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Evaluating the Potential Hydrological Performance of a Bioretention Media with 100% Recycled Waste Components

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Abstract: Bioretention systems are a popular type of Sustainable Drainage System (SuDS). However, their largest single component, the fill media, is often a non-sustainably sourced material. This study evaluates a bioretention fill media comprising 100% recycled waste components. The fill media components come from multiple waste streams, quarry waste from the construction sector, crushed glass and green waste compost from domestic waste, and sugar-beet washings from the food processing sector. The hydraulically important physical characteristics of the recycled fill media were evaluated against reported literature examples of bioretention fill media, alongside UK and international guidance documentation. The particle size distribution of the recycled fill media was found to be unlike that seen in the literature and was also not compliant with the UK's CIRIA 'The SuDS Manual' guidance ($d \geq 6$ mm = 45% vs. 0% target). However, this did not result in any additional non-compliance, with laboratory-derived saturated hydraulic conductivity ($K_s = 101$ mm/h) and porosity ($\phi = 44\%$) within recommended ranges ($100 \leq K_s \leq 300$ mm/h, $\phi > 30\%$). SWMM was used to predict the performance of a bioretention system installed with the recycled fill media compared to UK guidance configured systems. It was found that the recycled fill media would have similar performance to a UK guidance compliant system, irrespective of its particle size distribution. Further work is required to validate the predicted performance of the recycled media.

Keywords: bioretention; hydrological performance; growing media; recycled waste; physical characteristics

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1. Introduction

1.1. Background

'Bioretention Systems' are one type of Sustainable Drainage System (SuDS)—which sit under the wider Green Infrastructure (GI), Low Impact Development (LID) or Nature Based Solutions umbrella terms—in which vegetation and an engineered soil media are used to filter stormwater contaminants and sediments, and reduce stormwater volumes and flow rates [1]. A generic bioretention system will typically comprise: a vegetation layer set within a ponding zone; a fill media layer for water storage, filtration and plant support; and a drainage layer (Figure 1).

Traditional bioretention media is a mixture of 30–60% sand, 20–30% soil and 20–40% organic matter by volume [2–4]. The media is typically chosen to support plant life, and the texture (particle and pore size distributions) and hydraulic conductivity of the fill media govern its hydrological performance. The drainage layer facilitates the exfiltration of water to underlying soils (where exfiltration is permitted) or to the underdrain (where present). Bioretention system complexity may be increased by: incorporating transition layers between the fill media and drainage layers to prevent washout of material [5]; utilising a layered fill media with components designed for specific contaminant treatment [6]; creating internal water storage zones (IWS) which may remain saturated to promote anaerobic conditions [7]; or the fitting of outflow restriction devices to meet regulatory requirements [8]. A mulch layer (typically bark chippings or gravel) may overlie the growing media layer to maintain infiltration rates and/or minimise the risk of clogging surface soils [9].

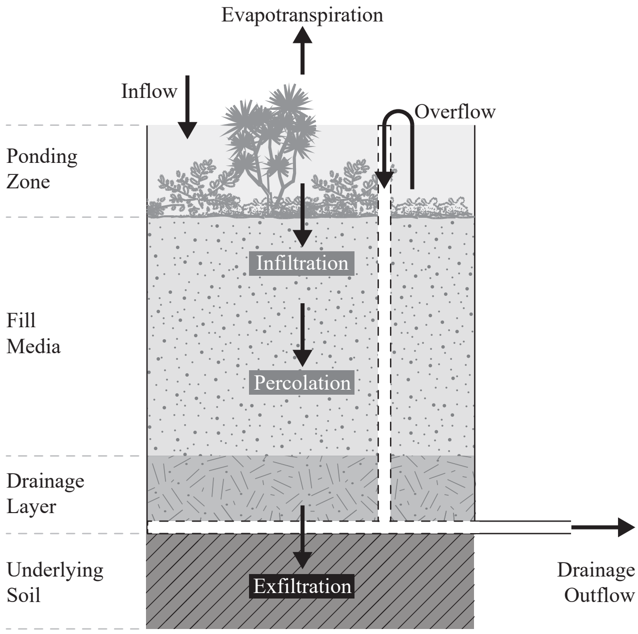

Figure 1. Schematic diagram of an unlined bioretention system with underdrain. Key hydrological processes are also indicated.

The single largest component, by volume, of a typical bioretention system is the fill media. The fill media's porosity provides the storage capacity for retaining stormwater such that it can be returned to the atmosphere via evapotranspiration (ET). In a lined bioretention system (where exfiltration is not permitted), ET is the only mechanism by which outflow volumes can be reduced. In a system with an unrestricted outlet, the fill media provides the only hydraulic control on outflow rates. The rate of water movement through the fill media is governed by two hydrological processes: the infiltration of water into the media surface; and the percolation of water through the fill media (Figure 1). Both of these processes are dictated by the fill media pore size distribution, which is an intrinsically difficult property to characterise. As such, more easily characterised properties resulting from the pore size distribution are often used to evaluate these processes, with the most commonly used being saturated hydraulic conductivity.

1.2. Sustainably-Sourced Fill Media

There are numerous global drivers for increasing the sustainability of construction materials, whether that be to meet net-zero carbon targets [10] or to prevent materials being sent to landfill [11]. As bioretention media comprise a mixture of sands, natural soils and organic matter, there is potential for significant natural resources to be consumed in their creation. In 2016, an estimated 51 million tonnes of excavation waste was generated by quarrying and construction activity in the UK [12]. Of this, only 11 million tonnes was recycled into new construction products.

There has been significant research into using recycled waste products to act as stormwater quality improvers, with varying success [13]. The waste products considered for incorporation within bioretention media have included: water treatment residual; coal ash; steel slag; amongst others. However, there has been less exploration of waste products as the main mineral component of bioretention fill media. Rahman et al. [11] concluded that appropriately processed reclaimed asphalt and crushed brick met the stringent requirements of various environmental protection authorities. It was therefore recommended that recycled waste materials could be reused viably as alternative mineral components in bioretention systems [11].

Moore and Hunt [14] identified the majority of embodied carbon in bioretention systems was from the transport of materials and construction of the system and not the construction materials themselves. However, the carbon sequestration potential of bioretention led to a prediction of the system being net carbon negative after 30 years of operation [14]. If the embodied carbon of the construction materials could be lowered, by incorporating locally-sourced recycled components, then the system would become net carbon negative earlier in the system's design life.

Whilst the benefits of using recycled waste products in bioretention systems are clear, it may be more difficult to ensure consistent hydrological performance between individual systems given the variability that may exist in waste product quality over time and with geographical availability. A robust characterisation and performance prediction framework needs to be established to build confidence in waste-derived bioretention media.

1.3. Predicting Hydrological Performance

Stormwater engineers need to understand how bioretention systems respond to both routine and extreme rainfall events. Considerable research effort has been invested in recent years to monitor the hydrological performance of installed bioretention devices in the field [3,4,8,15–17]. The data derived from such studies provide useful indications of hydrological performance, but they are often 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.

For these reasons, stormwater engineers require fit-for-purpose hydrological/hydraulic modelling tools to simulate the rainfall/runoff behaviour of these devices, including their performance in response to extreme events. SWMM [18] is the most well-known of the available open-source modelling tools. As already identified, the fill media is volumetrically the largest single component of any bioretention system, and has an important role to play in retaining stormwater and detaining runoff. It is therefore not surprising that rainfall/runoff models, such as SWMM, place considerable emphasis on the role of the fill media in determining hydrological performance.

To obtain robust predictions of hydrological performance, each of the components of the bioretention system needs to be comprehensively characterised. These physical characteristics are the input parameters to physically-based models, like SWMM. The resultant model predictions are therefore only as robust as the techniques used to characterise the individual bioretention components.

1.4. Aim and Objectives

This study aims to determine the hydrological suitability of a bioretention fill media whose components are all derived from waste products. This aim is supported by the following objectives:

- Characterise the hydrologically important physical properties of a bioretention media comprising 100% recycled waste components;
- Evaluate the physical characteristics of the fill media against global guidance documents and the established literature;
- Apply the SWMM model to demonstrate the potential hydrological performance of bioretention media with recycled waste components and compare it to that of systems based on current UK guidance.

2. Materials and Methods

2.1. The Fill Media

The fill 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 fill media is used extensively throughout Sheffield in the City Council's Grey-to-Green retrofit bioretention systems [19] and will henceforth be referred to as 'G2G media' or simply 'G2G'.

2.2. Physical Characterisation of Fill Media

In the UK, there is no single standard document for the physical characterisation of bioretention fill media. CIRIA's SuDS Manual directs readers to specific British Standards documents for Saturated Hydraulic Conductivity (BS EN ISO 22282-5:2012) [20] (intended to be determined in-situ post construction), and Porosity (BS 1377-2:1990) [21] whilst not specifying a methodology for determining Particle Size Distribution (PSD) [1]. Considerably stronger guidance exists for the physical characterisation of other green infrastructure fill/growing media, predominantly green roofs, with the provision of the German FLL's 'Guidelines for the Planning, Construction and Maintenance of Green Roofing' [22] and the British BS 8616:2019 'Specification for performance parameters and test methods for green roof substrates' [23]. Whilst the test methods of BS 8616:2019 are standardised and also found in separate standards documents, BS 8616:2019 brings them together to characterise engineered media for green roofs.

The G2G media was characterised using the testing procedures of BS 8616:2019 for: saturated hydraulic conductivity; porosity; field capacity; particle size distribution; and bulk density. These tests were conducted in a laboratory environment using fresh samples of G2G blended from two 1 m^3 bags of material. Each test was performed in triplicate, and results are presented as a mean value ±1 standard deviation. A simplified assessment of texture was conducted by assessing the mass of fines (<0.063 mm), sand (0.063–2.0 mm) and gravel (>2.0 mm). This classification is consistent with texture reporting in the majority of the peer-reviewed literature. The soil water release curve of the G2G media was determined via the hanging column method as described in ASTM D6836-16 [24] up to a maximum suction of 100 cm H_2O. A fitted bi-modal Durner model [25] was used to determine the residual moisture content of the media. This residual moisture content has been assumed to be equal to the permanent wilting point.

2.3. Hydraulic Characterisation Reported in Research Articles

A systematic search using Scopus was undertaken to identify relevant peer-reviewed journal articles published between January 2005 and April 2021. The search strings "bioretention AND water AND quantity", "bioretention AND hydrological AND performance", and "bioretention AND media AND performance" were used to identify 75 unique papers. From these, 19 papers were discarded because they did not provide textural, hydraulic conductivity, or hydrological performance data in an accessible format. The remaining 56 papers presented 140 bioretention media examples, 76 from field-scale systems (Table A1), 43 from lab-scale systems (Table A2), and 21 from pilot-scale systems (Table A3). A full list of studies and media is provided in Appendix A. Each selected media had an associated texture and/or saturated hydraulic conductivity value. Other key physical characteristics were extracted where available, including: system surface area; system depth; and whether the system was lined.

