clogging due to suspended solids in urban road runoff have not been considered here. The effects of increased hydraulic and sediment loadings on ageing/clogging risk, and hence the implications for longer-term maintenance of these systems, should be the topic of further research.

Disclosure statement

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Data availability statement

The processed detention column laboratory data (De-Ville and Stovin 2024) and the G2G media HCF (De-Ville, Peng, and Stovin 2024) are freely available via The University of Sheffield's Online Research Data Archive. Raw data may be made available upon request via the corresponding author.

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