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Hydraulic characterization of an unsaturated vegetated soil: the role of plant roots and hydraulic hysteresis

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1 **Hydraulic characterization of an unsaturated vegetated soil: the role** 2 **of plant roots and hydraulic hysteresis**

3

4 **Abstract**

5 Flowslides and debris flows in granular soils pose a serious threat to human life and man-made
6 structures. Due to rainwater infiltrating into superficial unsaturated soils, rainfall is the most common
7 triggering factor of such landslides, causing a decrease in matric suction and hence in soil shear
8 strength. Early warning systems based on accurate analyses of groundwater response to meteorological
9 factors are widely used to mitigate landslide risk. In such a context, the accuracy of the model adopted
10 to calculate the groundwater field is closely related to the reliability and meaningfulness of hydraulic
11 soil characterization. In this paper, an extensive laboratory investigation regarding the hydraulic
12 behaviour of pyroclastic unsaturated deposits from a vegetated slope monitored on Mount Faito
13 (Campania, Southern Italy) is presented to highlight the importance of hydraulic hysteresis and the
14 presence of roots in shallow soils. Water retention properties and hydraulic conductivity functions were
15 determined, focusing on a drying-wetting cycle. Tests on specimens sampled in the top ten centimetres
16 of the soil profile were also carried out to assess the effects of plant roots on soil hydraulic properties.
17 Inverse analyses were used to estimate the parameters of a hysteretic hydraulic model. Finally,
18 parametric numerical analyses, carried out via a finite element code, were used to highlight the
19 potential effects of the hydraulic characterization on the stability of sloping pyroclastic covers,
20 including all above factors.

21

22

23 **Keywords:** unsaturated soil; hydraulic soil characterization; pyroclastic soil; hydraulic hysteresis;
24 rooted soil

25 **1 Introduction**

26 Flowslides and debris flows can lead to huge human and economic losses. Rainfall is the most usual
27 trigger of such landslides, resulting from rainwater infiltration into unsaturated subsoil that induces a
28 decrease in matric suction and hence in soil shear strength. Flowslides and debris flows occur widely in
29 many geological settings, such as crystalline bedrocks covered by uppermost weathered soils^{1,2}, eluvial
30 and colluvial covers on clay shales^{3,4} and pyroclastic soils resting on igneous, carbonate or flysch
31 bedrock in the vicinity of volcanoes⁵⁻¹⁷. Several flowslides have occurred in shallow pyroclastic
32 deposits resting on steep slopes in the areas surrounding Mount Vesuvius (Campania, Southern Italy)
33 in the last twenty years, as the tragic events in Sarno (1998), Nocera (2005) and Ischia (2006).

34 Early warning systems, based on accurate analysis of the groundwater regime and its relationship with
35 meteorological factors, are widely used as a measure for forecasting and mitigation of rapid landslide
36 risk¹⁸. In this framework, physically-based models are required to correctly reproduce the hydro-
37 mechanical behaviour of unsaturated slopes through numerical analyses. Reliable predictions of matric
38 suction and volumetric water content in sloping subsoil can be obtained by considering the hysteretic
39 hydraulic behaviour of the soil and the effects of vegetation on soil hydraulic properties.

40 Accounting for the hysteresis of the water retention curve (WRC) and the hydraulic conductivity
41 function (HCF) produces a better estimation of the propagation of wetting fronts during heavy
42 rainfall¹⁹. Recent studies^{13,20} considered the hysteretic hydraulic soil response in such contexts.
43 Comegna et al¹³ investigated the influence of rainwater infiltration on hydraulic soil response and
44 hence on slope stability conditions, stressing the potential errors in the prediction of landslide
45 triggering when hydraulic hysteresis is neglected.

46 The effect of vegetation on soil hydraulic properties has been investigated only recently in the
47 geotechnical literature. Plant roots change the soil fabric progressively, which affects soil hydraulic
48 properties²¹. Several experimental works by Leung et al²², Ng et al^{23,24} and Ni et al^{25,26} have shown that
49 the presence of roots affects the shape of both soil WRCs and HCFs. Ng et al²⁴ and Ni et al²⁶ found that
50 the presence of one plant species generally provides a reduction in saturated soil permeability
51 compared to that of bare soil whereas mixed-species and/or high plant density lead to an increase in
52 permeability. In fact, competition among individuals leads to an increase in soil macro-porosity
53 associated with root decay and to an increase in permeability of the root-permeated soil^{27,28}.