2.4. Hydraulic Characterisation Reported in Guidance Documents

Fill media texture, media depth, and saturated hydraulic conductivity recommendations were collated from four guidance documents, two from the USA and two from the rest of the world (Table 1). These locations represent a breadth of international practice whilst focusing on areas where there has been extensive academic research into bioretention system configuration and its effects on hydraulic performance.

Table 1. Comparison of select Existing Global Guidance Documents.

Citation			**[5]**	**[1]**	**[26]**	**[27]**
Reference			FAWB	CIRIA	MD	NC
Location			Australia	UK	USA	USA
Guidance Level			National	National	State	State
Date of last revision			2015	2015	2009	2018
Fill Media Physical Characteristics						
Fines (Clay and Silt)	$d < 0.063$ mm	% (*w/w*)	<3	<5	40–70	8–15
Sand	$0.063 < d < 2.0$ mm	% (*w/w*)	94–100	85–100	35–65	75–85
Gravel	$d \geq 2.0$ mm	% (*w/w*)	<3	<10	0	0
Sat. Hydraulic Conductivity	K_s	mm/h	100–300	100–300	-	25–150
Media depth	D	mm	400–600	400–1000	750–1200	600–900

2.5. Bioretention Modelling in SWMM

SWMM version 5.1.015 [18] was used to evaluate the hypothetical hydrological performance of the G2G fill media when incorporated into a bioretention system compared with a CIRIA 'The SuDS Manual' [1]-compliant fill media. Each modelled bioretention system had a surface area of 1 m^2 and received inflow from a fully impermeable 9 m^2 (9×1 m) catchment for a total catchment area of 10 m^2, representing a loading ratio of 10:1. This set-up represents a unit-length of a typical roadside bioretention system installation. The physical parameters used to define the bioretention systems in SWMM's 'LID Control Editor' are presented in Table 2.

The surface layer of the bioretention systems was modelled as a flat smooth surface with no vegetation. This was done to focus on the hydraulic performance of the growing media alone. Evaporation from the bioretention systems was not considered and set to a constant value of 0 mm/h. The soil layer of the bioretention system (i.e., fill media layer of Figure 1) was parameterised with the results of the physical characterisation of the G2G media or guidance values presented in CIRIA's 'The SuDS Manual' [1] installed to a depth of 700 mm. This led to three bioretention system configurations being modelled (Table 2), with the C100 and C300 configurations representing the minimum and maximum guideline values of saturated hydraulic conductivity. Where guidance values were not provided the same values as G2G were used. The storage layer of the bioretention systems (i.e., drainage layer of Figure 1) was modelled as being 300 mm in depth with a void ratio of a representative storage media and no exfiltration into the underlying soil (replicating a lined system). The drain of the bioretention systems was configured to provide no impedance to outflow, thereby ensuring that the only hydraulic control on flow rate was provided by the growing media within the soil layer of the model.

Using a 1-min time-step, three simulated 1-hour design storms for Newcastle, UK, were applied to the bioretention systems with return periods of 10, 30 and 100 years. Newcastle was chosen for design rainfall as the modelled systems represented a series of pilot-scale bioretention test beds currently being monitored there at the UKCRIC National Green Infrastructure Facility [28,29]. The initial moisture content at the onset of simulated inflow was set to the fill media's field capacity, creating a detention only scenario with no initial losses.

The full model initialisation file and required rainfall files are available through The University of Sheffield's Online Research Data (ORDA) service [30].

Table 2. SWMM Model Bioretention System Parameters. Note: C100 and C300 refer to CIRIA guidance values at the lower and upper permissible limits for K_s.

Parameter	Unit	G2G	C100	C300	Notes
Surface					
Berm Height	mm	100	100	100	Allowable Ponding design depth
Vegetation Volume Fraction	m^3/m^3	0	0	0	No vegetation
Surface Roughness	[-]	0	0	0	Smooth surface
Surface Slope	%	0	0	0	Flat surface
Soil					
Thickness, D	mm	700	700	700	Fill Media design depth
Porosity, ρ	m^3/m^3	0.44	0.44	0.44	From G2G characterisation
Field Capacity, θ_{fc}	m^3/m^3	0.15	0.15	0.15	From G2G characterisation
Wilting Point, θ_w	m^3/m^3	0.12	0.12	0.12	From G2G characterisation
Conductivity, K_s	mm/h	101	100	300	From G2G characterisation and CIRIA guidance
Conductivity Slope	[-]	26.1	46.5	46.5	From PSD: $0.48 \times (\%Sand) + 0.85 \times (\%Clay)$
Suction Head	mm	49.8	50.0	34.9	From K_s: $226.44 \times K_s^{-0.328}$
Storage					
Thickness	mm	300	300	300	Drainage Layer design depth
Void Ratio	[-]	0.756	0.756	0.756	Representative value
Seepage Rate	mm/h	0	0	0	No exfiltration, lined system
Clogging Factor	[-]	0	0	0	Not exploring clogging effects
Drain					
Flow Coefficient, C	[-]	99,999	99,999	99,999	No impedance to outflow
Flow Exponent, n	[-]	0	0	0	No impedance to outflow
Offset	mm	0	0	0	Drain at base of system

3. Results

3.1. Fill Media Physical Characteristics

The hydraulically important physical characteristics of the G2G media are presented in Table 3 and the soil water release curve is presented in Figure 2. A full particle size distribution is presented in Figure 3. Saturated hydraulic conductivity was highly variable between the three measurements, with a standard deviation greater than 80% of the mean value. All other physical characteristics were relatively consistent, with much lower standard deviations. Porosity was greater than the minimum value of 30% proposed by the CIRIA guidance [1]. Field capacity values were at the lower end of the range of values reported in the literature (10–32% [31]); this is likely due to the high gravel content of G2G compared to other reported bioretention media textures.

Table 3. G2G Fill Media Physical Characteristics.

Parameter	Unit	Value
Saturated Hydraulic Conductivity, K_s	mm/h	101 ± 82
Porosity, ϕ	m^3/m^3	0.443 ± 0.005
Field Capacity, θ_{fc}	m^3/m^3	0.149 ± 0.002
Dry Bulk Density, ρ_b	kg/m^3	1171 ± 11
Texture		
Fines ($d < 0.063$ mm)	% mass	1.2 ± 0.7
Sand ($0.063 < d \leq 2.0$ mm)	% mass	42.5 ± 6.9
Gravel ($d > 2.0$ mm)	% mass	56.3 ± 7.0

Table 3. *Cont.*

Parameter	Unit	Value
Durner Model Parameters		
θ_s	m^3/m^3	0.443
θ_r	m^3/m^3	0.124
w_1	[-]	0.909
α_1	cm^{-1}	0.177
n_1	[-]	1.826
α_2	cm^{-1}	0.051
n_2	[-]	11.413

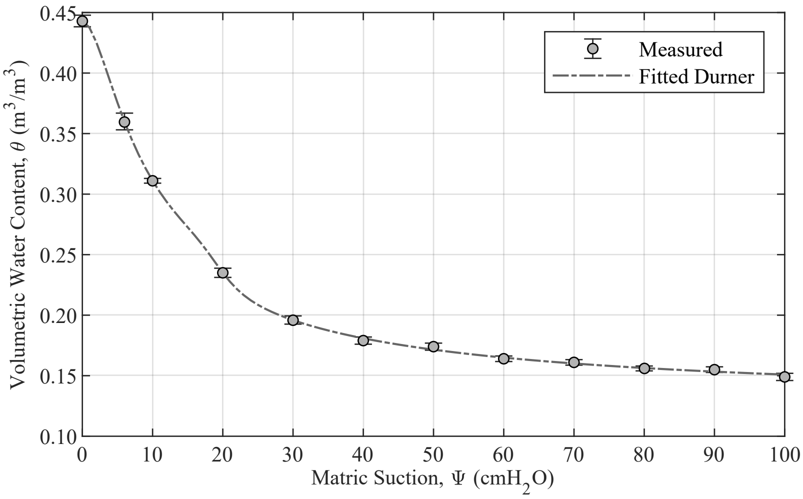

Figure 2. Measured Soil Water Release Curve for the G2G media and fitted Durner model. Error bars represent ±1 standard deviation.

3.2. Comparisons with Guidance Documentation and the Existing Literature

A comparison between the physical characteristics of G2G and suggested value ranges from the four guidance documents is presented in Figure 3. Figures 4 and 5 summarise the comparison between the physical characteristics of G2G and examples of fill media found in the literature.

The mean saturated hydraulic conductivity of G2G is within the suggested range of three of the four guidance documents (Figure 3a), with MD guidance not stipulating a specific saturated hydraulic conductivity range. Permissible conductivity for MD is instead indicated by means of an acceptable draw-down time for the ponding zone [26]. The saturated hydraulic conductivity of G2G sits within, but toward the lower end of, the range of values presented in the literature and most closely matched examples found in field-scale studies (Figure 4a). These field-scale studies report reduced values of saturated hydraulic conductivity compared to lab- and pilot-scale studies. This difference may highlight the inability of lab- and pilot-scale studies to robustly represent the physical properties of fill media in field-scale systems. It should also be noted that lab-scale studies may have explicitly explored 'non-compliant' media, as this study does, whereas field-scale systems are likely to have been installed following available local guidance. This may also account for some of the differences observed between lab- and field-scale results in the literature.

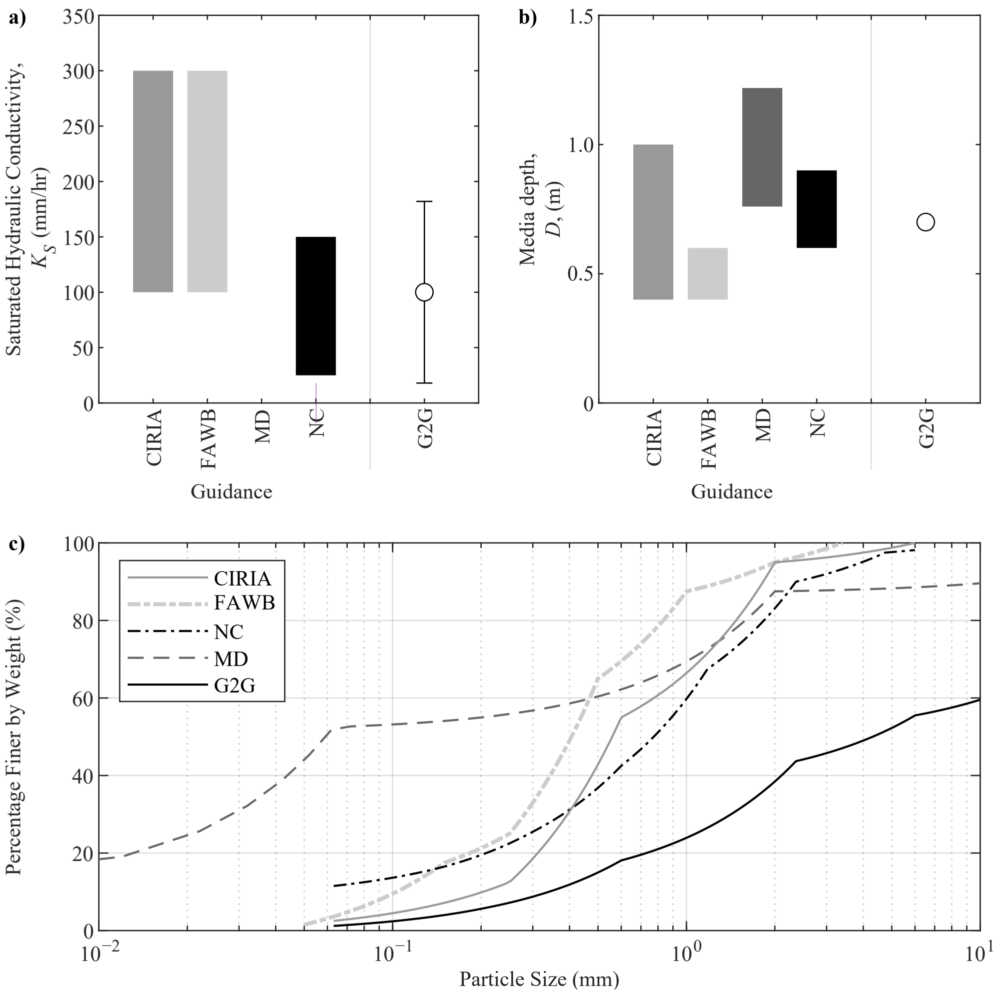

Figure 3. Comparison of G2G and Guidance Document ranges for: (**a**) Saturated Hydraulic Conductivity, with G2G plotted as mean ±1 standard deviation; (**b**) media depth, with G2G plotted as a single value; and (**c**) particle size distribution (plotted at the middle of the allowable range; linear interpolation of data is presented on the logarithmic *x*-axis).

