Urban Green DaMS: Hydraulic Conductivity Function Data

Simon De-Ville[a,b], Zhangjie Peng[a,c], Virginia Stovin[a]

[a] *Department of Civil & Structural Engineering. The University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield, South Yorkshire, S1 3JD, United Kingdom*
[b] *Department of Civil & Environmental Engineering. University of Liverpool, School of Engineering, The Quadrangle, Brownlow Hill, Liverpool, Merseyside, L69 3GH, United Kingdom*
[c] *Centre for Resilience in Environment, Water and Waste (CREWW). University of Exeter, CREWW Building, North Park Road, Exeter, Devon, EX4 4TA, United Kingdom*

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D1. Introduction

This dataset is a complete record of all data compiled as part of a series of three infiltration column tests to identify the unsaturated hydraulic conductivity of a bioretention media. The experimental work was conducted at The University of Sheffield, Sheffield, UK, from December 2019 to February 2021 (15 months). The dataset was collected, processed and compiled for publication by Dr Simon De-Ville as part of the Urban Green DaMS project, EPSRC Grant Number EP/S005536/1.

D2. Data Structure

The data consists of a single data file. Within the file is a data table with the following variables:

- `Trial`, the trial number (1, 2, or 3).
- `State`, indicates the moisture state for which the conductivity value was calculated (SS: Steady State or TS: Transient State).
- `VWC`, the volumetric water content (m^3/m^3) at which the conductivity value was calculated.
- `K`, the calculated hydraulic conductivity (mm/hr).

Also included is a simple Matlab script that plots the HCF data and compares this to two HCF relationships. Please refer to the code comments for the specifics on how this script operates.

D3. Experimental Set-up

D3.1. The Bioretention Media

The bioretention media for this study was sourced locally within Sheffield, UK, and comprises 100% recycled waste components. The waste components used to make the fill media are (by weight): 50% Quarry Waste Material (5–20 mm); 25% Crushed Recycled Glass; 15% Green Waste Compost; and 10% Sugar-beet Washings (topsoil). The media has a lab-derived saturated hydraulic conductivity of 101 mm/hour, porosity of 0.443 m^3/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 fill media is used extensively throughout Sheffield in the City Council's Grey-to-Green retrofit bioretention systems and shall henceforth be referred to as 'G2G media' or simply 'G2G'. A complete characterisation of the media is presented in:

> De-Ville, S., Green, D., Edmondson, J., Stirling, R., Dawson, R., and Stovin, V., **2021**. Evaluating the Potential Hydrological Performance of a Bioretention Media with 100% Recycled Waste Components, *Water*, 13, 2014.

D3.2. The Infiltration Column

This study utilised the infiltration column methodology for determining unsaturated hydraulic conductivity as presented by:

> Peng, Z., Smith, C., and Stovin, V., **2020**. The importance of unsaturated hydraulic conductivity measurements for green roof detention modelling, *Journal of Hydrology*, 590.

A brief summary of the method is presented below and in section D4. Figure D3.1 illustrates the apparatus used for HCF determinations. The apparatus comprises an infiltration flow control system, sample column, moisture content measurement devices, suction head measurement devices and an outflow measurement system.

The infiltration rate was controlled by a peristaltic pump. Hypodermic needles (BD, Microlance 3 26G and 21G) were used to distribute the water evenly to the substrate surface. The small needles (26G) are capable of distributing a low flow rate (≤1.4 mm/min) and the large needles (21G) are suitable for high flow rates (≥1.4 mm/min). The water distribution panel consists of 37 needles; they are arranged in a regular octagon with three needles along each side,