The chosen depth of G2G for simulation (700 mm) conforms to the CIRIA and NC guidance only (Figure 3b). However, the minimum suggested depth of the MD guidance is 750 mm, so the simulation depth is considered acceptable. The low media depths in the FAWB guidance are to permit retrofit into roadside environments that may already have utility ducting installed [5], a scenario not considered herein. A fill media depth of 700 mm is a typical depth seen in the literature across all study types (Figure 4b). Field-scale studies exhibit higher values of media depth, which is likely a result of lab- and pilot-scale studies being microcosms of larger systems.

The particle size distribution of G2G diverges notably from guidance values. Figure 3c demonstrates that G2G is dominated by particles in excess of 6 mm in diameter (44.5% by mass). All guidance documents, except MD, suggest that material greater than 6 mm in diameter should be minimal to none. This low gravel content is to maximise the porosity of the fill media and therefore the volume available for water storage. The high percentage of material greater than 6 mm in diameter for G2G is due to the quarry waste component, where particle sizes can be up to 50 mm in diameter. The level of fines ($d < 0.063$ mm) in G2G is lower than all guidance documentation, further demonstrating the non-compliant PSD. However, a low fines content is desirable to ensure free drainage and provide resilience against sediment deposition.

Figure 5 demonstrates that the high gravel content of G2G is not seen in the majority of the literature fill media examples. The fines content of G2G is low in comparison to other media despite being in-line with the majority of guidance documentation. Classifying literature sources by study type—whether they are field-, lab- or pilot-scale studies—highlights these key differences in the G2G media texture from literature examples (Figure 4). The texture of G2G does not conform to the typical make-up of fill media for any study type.

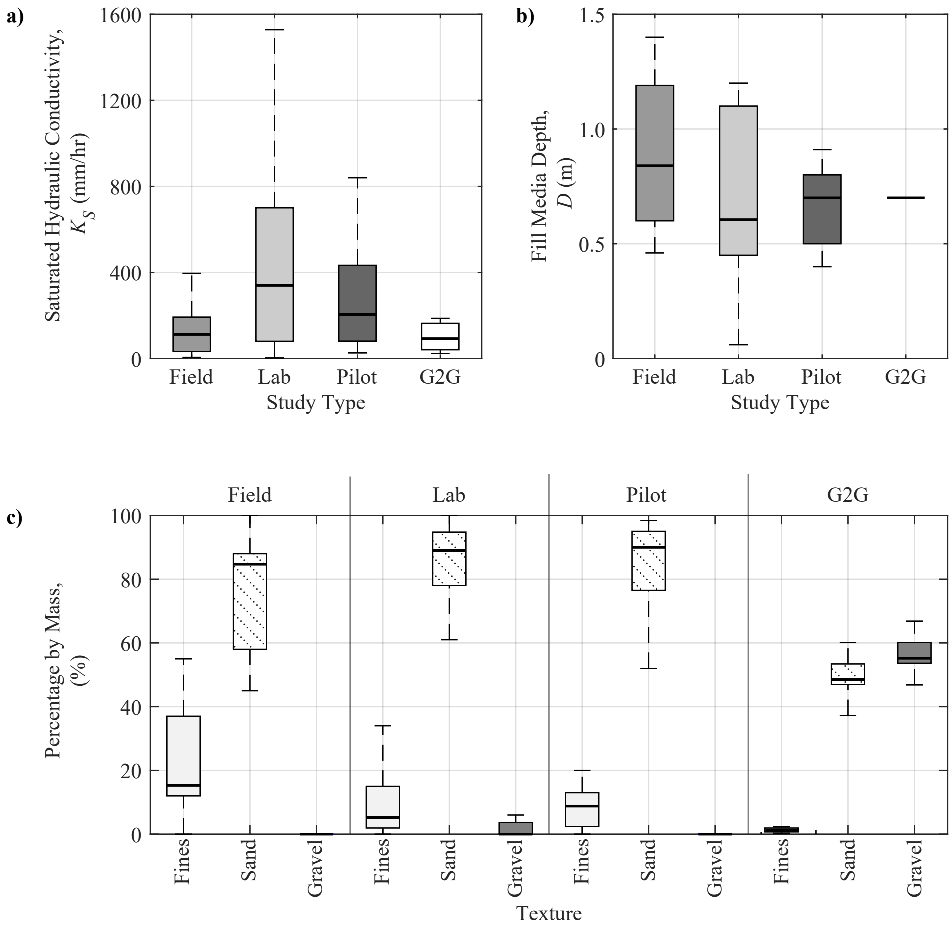

Figure 4. Comparison of G2G and literature examples of fill media physical characteristics: (**a**) saturated hydraulic conductivity; (**b**) media depth; and (**c**) media texture, fines (<0.063 mm), sand (0.063–2.0 mm) and gravel (>2.0 mm).

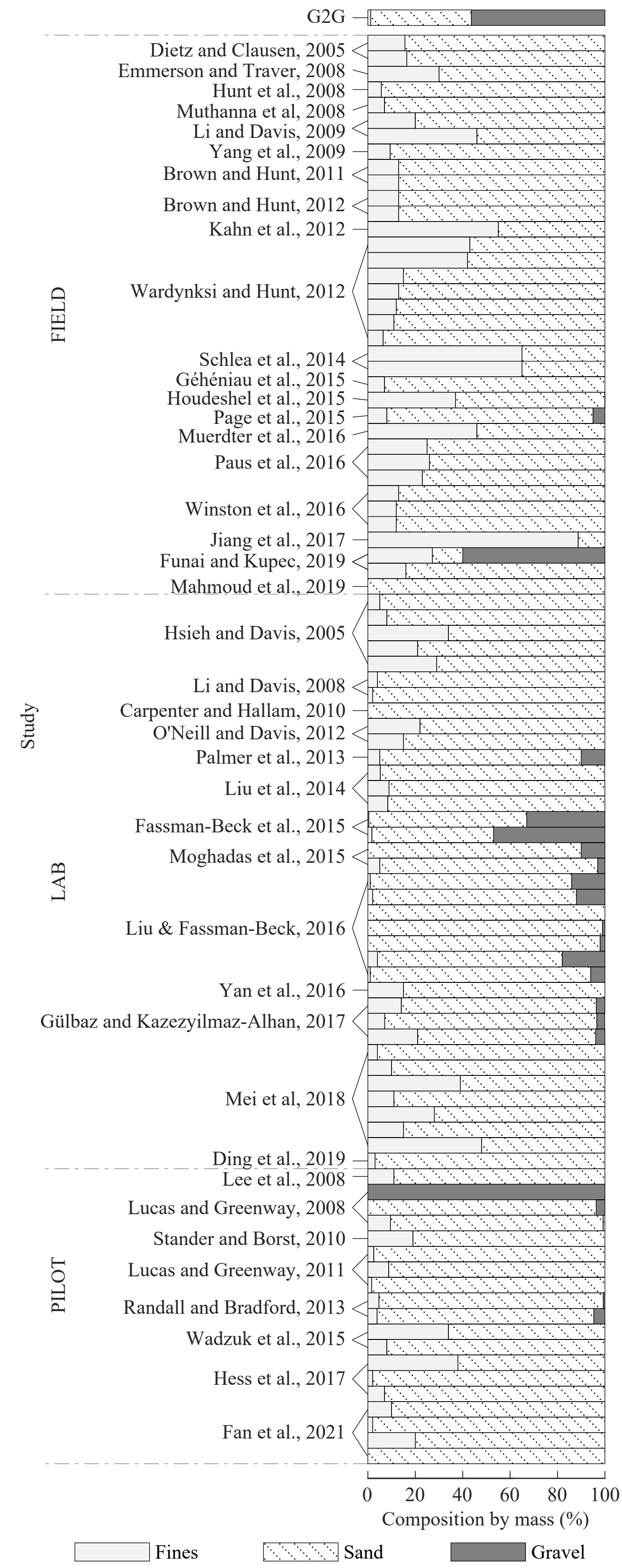

Figure 5. Comparison of G2G and literature examples of fill media composition by particle size class. Fines (<0.063 mm), sand (0.063–2.0 mm) and gravel (>2.0 mm).

3.3. Potential Hydrological Performance (SWMM Model)

The hydraulic responses of the three trialled bioretention configurations (Table 2) during a 60-min 10-year return period rainfall event (M10-60) for Newcastle, UK, are presented in Figure 6. The design storm is symmetrical, with a peak intensity of 1.43 mm/min. The inflow to the bioretention systems can be seen to closely resemble the profile of the design rainfall (Figure 6a), with a temporal shift in peak inflow by two minutes from the peak design rainfall due to overland flow routing across the impervious catchment (Figure 6b). The outflow profiles of the G2G and C100 system configurations are nearly identical, thus suggesting that the performance of G2G is consistent with a CIRIA compliant fill media. This is due to the very similar values of saturated hydraulic conductivity (101 vs. 100 mm/h). The higher saturated hydraulic conductivity of the C300 configuration (300 mm/h) leads to a much earlier and higher peak runoff than the other two trialled configurations. These outflow data suggest that saturated hydraulic conductivity is a dominant factor in predicting the overall hydraulic performance of the system. Hence, the non-compliant particle size distribution of G2G leads to no discernible difference to the in-storm hydraulic response.