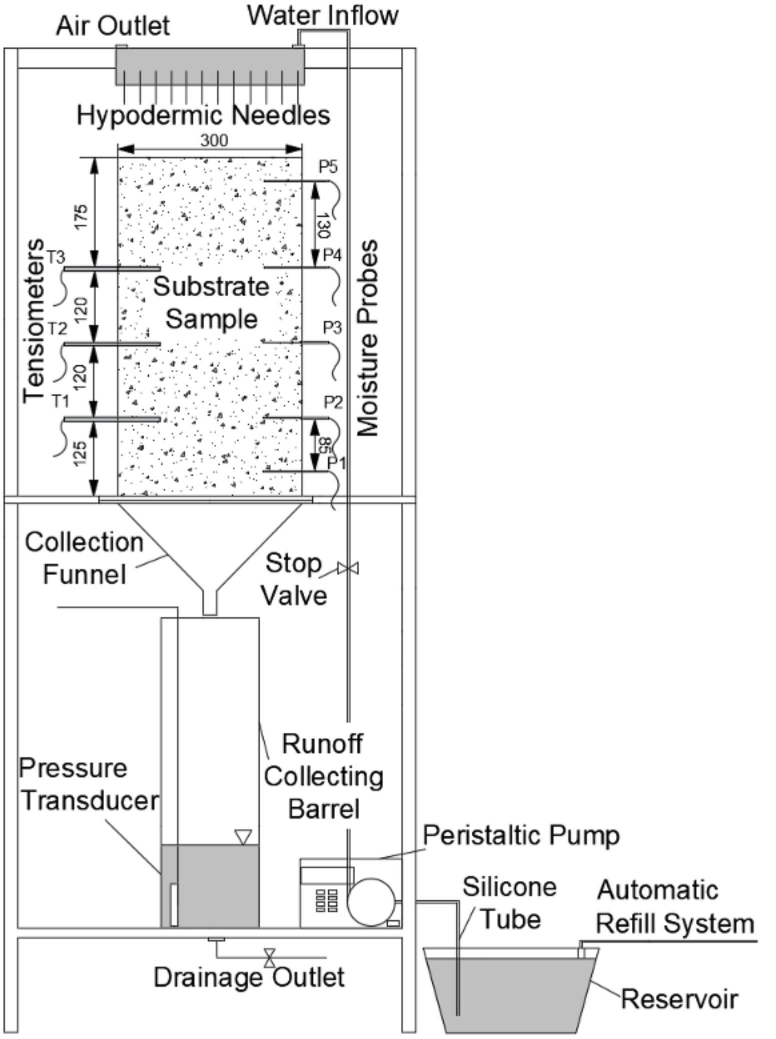

Figure D3.1: Infiltration column apparatus for HCF determinations (Peng et al., 2020)

seven needles across the longest axes and five needles across the shortest axes. The distance between adjacent needles is 40 mm, so the octagon has sides of 120 mm, and is 240 mm long across its longest axes.

The sample column is 540 mm high and has an internal diameter of 300 mm. The height was chosen to ensure that there is a volume of substrate that is not influenced by the boundary conditions and the diameter was chosen to minimise wall effects. A perforated base covered by a layer of mesh and filter sheet (Zinco, Systemfilter SF) was placed above a funnel. A runoff collecting barrel with a pressure transducer (Druck Inc. PDCR 1830) was used to measure water depth in a straight-sided collection barrel, which was subsequently used to determine the outflow from the substrate.

Five moisture probes (P1 to P5, Meter, 5TM) and three tensiometers (T1 to T3, Meter, T5x) were placed at different depths to measure the change in moisture content and suction head respectively. The moisture probes were put into place while the column was being filled with substrates and the substrate around the probes was gently pressed in place to obtain a good hydraulic connection. The tensiometers were placed using a similar methodology. Substrate was placed gently within the column using a trowel. Considering the strength of the apparatus, no compaction was applied to the substrate. The moisture probes, tensiometers and pressure transducers were connected to a Campbell Scientific CR1000 data logger. Continuous readings from the sensors were recorded at 1-minute time intervals. Before tests, the moisture probes were calibrated for the bioretention media (see section D5) and the depth versus pressure relationship was calibrated for the collection barrel.

D4. Calculating Hydraulic Conductivity

The infiltration column method gives vertical hydraulic conductivities for the bioretention media. For relatively high hydraulic conductivities (in this case, $K(\theta) > 4.5$ mm/hr), the steady state method is appropriate, whilst the transient method permits characterisation at lower hydraulic conductivities. The measured runoff rate and moisture content under steady state conditions were related to determining the HCF at high hydraulic conductivity, and the paired moisture content and suction head measurements under transient conditions were used to characterise the HCF at low hydraulic conductivities. In this section, the method for calculating the hydraulic conductivity using experimental data is explained in detail.

D4.1. Steady State

The steady state condition applies when moisture content does not change with depth, and water flow is driven only by gravity. In this state, as no gradient is present with depth, the hydraulic conductivity is equal to the imposed infiltration rate or the outflow rate. However, due to the heterogeneous nature of bioretention media, variations between probe readings at specific positions in the substrate are always present; in this study steady state was judged to be attained when the change in moisture content over an hour at all five depths was less than the resolution of the moisture content probes (0.1 Dielectric Permittivity Units).

Outflow measurements were conducted once a steady state had been attained and ended when steady state conditions were no-longer present. This variable collection time ranged between 60 minutes and 37 hours. To exclude the influence of boundary conditions, the moisture contents measured by the topmost and bottommost probes were excluded from the analysis. The measured moisture contents from the remaining three probes at steady state were averaged to provide the mean moisture content corresponding to each outflow rate.

The steady state tests began with the highest flow rate. The flow rate was then decreased and the same procedures were repeated for the next flow rate. A value of mean moisture content and K were identified for every flow rate and steady state period.

D4.2. Transient State

The transient method, which is also referred to as the instantaneous profile method, permits unsaturated hydraulic conductivity to be calculated using transient measurements of moisture content and suciton head. The transient measurements were conducted under conditions of no inflow, after all the steady state measurements were finished. The sample column used to hold the substrate has a perforated base, so when inflow stops, drainage dominates initially, followed by evaporation later on. The total hydraulic head at two adjacent vertical measurement positions was calculated from measured suction heads to determine the direction of flow, and then the measured data was used to calculate the hydraulic conductivity using Eqs. D4.1 to D4.3. The calculated hydraulic conductivity was then correlated with the averaged moisture content over the two adjacent positions.

The hydraulic gradient between each of the depths in the substrate column where moisture content is measured can be calculated by:

$$\left(\frac{dH}{dz}\right)_m = -1 - \left(\frac{h_m - h_{m-1}}{z_{m-1} - z_m}\right) \tag{D4.1}$$

where H is the total hydraulic head, m is an integer assigned to each of the measurement point/moisture probes (the upper moisture probe shall be assigned $m = 1$ with increasing values assigned to each probe with depth of the substrate column), h is the matric suction head, and z is the elevation of each probe.

During a given time interval Δt and depth interval $z_{m+1} - z_m$, the unit flow rate downstream from a point m is given as:

$$q^j = \sum_{m=1}^{n} \left(\theta_m^j - \theta_m^{j-1}\right)(z_{m+1} - z_m) \tag{D4.2}$$

where q is the unit flow rate, j is the current time step, θ is the measured moisture content and n is the total number of measurement points used in the calculation, other symbols are as defined before.

The hydraulic conductivity K_j can be calculated using the following equation:

$$K_j = -\frac{q^j}{\Delta t\left(\frac{dH}{dz}\right)_m} \tag{D4.3}$$

As the drying process starts from the top of the substrate, the decrease in moisture content and suction head in the bottom layer of the substrate occurs slowly. The responses of the tensiometers are slower than the moisture probes and they failed to capture the dynamics in the substrate at the very beginning of the drainage process. The measured moisture content and suction were therefore recorded after the tensiometers started to give reasonable measurements (reasonable measurements refers to readings from tensiometers below 0 cm). The recorded data was used to calculate hydraulic conductivity using the above equations A 1-hour timestep was used to identify conductivity values during the drainage phase.

D5. Moisture Content Probe Media Specific Volumetric Water Content Calibration

D5.1. Rationale

Moisture content probes (METER 5TMs) have been utilised to evaluate the moisture content dynamics of the Grey-to-Green (G2G) media in the evapotranspiration column experiments. METER suggest that their factory calibration 'may not be applicable to all soil types,' and so a specific G2G calibration is desirable.

D5.2. Methods

D5.2.1. Experimental Set-up

A single 5TM moisture content probe was placed horizontally at the mid-depth of a 130 mm deep layer of air-dried G2G. The probe was oriented so all measurement prongs were aligned horizontally. The G2G media was contained within a 300 mm diameter acrylic column with a perforated base overlain by a fine mesh to retain the media within the column (Figure D5.1). A constant intensity inflow was evenly applied to the upper surface of the media via a dripper network to raise the moisture content to a 'high value' above typical operating moisture content. In practice, this led to the saturation of the media and the generation of a modest ponded head ($<$ 10 mm). The inflow was stopped, the media was allowed to freely drain and then continue to dry via evaporation. The mass of the fill media was monitored using a calibrated load cell array. The total experiment duration was 105-days.

D5.2.2. Data Analysis

Volumetric water content (VWC, θ) was determined from gravimetric water content by assuming the density of water to be 1000 kg/m^3. Throughout the experiment, the rate of evaporation declined as matric suctions within the drying media increased. This led to the collection of considerably more data points in 'dry' conditions compared to 'wet' conditions. This skewed distribution of data points will lead to a biased calibration toward the drier media condition. A uniformly weighted distribution of dielectric values was determined by identifying the mean VWC for 0.01 increments of dielectric (sensor resolution). These uniformly weighted data were used to generate a cubic best fit calibration equation.

D5.3. Results

The observed relationship between dielectric permittivity (DP) and volumetric water content (VWC) is presented in Figure D5.2. The results follow similar patterns to those presented in the literature, with decreased sensitivity (higher gradient, large change in VWC for small change in DP) at the dry and wet ends of the moisture content ranges, and a region of elevated sensitivity (low gradient) at the midpoint of the moisture content range. This relationship suggests the data is suitable for the application of a cubic best-fit calibration curve.