Inflow to the bioretention systems becomes greater than the infiltration capacity of the fill media from 22 min after the onset of rainfall (for G2G and C100), causing water to pond at the surface of the bioretention system (Figure 6c). Infiltration capacity is also exceeded in the C300 configuration from 27 min after the onset of rainfall. This ponding leads to a short sharp overflow peak for the G2G and C100 configurations with their lower saturated hydraulic conductivity 40 min after the onset of rainfall (Figure 6d). The higher saturated hydraulic conductivity of the C300 configuration allows the system to contain the inflow to the ponding zone, resulting in no overflow.

Ponding begins to occur prior to saturation of the fill media for all bioretention configurations (Figure 6e), thus demonstrating that the infiltration rate is the limiting factor for outflow during this scenario. The higher saturated hydraulic conductivity of the C300 configuration permits fill media moisture content to rise more rapidly than for either C100 or G2G. The rate of moisture loss after the peak in moisture content is governed by the fill media's hydraulic conductivity function. It is during this period of moisture loss that differences in performance emerge between the C100 and G2G configurations. The shallower hydraulic conductivity function gradient of G2G leads to higher values of soil percolation at moisture contents below saturation. This permits the G2G configuration to recover 13.5% of absolute storage in the first 70 min after peak moisture content, compared with the 10.5% of C100.

When the rainfall intensity is increased, as per a 60-min duration 30-year return period event, the restrictive infiltration rate of all configurations leads to greater overflow volumes. The same is true for the 100-year return period event. Plots of the model response to these rainfall events are presented in Appendix B.

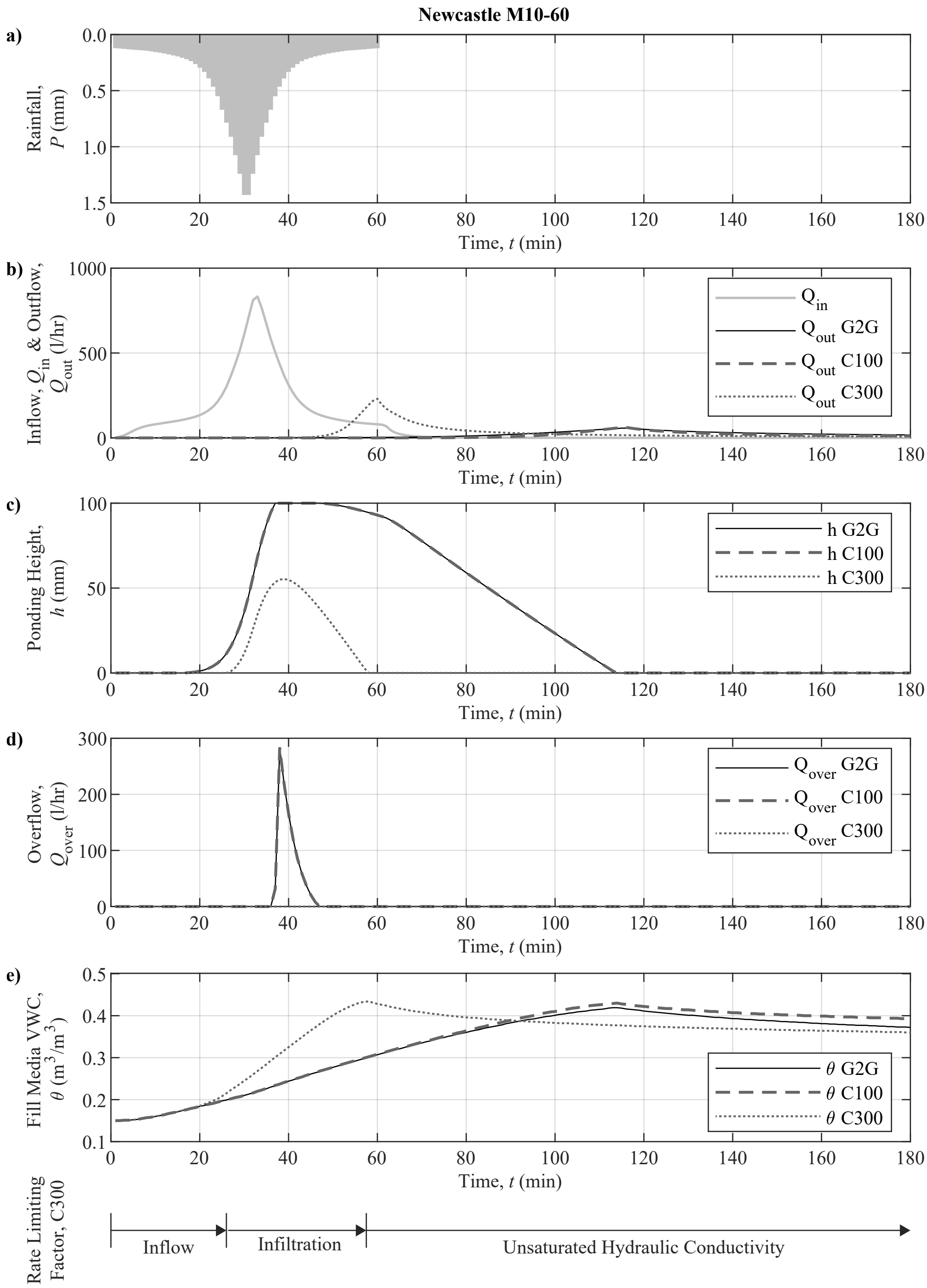

Figure 6. Modelled hydraulic response of bioretention systems in response to a 10-year return period 60-min duration storm event for Newcastle, UK. (**a**) Rainfall depth; (**b**) system inflow and outflow; (**c**) ponding height; (**d**) overflow; and (**e**) volumetric water content (VWC) of the fill media.

4. Discussion

4.1. Uncertainties of Test Methods and Implications for Predicted Performance

For the majority of the physical characteristics identified in Table 3, there is a low standard deviation between the characterised replicates (<10% of identified mean). However, for saturated hydraulic conductivity, the standard deviation is >80% of the mean value. The modelling exercise has revealed that predicted performance is more sensitive to saturated hydraulic conductivity than to the media's particle size distribution.

The model's sensitivity to saturated hydraulic conductivity is further demonstrated in Figure 7 by means of a sensitivity analysis. A saturated hydraulic conductivity of 19 mm/h ($\overline{K_s} - \sigma$) leads to heavily restricted infiltration, causing high volumes of inflows to overflow (35%). This is in contrast to the modest overflow of the mean saturated hydraulic conductivity value (101 mm/h, 3% overflow) and for $\overline{K_s} + \sigma$ (183 mm/h) where there was no overflow. This variation in the physically characterised saturated hydraulic conductivity leads to very different design outcomes, with the system failing (causing overflow) for two of the three scenarios.

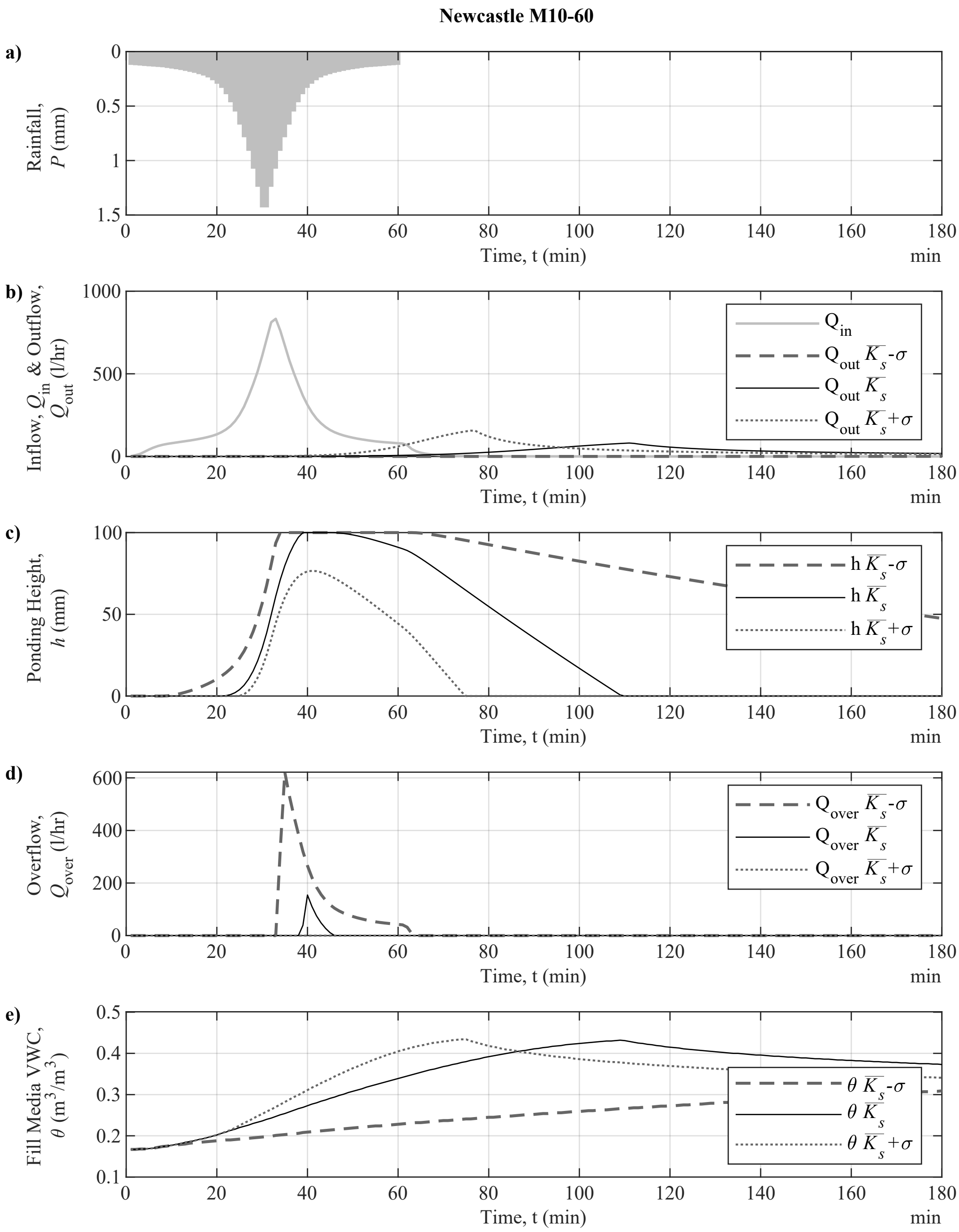

Figure 7. Modelled hydraulic response of the G2G bioretention system with mean saturated hydraulic conductivity ($\overline{K_s}$), mean saturated hydraulic conductivity minus 1 standard deviation ($\overline{K_s} - \sigma$) and mean saturated hydraulic conductivity plus 1 standard deviation ($\overline{K_s} + \sigma$) in response to a 10-year return period 60-min duration storm event for Newcastle, UK. (**a**) Rainfall depth; (**b**) system inflow and outflow; (**c**) ponding height; (**d**) overflow; and (**e**) volumetric water content (VWC) of the fill media.