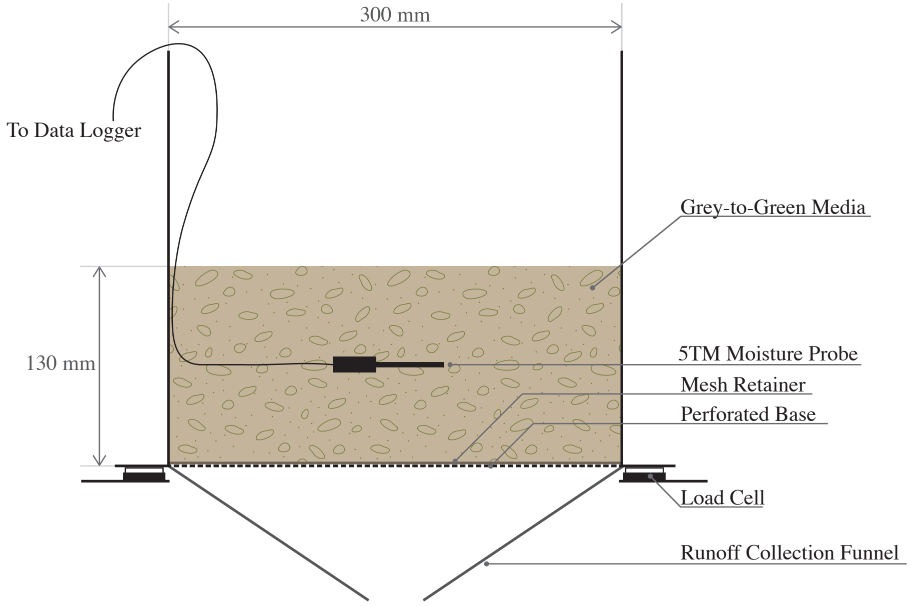

Figure D5.1: Schematic Diagram of Experimental Set-up.

What is not shown from Figure D5.2 is that 50% of the collected data is for dielectric values of < 7.83. This represents less than one-fifth of the range of observed dielectric values (4.60 23.6). A cubic best-fit calibration curve was fitted to the uniformly distributed data set with the resultant relationship:

$$\theta = 1.1775 \times 10^{-4}\mathrm{DP}^3 - 0.0045 \times \mathrm{DP}^2 + 0.0720\mathrm{DP} - 0.2158 \tag{D5.1}$$

where the model fit statistic R^2 (Nash and Sutcliffe, 1970) had a value of 0.991.

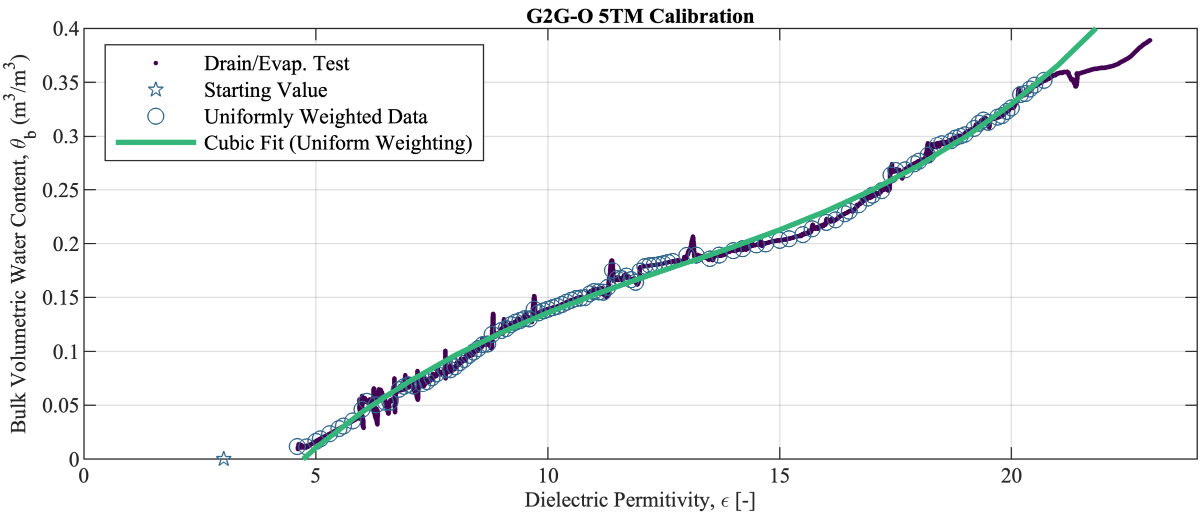

Figure D5.2: Scatter plot of observed Dielectric Permittivity and Volumetric Water Content data, including uniformly weighted data points and the resulting cubic best fit model.