Saturated hydraulic conductivity is an inherently difficult physical property to characterise repeatedly. This is made more difficult by the heterogeneous nature of bioretention fill media, and in particular the G2G media with its high content of particles greater than 6 mm in diameter. Saturation can lead to the creation of preferential flow paths that may strengthen or degrade with repeat testing, and these pathways are unlikely to exist between separate samples of the same fill media. In field-scale bioretention systems, the saturated hydraulic conductivity is likely to vary significantly across a system's surface owing to differences in sediment deposition, vegetation root growth and fill media compaction. As a result of the above processes, the values of saturated hydraulic conductivity are also liable to change over time. For these reasons, lab-derived saturated hydraulic conductivity values in this study may be different to in-situ characterisations. There is a need to understand the magnitude of any discrepancy between the lab- and field-scale characterisations with the impacts this may have on predicted hydrological performance.

Sensitivity of the SWMM model to other system physical characteristics was explored by Fassman–Beck and Saleh [32], where it was highlighted that there is also a strong sensitivity to fill media porosity and field capacity. All trialled configurations in this study used the same porosity and field capacity value due to these properties being difficult to predict from the available guidance data. However, in a separate analysis (not shown here) it was found that a 20% increase in porosity and field capacity for the CIRIA-compliant configurations (decreased particle sizes typically leads to increased porosity) led to only modest improvements in in-storm hydraulic performance. The improvement in performance was limited (particularly for the C100 configuration) by the value of saturated hydraulic conductivity. as this is the clear governor of in-storm hydraulic performance, coupled with the design storm scenario which was established to predominantly explore detention performance. It is anticipated that porosity and field capacity changes may make more difference to retention performance of bioretention systems, provided there is the means to recover the available storage between rainfall events.

The SWMM model utilises many widely accepted simplifications of physical processes (e.g., Green Ampt infiltration, log-linear unsaturated hydraulic conductivity functions), which creates a one-dimensional representation of these processes. Therefore, an average value of media characteristics is likely to provide a central estimate of potential performance. Deviation around this central estimate is heavily dependent on confidence in the characterised physical property values. Stormwater engineers therefore need to be conscious of this uncertainty as, at least in the above scenario for saturated hydraulic conductivity, it can mean the difference between a successful and unsuccessful design.

4.2. Deviation from Guidance and Implications for Predicted Performance

The G2G fill media diverges from CIRIA guidance for particle size distribution. However, this does not lead to non-compliance for other hydraulically important physical characteristics, with saturated hydraulic conductivity and porosity in the allowable ranges. When the laboratory-derived physical characteristics of G2G are used to compare predicted performance to a CIRIA-compliant media, there is little divergence in performance for similar values of saturated hydraulic conductivity even with differing values of conductivity slope as defined by the fill media's particle size distribution (Figure 6, G2G vs. C100).

In reality the fill media's role is not just to provide a hydraulic function, but also to support vegetation, filter sediments and provide water quality benefits (amongst other design objectives). The G2G fill media exhibits a faster drainage rate (unsaturated hydraulic conductivity) than the lowest conductivity CIRIA configuration which may induce water stress in the vegetation more rapidly than is desirable. This faster drainage rate may also reduce residence times, reducing the treatment potential for water quality benefits. As with all forms of GI, there is a need to balance the physical characteristics of bioretention fill media to meet the desired design objectives. Visual inspection of Sheffield City Council's mature bioretention systems, installed with the G2G fill media, would suggest that it is more than capable of supporting a wide array of vegetation, with no reported sedimentation or clogging issues or concerns raised after five years of operation.

GI and SuDS are inherently more flexible than conventional hard-engineering solutions, but such flexibility creates a more challenging drainage design environment. Whilst guidance documentation is a useful starting point for design, in a UK context this guidance is not a set of definitive values, and stormwater engineers are free to specify alternative fill media (or other physical configurations) provided its performance conforms to local authority drainage design specifications. This freedom allows stormwater engineers to create designs that meet project-specific design objectives and maximise other low carbon goals including recycled materials. Ultimately, stormwater engineers need to be equipped with robust modelling tools such that they are able to confidently predict the performance of unique bioretention systems to meet stormwater management regulations.

4.3. Enhanced Predictions of Performance

There are several monitoring studies in the literature that report summary performance metrics [2,33–37] which provide limited predictive value for future storm events. However, the collected monitoring data are invaluable for validating and refining model capabilities, particularly where high temporal resolution (e.g., 5-min time steps or smaller) rainfall/inflow and outflow data are available alongside detailed characterisations of the growing media (and other physical configuration details). Model developers should be encouraged to validate their tools against as wide a range of these real data sets as possible.

Monitoring studies can also provide useful assessments of continuous performance over time and hydraulic responses to varying rainfall intensities. Data of this type are valuable in transitioning design practices from single storm pass/fail assessments of performance (like that presented here) to more progressive long-term assessments of performance which properly account for inter-event design processes. To use these continuous assessments of performance in design requires even greater confidence in the modelling approaches of complex soil/water/air interactions. This confidence can only be provided by well executed long-term monitoring studies and further validation of modelling approaches.

The authors are conscious of the uncritical application of the SWMM model in this study to demonstrate differences in performance between various bioretention configurations. The SWMM model calculations are based on saturated hydraulic conductivity, using simplified laws derived from conventional soils to estimate unsaturated hydraulic conductivity (K). The (unsimplified) laws that estimate K from K_s have been repeatedly shown to perform poorly for engineered media, and the simplified equations implemented in SWMM introduce further uncertainties into model predictions. Therefore, whilst we can show that SWMM is sensitive to the value of K_s, we do not yet have the evidence to confirm that the model predictions are reasonable.

As part of a wider study, a pilot-scale bioretention test facility has been established to provide the required monitoring data such that a validation of the SWMM model, and/or alternative models, can be conducted for a system installed with the G2G fill media [28,29]. It is anticipated that this ongoing work will lead to enhanced predictions of performance compared to those presented here.

5. Conclusions

A bioretention media composed entirely of recycled waste components was evaluated against reported media configurations in the literature, alongside UK and international guidance documentation, to determine its suitability. The particle size distribution was found to be non-compliant with UK guidance due to material greater than 6 mm in diameter as a result of included quarry waste. However, this did not lead to further non-compliance in other hydraulically important physical characteristics with laboratory-derived saturated hydraulic conductivity and porosity being within permitted ranges. The recycled fill media had physical characteristics largely in-line with those reported for other bioretention studies, with the exception of the high gravel content (particles greater than 2 mm in diameter).

Predictions of hydraulic performance in response to a design storm rainfall were facilitated using SWMM. These predictions indicated that the non-compliant particle size distribution led to minimal differences in performance compared to a UK guidance compliant media. The SWMM modelling exercise also highlighted a much stronger sensitivity to values of saturated hydraulic conductivity than to particle size distribution. Levels of uncertainty were highest in the physical measurement of saturated hydraulic conductivity which, when combined with the model sensitivity to saturated hydraulic conductivity, can lead to large variations in predicted performance.

This study has highlighted a continued need for bioretention monitoring data to develop and validate more robust modelling tools. Using these more robust tools, stormwater engineers will have more confidence in using non-compliant media (like that presented here) when the resultant hydraulic performance requirements are met.

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Appendix A. Bioretention Fill Media in the Literature

Table A1. Media Characteristics and Hydrological Performance of Field Scale Bioretention Systems.

ID	Citation	Reference	Location	Fines [1] %	Sand [2] %	Gravel [3] %	K_S mm/h	A m^2	d (m) m	Lined?
F1	[2]	RG1	USA	16	84	0	126	9	0.6	Y
F2		RG2	USA	16	84	0	103	9	0.6	Y
F3	[7]	G2	USA	-	-	-	396	10	1.2	N
F4		C1	USA	-	-	-	76	9	1.2	N
F5	[38]	Cell A	USA	-	-	-	-	28	1.2	Y
F6		Cell B	USA	-	-	-	-	28	0.9	Y
F7	[9]	-	USA	30	70	0	5	144	1.4	N
F8	[3]	Hall Marshall	USA	6	94	0	11	229	1.2	N
F9	[15]	RG1	Nor	7	93	0	-	1	0.5	Y

Table A1. *Cont.*

ID	Citation	Reference	Location	Fines [1] %	Sand [2] %	Gravel [3] %	K_S mm/h	A m^2	d (m) m	Lined?
F10	[39]	Burnsville	USA	-	-	-	468	28	1.2	N
F11		RWMWD#4	USA	-	-	-	144	29	1.2	N
F12		RWMWD#5	USA	-	-	-	29	59	1.2	N
F13		UM—St Paul	USA	-	-	-	104	67	1.2	N
F14		Cottage Grove	USA	-	-	-	720	70	1.0	N
F15		RWMWD#1	USA	-	-	-	194	147	1.2	N
F16		Thompson Lake	USA	-	-	-	191	278	1.2	N
F17		UM—Duluth	USA	-	-	-	58	1350	0.5	N
F18	[40]	Monash	Aus	-	-	-	-	45	0.7	Y
F19		McDowall	Aus	-	-	-	-	20	0.4	N
F20	[41]	Cell CP	USA	20	80	0	-	181	0.8	N
F21		Cell SS	USA	46	54	0	-	102	0.9	N
F22	[42]	G1	USA	-	-	-	-	25	1.2	N
F23		G2	USA	-	-	-	-	24	1.2	N
F24		L1	USA	-	-	-	-	16	0.6	N
F25		L2	USA	-	-	-	-	10	0.6	Y
F26	[43]	-	USA	-	-	-	-	409	0.8	N
F27	[44]	North Cell	USA	-	-	-	150	102	0.6	N
F28		South Cell	USA	-	-	-	150	102	0.9	N
F29	[33]	-	USA	9	91	0	120	7	0.5	N
F30	[45]	80c/20s/0t	USA	-	-	-	466	-	0.8	N
F31		20c/50s/30t	USA	-	-	-	20	-	0.8	N
F32	[46]	-	USA	-	-	-	-	400	0.3	N
F33	[4]	0.6 m	USA	13	87	0	13	425	0.6	N
F34		0.9 m	USA	13	87	0	-	300	0.9	N
F35		SCL Cell 0.6 IWS	USA	-	-	-	-	-	1.0	N
F36		SCL Cell 0.3 IWS	USA	-	-	-	-	-	1.0	N
F37		Sand Cell 0.6 IWS	USA	-	-	-	-	-	1.0	N
F38		Sand Cell 0.3 iWS	USA	-	-	-	-	-	1.0	N
F39	[47]	-	NZ	-	-	-	224	200	0.6	Y
F40	[34]	0.6 Repaired	USA	13	87	0	45	322	0.6	N
F41		0.9 Repaired	USA	13	87	0	45	226	0.9	N
F42	[48]	-	Can	55	45	0	-	32	1.2	N
F43	[49]	Site 1	USA	43	57	0	81	-	-	-
F44		Site 2	USA	42	58	0	26	-	-	-
F45		Site 3	USA	15	85	0	34	-	-	-
F46		Site 4	USA	13	87	0	171	-	-	-
F47		Site 5	USA	12	88	0	391	-	-	-
F48		Site 6	USA	11	89	0	15	-	-	-
F49		Site 7	USA	6	94	0	32	-	-	-
F50	[35]	AB	USA	65	35	0	29	27	-	N
F51		FGH	USA	65	35	0	29	19	-	N
F52	[8]	-	Can	7	93	0	684	250	1.3	N
F53	[50]	-	USA	37	63	1	-	10	1.2	Y
F54	[16]	-	China	-	-	-	-	165	1.0	N
F55	[51]	1	Aus	-	-	-	180	7	0.9	Y
F56		2	Aus	-	-	-	180	7	0.9	Y
F57		3	Aus	-	-	-	180	7	0.9	Y

Table A1. *Cont.*

ID	Citation	Reference	Location	Fines [1] %	Sand [2] %	Gravel [3] %	K_S mm/h	A m^2	d (m) m	Lined?
F58	[52]	BRC Media	USA	8	87	5	-	19	0.6	N
F59	[53]	-	USA	46	54	0	-	102	0.9	N
F60	[36]	RIS	Nor	25	75	0	50	40	0.8	Y
F61		L34B	Nor	26	74	0	525	6	-	N
F62		NB21	Nor	23	77	0	315	1	0.8	N
F63	[54]	UC	USA	13	87	0	168	182	0.6	N
F64		HA South	USA	12	88	0	100	57	0.8	N
F65		HA North	USA	12	88	0	100	79	0.9	N
F66	[55]	-	China	89	11	0	-	24	0.5	Y
F67	[56]	2008	USA	-	-	-	-	35	1.8	Y
F68		2013	USA	-	-	-	-	35	1.8	Y
F69	[57]	VL	USA	-	-	-	-	4	0.6	Y
F70		VH	USA	-	-	-	-	4	0.6	Y
F71		VH RR	USA	-	-	-	-	4	0.6	Y
F72		VH SM	USA	-	-	-	-	4	0.6	Y
F73		VH SM RR60	USA	-	-	-	-	4	0.6	Y
F74	[58]	EC2	USA	27	13	60	-	18	0.6	N
F75		EC3	USA	16	84	0	-	18	0.6	N
F76	[37]	-	USA	0	100	0	1300	55	0.8	Y
Min				0	11	0	5	1	0.3	
Median				16	84	0	120	29	0.9	
Max				89	100	60	1300	1350	1.8	

[1] < 0.063 mm; [2] 0.063 < d < 2.0 mm; [3] > 2.0 mm.

Table A2. Media Characteristics of Lab Scale Bioretention Trials.

ID	Citation	Reference	Location	Fines [1] %	Sand [2] %	Gravel [3] %	K_S mm/h	d m
L1	[59]	Sand I	USA	5	95	0	504	1.1
L2		Sand II	USA	8	92	0	4890	1.1
L3		Soil I	USA	34	66	0	168	1.1
L4		Soil II	USA	21	79	0	570	1.1
L5		Soil III	USA	29	71	0	240	1.1
L6	[60]	Soil I	USA	4	96	0	440	0.1
L7		Soil II	USA	2	98	0	717	0.1
L8	[45]	100c/0s/0t	USA	-	-	-	184	-
L9		0c/100s/0t	USA	0	100	0	260	-
L10		0c/0s/100t	USA	-	-	-	17	-
L11		80c/20s/0t	USA	-	-	-	456	-
L12		20c/50s/30t	USA	-	-	-	47	-
L13		50c/50s/0t	USA	-	-	-	55	-
L14		35c/65s/0t	USA	-	-	-	70	-
L15	[61]	BSM	USA	22	78	0	-	0.1
L16		LFBSM	USA	15	85	0	-	0.1
L17	[62]	BSM	USA	5	85	10	1217	0.6
L18	[63]	TerraSolve	USA	5	95	0	-	0.6
L19		Biofilter	USA	9	91	0	-	0.6
L20		VT Mix	USA	8	92	0	-	0.6
L21	[64]	CMA	NZ	0	67	33	831	0.6
L22		CMB	NZ	2	51	47	1528	0.6

Table A2. *Cont.*

ID	Citation	Reference	Location	Fines [1] %	Sand [2] %	Gravel [3] %	K_S mm/h	d m
L23	[65]	S1	Swe	0	90	10	-	1.2
L24		S2	Swe	5	92	3	-	1.2
L25	[66]	PumSan	NZ	1	85	14	2736	-
L26		PumSan + 10%Cmp	NZ	2	86	13	2988	-
L27		MarSan	NZ	0	100	0	792	-
L28		MarSan + 10%Cmp	NZ	0	99	1	864	-
L29		MarSan + 20%Cmp	NZ	0	98	2	648	-
L30		PumSan + 20%Top+10%Cmp	NZ	4	78	18	684	-
L31		MarSan + 20%Top+10%Cmp	NZ	1	93	6	468	-
L32	[67]	BSM	USA	15	85	0	90	0.1
L33	[68]	C1	Tur	14	82	4	300	0.7
L34		C3	Tur	7	90	3	380	0.7
L35		C4	Tur	21	75	4	140	0.7
L36	[69]	Media I	China	4	96	0	285	-
L37		Media II	China	10	90	0	99	-
L38		Media III	China	39	61	0	4	-
L39		Media IV	China	11	89	0	39	-
L40		Media V	China	28	72	0	11	-
L41		Media VI	China	15	85	0	51	-
L42		Media VII	China	48	52	0	3	-
L43	[70]	-	Can	3	97	0	550	0.5
Min				0	51	0	3	0.1
Median				5	89	0	340	0.6
Max				48	100	47	4890	1.2

[1] < 0.063 mm; [2] 0.063 < d < 2.0 mm; [3] > 2.0 mm.

Table A3. Media Characteristics of Pilot Scale Bioretention Trials.

ID	Citation	Reference	Location	Fines [1] %	Sand [2] %	Gravel [3] %	K_S mm/h	d (m) m
P1	[71]	-	Korea	11	89	0	90	0.8
P2	[72]	Gravel	Aus	0	0	100	>180	0.8
P3		Sand	Aus	0	96	4	>180	0.8
P4		Loam	Aus	10	90	0	45	0.8
P5	[73]	-	USA	19	81	0	-	0.6
P6	[74]	RM10	Aus	3	98	0	264	0.7
P7		K40	Aus	9	91	0	461	0.7
P8		WTR30	Aus	2	98	0	424	0.7
P9	[75]	Base Mix A	Can	5	95	1	-	0.5
P10		Base Mix B	Can	4	91	5	-	0.5
P11	[76]	Bioinfiltration Mix	USA	34	66	0	-	0.9
P12		Engineered Media	USA	8	92	0	-	0.8
P13	[77]	Sandy Loam	USA	38	62	0	-	0.7
P14		Sand (UV)	USA	2	98	0	-	0.7
P15		Sand (IWS)	USA	7	93	0	-	0.7
P16	[78]	Control	China	11	62	-	840	0.8
P17		Biochar	China	9	52	-	3280	0.8
Min				0	0	0	45	0.5
Median				8	91	0	264	0.74
Max				38	98	100	3280	0.9

[1] < 0.063 mm; [2] 0.063 < d < 2.0 mm; [3] > 2.0 mm.

Appendix B. SWMM Model Response to Design Rainfall Events

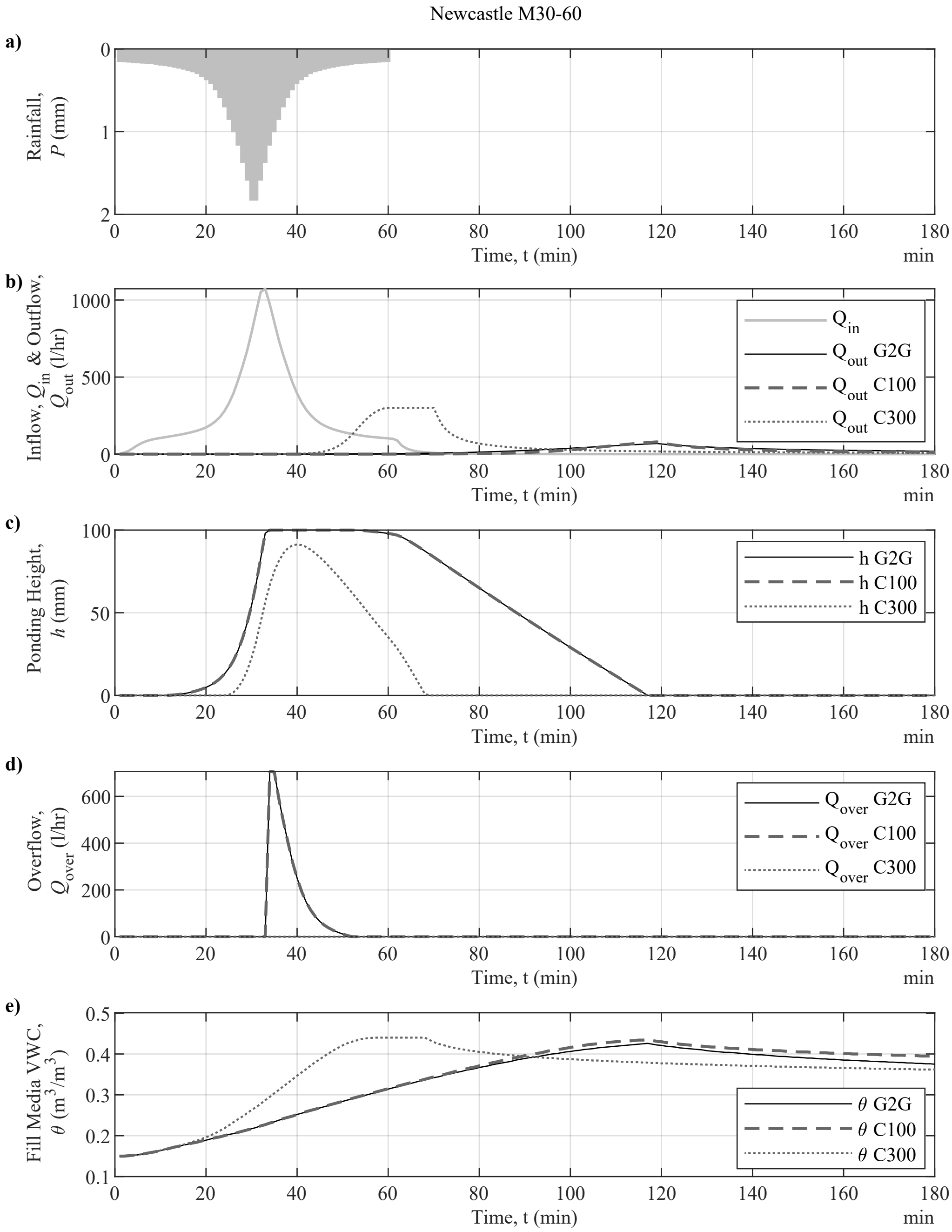

Figure A1. Modelled hydraulic response of bioretention systems in response to a 30-year return period 60-min duration storm event for Newcastle, UK. (**a**) Rainfall depth; (**b**) system inflow and outflow; (**c**) ponding height; (**d**) overflow; and (**e**) volumetric water Content (VWC) of the fill media.

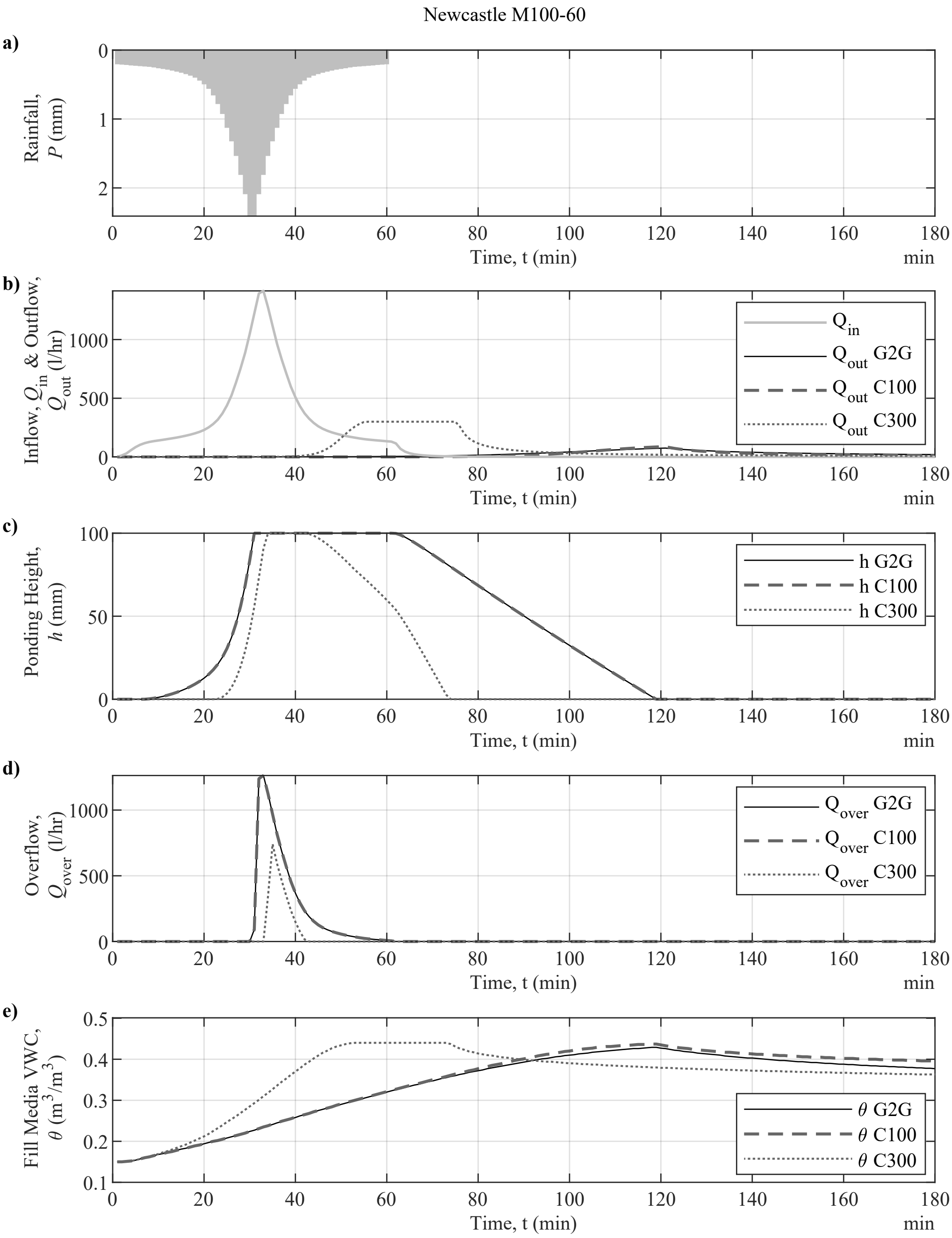

Figure A2. Modelled hydraulic response of bioretention systems in response to a 100-year return period 60-min duration storm event for Newcastle, UK. (**a**) Rainfall depth; (**b**) system inflow and outflow; (**c**) ponding height; (**d**) overflow; and (**e**) volumetric water content (VWC) of the fill media.

References

1. Woods Ballard, B.; Wilson, S.; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; Kellagher, R. *The SuDS Manual C753*; Technical Report; CIRIA: London, UK, 2015.
2. Dietz, M.E.; Clausen, J.C. A field evaluation of rain garden flow and pollutant treatment. *Water Air Soil Pollut.* **2005**, *167*, 123–138. [CrossRef]
3. Hunt, W.F.; Smith, J.T.; Jadlocki, S.J.; Hathaway, J.M.; Eubanks, P.R. Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. *J. Environ. Eng.* **2008**, *134*, 403–408. [CrossRef]
4. Brown, R.A.; Hunt, W.F. Evaluating Media Depth, Surface Storage Volume, and Presence of an Internal Water Storage Zone on Four Sets of Bioretention Cells in North Carolina. In Proceedings of the World Environmental and Water Resources Congress 2011, Palm Springs, CA, USA, 22–26 May 2011; pp. 405–414. [CrossRef]

5. FAWB. *Adoption Guidelines for Stormwater Biofiltration Systems*; Technical Report; Facility for Advancing Water Biofiltration, Monash University: Melbourne, VIC, Australia, 2009.
6. LeFevre, G.H.; Paus, K.H.; Natarajan, P.; Gulliver, J.S.; Novak, P.J.; Hozalski, R.M. Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *J. Environ. Eng.* **2015**, *141*, 04014050. [CrossRef]
7. Hunt, W.F.; Jarrett, A.R.; Smith, J.T.; Sharkey, L.J. Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *J. Irrig. Drain. Eng.* **2006**, *132*, 600–608. [CrossRef]
8. Géhéniau, N.; Fuamba, M.; Mahaut, V.; Gendron, M.R.; Dugué, M. Monitoring of a Rain Garden in Cold Climate: Case Study of a Parking Lot near Montréal. *J. Irrig. Drain. Eng.* **2014**, *141*, 04014073. [CrossRef]
9. Emerson, C.H.; Traver, R.G. Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices. *J. Irrig. Drain. Eng.* **2008**, *134*, 598–605. [CrossRef]
10. Helm, D.; Mayer, C.; Collins, C.; Austen, M.; Bateman, I.J.; Leinster, P.; Willis, K. *Advice on Using Nature Based Interventions to Reach Net Zero Greenhouse Gas Emissions by 2050*; Technical Report; UK Department for Environment, Food & Rural Affairs: London, UK, 2020.
11. Rahman, M.A.; Imteaz, M.A.; Arulrajah, A. Suitability of reclaimed asphalt pavement and recycled crushed brick as filter media in bioretention applications. *Int. J. Environ. Sustain. Dev.* **2016**, *15*, 32–48. [CrossRef]
12. GCB. *Zero Avoidable Waste in Construction*; Technical Report; Construction Products Association: London, UK, 2020.
13. Marvin, J.T.; Passeport, E.; Drake, J. State-of-the-Art Review of Phosphorus Sorption Amendments in Bioretention Media: A Systematic Literature Review. *J. Sustain. Water Built Environ.* **2020**, *6*, 03119001. [CrossRef]
14. Moore, T.L.; Hunt, W.F. Predicting the carbon footprint of urban stormwater infrastructure. *Ecol. Eng.* **2013**, *58*, 44–51. [CrossRef]
15. Muthanna, T.M.; Viklander, M.; Thorolfsson, S.T. Seasonal climatic effects on the hydrology of a rain garden. *Hydrol. Process.* **2008**, *22*, 1640–1649. [CrossRef]
16. Jia, H.; Wang, X.; Ti, C.; Zhai, Y.; Field, R.; Tafuri, A.N.; Cai, H.; Yu, S.L.; Jia, H.; Wang, X.; et al. Field monitoring of a LID-BMP treatment train system in China. *Environ. Monit. Assess.* **2015**, *187*, 373. [CrossRef]
17. Aravena, J.E.; Dussaillant, A. Storm-Water Infiltration and Focused Recharge Modeling with Finite-Volume Two-Dimensional Richards Equation: Application to an Experimental Rain Garden. *J. Hydraul. Eng.* **2009**, *135*, 1073–1080. [CrossRef]
18. Rossman, L. *Storm Water Management Model User's Manual Version 5.1-Manual*; Technical Report; US EPA: Washington, DC, USA, 2015.
19. Susdrain. Grey to Green Phase 1, Sheffield. 2016. Available online: https://www.susdrain.org/case-studies/pdfs/006_18_03_28_susdrain_suds_awards_grey_to_green_phase_1_light.pdf (accessed on 22 July 2021).
20. The British Standards Institution. *BS EN ISO 22282-5:2012 Geotechnical Investigation and Testing—Geohydraulic Testing. Part 5: Infiltrometer Tests*; Technical Report; The British Standards Institution: London, UK, 2012.
21. The British Standards Institution. *BS 1377-2:1990 Methods of Test for Soils for Civil Engineering Purposes—Part 2: Classification Tests*; Technical Report; The British Standards Institution: London, UK, 1990.
22. Breuning, J.; Yanders, A. *Introduction to the FLL Guidelines for the Planning, Construction and Maintenance of Green Roofing*; Technical Report; Green Roof Technology: Baltimore, MD, USA, 2008.
23. The British Standards Institution. *BS 8616:2019 Specification for Performance Parameters and Test Methods for Green Roof Substrates*; Technical Report; The British Standards Institution: London, UK, 2019.
24. ASTM International. *ASTM D6836-16, Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge*; Technical Report; ASTM International: West Conshohocken, PA, USA, 2016.
25. Durner, W. Hydraulic conductivity estimation for soils with heterogeneous pore structure. *Water Resour. Res.* **1994**, *30*, 211–223. [CrossRef]
26. MDDE. *Maryland Stormwater Design Manual*; Technical Report; Maryland Department of the Environment: Baltimore, MD, USA, 2009.
27. NCDEQ. *Stormwater Design Manual*; Technical Report; North Carolina Department for Environmental Quality: Raleigh, NC, USA, 2017.
28. Green, D.; Stirling, R.; De Ville, S.; Stovin, V.; Dawson, R. Investigating bioretention cell performance: A large-scale lysimeter study. In Proceedings of the EGU General Assembly Conference Abstracts, Online, 25–30 April 2021; pp. EGU21-10259. [CrossRef]
29. Green, D.; Stirling, R. Monitoring Green Infrastructure: Design and commissioning of pilot scale bioretention cell lysimeters. *Dataset* **2021**. [CrossRef]
30. De-Ville, S. Urban Green DaMS: Recycled Bioretention Media SWMM Modelling Input Datafiles, Dataset. 2021. Available online: https://figshare.shef.ac.uk/articles/dataset/Urban_Green_DaMS_Recycled_Bioretention_Media_SWMM_Modelling_Input_Datafiles/14695482 (accessed on 22 July 2021)
31. Liu, R.; Fassman-Beck, E. Pore Structure and Unsaturated Hydraulic Conductivity of Engineered Media for Living Roofs and Bioretention Based on Water Retention Data. *J. Hydrol. Eng.* **2018**, *23*, 04017065. [CrossRef]
32. Fassman-Beck, E.; Saleh, F. Sources and Impacts of Uncertainty in Uncalibrated Bioretention Models Using SWMM 5.1.012. *J. Sustain. Water Built Environ.* **2021**, *7*, 04021006. [CrossRef]

33. Yang, H.; Florence, D.C.; McCoy, E.L.; Dick, W.A.; Grewal, P.S. Design and hydraulic characteristics of a field-scale bi-phasic bioretention rain garden system for storm water management. *Water Sci. Technol.* **2009**, *59*, 1863–1872. [CrossRef]
34. Brown, R.A.; Hunt, W.F. Improving bioretention/biofiltration performance with restorative maintenance. *Water Sci. Technol.* **2012**, *65*, 361–367. [CrossRef]
35. Schlea, D.; Martin, J.; Ward, A.; Brown, L.; Suter, S. Performance and Water Table Responses of Retrofit Rain Gardens. *J. Hydrol. Eng.* **2014**, *19*, 05014002. [CrossRef]
36. Paus, K.H.; Muthanna, T.M.; Braskerud, B.C. The hydrological performance of bioretention cells in regions with cold climates: Seasonal variation and implications for design. *Hydrol. Res.* **2015**, *47*, nh2015084. [CrossRef]
37. Mahmoud, A.; Alam, T.; Yeasir, A.; Rahman, M.; Sanchez, A.; Guerrero, J.; Jones, K.D. Evaluation of field-scale stormwater bioretention structure flow and pollutant load reductions in a semi-arid coastal climate. *Ecol. Eng. X* **2019**, *1*, 100007. [CrossRef]
38. Davis, A.P. Field Performance of Bioretention: Hydrology Impacts. *J. Hydrol. Eng.* **2008**, *13*, 90–95. [CrossRef]
39. Asleson, B.C.; Nestingen, R.S.; Gulliver, J.S.; Hozalski, R.M.; Nieber, J.L. Performance Assessment of Rain Gardens. *JAWRA J. Am. Water Resour. Assoc.* **2009**, *45*, 1019–1031. [CrossRef]
40. Hatt, B.E.; Fletcher, T.D.; Deletic, A. Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *J. Hydrol.* **2009**, *365*, 310–321. [CrossRef]
41. Li, H.; Davis, A.P. Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. *J. Environ. Eng.* **2009**, *135*, 567–576. [CrossRef]
42. Li, H.; Sharkey, L.J.; Hunt, W.F.; Davis, A.P. Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. *J. Hydrol. Eng.* **2009**, *14*, 407–415. [CrossRef]
43. Line, D.E.; Hunt, W.F. Performance of a Bioretention Area and a Level Spreader-Grass Filter Strip at Two Highway Sites in North Carolina. *J. Irrig. Drain. Eng.* **2009**, *135*, 217–224. [CrossRef]
44. Passeport, E.; Hunt, W.F.; Line, D.E.; Smith, R.A.; Brown, R.A. Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution. *J. Irrig. Drain. Eng.* **2009**, *135*, 505–510. [CrossRef]
45. Carpenter, D.D.; Hallam, L. Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance. *J. Hydrol. Eng.* **2010**, *15*, 404–416. [CrossRef]
46. Chapman, C.; Horner, R.R. Performance Assessment of a Street-Drainage Bioretention System. *Water Environ. Res.* **2010**, *82*, 109–119. [CrossRef]
47. Trowsdale, S.A.; Simcock, R. Urban stormwater treatment using bioretention. *J. Hydrol.* **2011**, *397*, 167–174. [CrossRef]
48. Khan, U.T.; Valeo, C.; Chu, A.; van Duin, B. Bioretention cell efficacy in cold climates: Part 1 - hydrologic performance. *Can. J. Civ. Eng.* **2012**, *39*, 1210–1221. [CrossRef]
49. Wardynski, B.J.; Hunt, W.F. Are Bioretention Cells Being Installed Per Design Standards in North Carolina? A Field Study. *J. Environ. Eng.* **2012**, *138*, 1210–1217. [CrossRef]
50. Houdeshel, C.D.; Hultine, K.R.; Johnson, N.C.; Pomeroy, C.A. Evaluation of three vegetation treatments in bioretention gardens in a semi-arid climate. *Landsc. Urban Plan.* **2015**, *135*, 62–72. [CrossRef]
51. Lucke, T.; Nichols, P.W. The pollution removal and stormwater reduction performance of street-side bioretention basins after ten years in operation. *Sci. Total Environ.* **2015**, *536*, 784–792. [CrossRef] [PubMed]
52. Page, J.L.; Winston, R.J.; Mayes, D.B.; Perrin, C.; Hunt, W.F. Retrofitting with innovative stormwater control measures: Hydrologic mitigation of impervious cover in the municipal right-of-way. *J. Hydrol.* **2015**, *527*, 923–932. [CrossRef]
53. Muerdter, C.; Özkök, E.; Li, L.; Davis, A.P. Vegetation and Media Characteristics of an Effective Bioretention Cell. *J. Sustain. Water Built Environ.* **2016**, *2*, 04015008. [CrossRef]
54. Winston, R.J.; Dorsey, J.D.; Hunt, W.F. Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. *Sci. Total Environ.* **2016**, *553*, 83–95. [CrossRef] [PubMed]
55. Jiang, C.; Li, J.; Li, H.; Li, Y.; Chen, L. Field Performance of Bioretention Systems for Runoff Quantity Regulation and Pollutant Removal. *Water Air Soil Pollut.* **2017**, *228*. [CrossRef]
56. Willard, L.L.; Wynn-Thompson, T.; Krometis, L.H.; Neher, T.P.; Badgley, B.D. Does It Pay to be Mature? Evaluation of Bioretention Cell Performance Seven Years Postconstruction. *J. Environ. Eng.* **2017**, *143*, 04017041. [CrossRef]
57. Shrestha, P.; Hurley, S.E.; Wemple, B.C. Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems. *Ecol. Eng.* **2018**, *112*, 116–131. [CrossRef]
58. Funai, J.T.; Kupec, P. Evaluation of Three Soil Blends to Improve Ornamental Plant Performance and Maintain Engineering Metrics in Bioremediating Rain Gardens. *Water Air Soil Pollut.* **2019**, *230*, 3. [CrossRef]
59. Hsieh, C.h.; Davis, A.P. Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff. *J. Environ. Eng.* **2005**, *131*, 1521–1531. [CrossRef]
60. Li, H.; Davis, A.P. Urban Particle Capture in Bioretention Media. II: Theory and Model Development. *J. Environ. Eng.* **2008**, *134*, 419–432. [CrossRef]
61. O'Neill, S.W.; Davis, A.P. Water Treatment Residual as a Bioretention Amendment for Phosphorus. II: Long-Term Column Studies. *J. Environ. Eng.* **2012**, *138*, 328–336. [CrossRef]
62. Palmer, E.T.; Poor, C.J.; Hinman, C.; Stark, J.D. Nitrate and Phosphate Removal through Enhanced Bioretention Media: Mesocosm Study. *Water Environ. Res.* **2013**, *85*, 823–832. [CrossRef]

63. Liu, J.; Sample, D.J.; Owen, J.S.; Li, J.; Evanylo, G. Assessment of Selected Bioretention Blends for Nutrient Retention Using Mesocosm Experiments. *J. Environ. Qual.* **2014**, *43*, 1754. [CrossRef]
64. Fassman-Beck, E.; Wang, S.; Simcock, R.; Liu, R. Assessing the Effects of Bioretention's Engineered Media Composition and Compaction on Hydraulic Conductivity and Water Holding Capacity. *J. Sustain. Water Built Environ.* **2015**, *1*, 04015003. [CrossRef]
65. Moghadas, S.; Gustafsson, A.M.; Viklander, P.; Marsalek, J.; Viklander, M. Laboratory study of infiltration into two frozen engineered (sandy) soils recommended for bioretention. *Hydrol. Process.* **2016**, *30*, 1251–1264. [CrossRef]
66. Liu, R.; Fassman-Beck, E. Effect of Composition on Basic Properties of Engineered Media for Living Roofs and Bioretention. *J. Hydrol. Eng.* **2016**, *21*, 06016002. [CrossRef]
67. Yan, Q.; Davis, A.P.; James, B.R. Enhanced Organic Phosphorus Sorption from Urban Stormwater Using Modified Bioretention Media: Batch Studies. *J. Environ. Eng.* **2016**, *142*, 04016001. [CrossRef]
68. Gülbaz, S.; Kazezyılmaz-Alhan, C.M. Experimental Investigation on Hydrologic Performance of LID with Rainfall-Watershed-Bioretention System. *J. Hydrol. Eng.* **2017**, *22*, D4016003. [CrossRef]
69. Mei, Y.; Gao, L.; Zhou, H.; Wei, K.H.; Cui, N.Q.; Chang, C.C. Ranking media for multi-pollutant removal efficiency in bioretention. *Water Sci. Technol.* **2018**. [CrossRef]
70. Ding, B.; Rezanezhad, F.; Gharedaghloo, B.; Van Cappellen, P.; Passeport, E. Bioretention cells under cold climate conditions: Effects of freezing and thawing on water infiltration, soil structure, and nutrient removal. *Sci. Total Environ.* **2019**, *649*, 749–759. [CrossRef] [PubMed]
71. Lee, J.Y.; Kim, H.; Han, M. The Evaluation of Bioretention Mesocosm for Treatment of Urban Stromwater Runoff. *Int. J. Urban Sci.* **2008**, *12*, 116–128. [CrossRef]
72. Lucas, W.C.; Greenway, M. Nutrient Retention in Vegetated and Nonvegetated Bioretention Mesocosms. *J. Irrig. Drain. Eng.* **2008**, *134*, 613–623. [CrossRef]
73. Stander, E.K.; Borst, M.; O'Connor, T.P.; Rowe, A.A. Measure Twice, Build Once: Bench-Scale Testing to Evaluate Bioretention Media Design. In *Low Impact Development 2010*; American Society of Civil Engineers: Reston, VA, USA, 2010; pp. 126–138. [CrossRef]
74. Lucas, W.C.; Greenway, M. Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part I-Hydraulic Response. *Water Environ. Res.* **2011**, *83*, 692–702. [CrossRef]
75. Randall, M.T.; Bradford, A. Bioretention gardens for improved nutrient removal. *Water Qual. Res. J.* **2013**, *48*, 372–386. [CrossRef]
76. Wadzuk, B.M.; Hickman, J.M.; Traver, R.G. Understanding the Role of Evapotranspiration in Bioretention: Mesocosm Study. *J. Sustain. Water Built Environ.* **2015**, *1*, 04014002. [CrossRef]
77. Hess, A.; Wadzuk, B.; Welker, A. Evapotranspiration in Rain Gardens Using Weighing Lysimeters. *J. Irrig. Drain. Eng.* **2017**, *143*, 04017004. [CrossRef]
78. Tian, J.; Jin, J.; Chiu, P.C.; Cha, D.K.; Guo, M.; Imhoff, P.T. A pilot-scale, bi-layer bioretention system with biochar and zero-valent iron for enhanced nitrate removal from stormwater. *Water Res.* **2019**, *148*, 378–387. [CrossRef] [PubMed]