54 Recently, Jotisankasa et al²⁹, have tested the effects of Vetiver grass on the WRC and HCF in two types
55 of soils: a low plasticity silt and a clayey sand. They found that roots disturb the pore-size distribution
56 of vegetated soil in the range of macro-pores greater than about 1.5 mm, and hence affect soil hydraulic
57 properties mainly in the range of matric suction values lower than 1 kPa. In particular, in low plasticity
58 silt, for root densities lower than 6.5 kg/m³, saturated permeability values increased up to 2 to 5 times
59 of those of bare soils, mainly due to desiccation cracks and preferential flow induced by drying and
60 wetting cycles. On the contrary, for root densities higher than the aforementioned threshold,
61 permeability values decreased due to the obstruction of macro-voids caused by roots.

62 Jotisankasa et al²⁹ identified four main phenomena occurring during plant growth affecting soils
63 hydraulic conductivity: i) cycles of wetting and drying due to plant watering and evapotranspiration; ii)
64 decay of roots that generates preferential flow paths along the impoverished roots; iii) obstruction of
65 macro-pores by plant roots; and iv) organic carbon released by plant (the so-called root exudation). The
66 first two phenomena provide an increase in saturated hydraulic conductivity values, the third one a
67 decrease. Then, the fourth phenomena generate an increment of the saturated volumetric water content.
68 The combined effects due to all these features simultaneously is hardly quantifiable over root growth
69 and these change with the soil type, the plant species and their interaction.

70 Within this interpretative framework, the paper reports the results of extensive hydraulic
71 experimentation carried out in laboratory on pyroclastic soil samples, with and without roots, collected
72 at a test site on Mt. Faito (Campania, Southern Italy), close to an area involved in several flowslide
73 phenomena. The experimental technique used in this research was developed for pyroclastic soil of the
74 same regional context by Nicotera et al³⁰ who determined drying paths of WRCs and HCFs; however,
75 in this case the study was extended to wetting paths too.

76 Each specimen was subjected to a saturated hydraulic conductivity test at constant head and to some
77 drying-wetting cycles. Inverse analyses of measurements for each laboratory test were carried out with
78 a finite element method code, HYDRUS-1D, in order to estimate hydraulic model parameters for main
79 drying (MDC) and main wetting (MWC) branches of WRC and HCF. Furthermore, the model of
80 Parker and Lenhard³¹ was adopted to interpret the hydraulic hysteresis.

81 Lastly, some results of numerical analyses are shown to assess the effects of hydraulic hysteresis and
82 roots presence on matric suction and water content distribution along a soil column during heavy
83 rainfall. The response to rainfall was modelled with reference to a soil column typical of the test site at

84 Mt. Faito (Campania, Southern Italy), varying the initial soil condition and the duration of heavy
85 rainfall.

86

87 **2 Test site**

88 The investigated soils belong to the pyroclastic cover of the Lattari Mountains on the Sorrento
89 Peninsula in Campania (southern Italy). Several flowslides, debris flows and debris avalanches have
90 occurred on the Lattari Mts. and in the surrounding areas, such as in Pagani (1972), Pozzano (1997),
91 Nocera (2005), and more recently Vico Equense (2018)¹⁶. The study area is located at an altitude of
92 about 850 m on a North-facing slope of Mt. Faito (40°40'32.29"N, 14°28'23.35"E) (Figure 1a). Mature
93 individuals of *Castanea sativa* Mill. are cultivated in this area for fruit production. The understory is
94 mostly composed of ferns (*Pteridium aquilinum*) and shrubs (e.g. *Rubus ulmifolius* and *Corylus*
95 *avellana*). Vegetation starts to grow in mid-April, reaching its peak in July, and dries out in November.
96 Trees become dormant during the wet season when trees shed leaves, forming a groundcover mostly
97 consisting of dried leaves.

98 The stratigraphic profile observed in the field is composed of a series, 2.5 m thick, of pyroclastic soils
99 resting on fractured limestone. These soil layers are attributable to two different explosive volcanic
100 falls: (i) the shallower younger soil dates to the 79 AD eruption of Mt. Vesuvius; (ii) the deeper older
101 layers are of uncertain origin, but preliminary tephro-stratigraphic data attribute them to a Phlegraean
102 eruption occurring around 130,000 years ago³². From top to bottom, the stratigraphic sequence consists
103 of the following layers (Figures 1b-e)¹⁶:

- 104 • layer A, the topsoil; the upper part of this layer, called A1 (0.20-0.30 m thick), is affected by
105 biogeochemical processes due to the action of microorganisms and vegetation; the lower part,
106 A2 (0.40-1.00m thick), is an ash consisting of pumice-rich silty sand;
- 107 • layer B, which consists of coarse ungraded white pumices (gravel particles with a diameter of
108 20-40 mm), in a fine sandy pyroclastic matrix; the thickness is quite variable, ranging between
109 0.5 and 1.2 m;
- 110 • layer C, whose upper part is attributed to an ancient Phlegraean pyroclastic fall, referred to as
111 C1 (0.40-0.80 m thick), made of yellowish silty sands; the lower part, C2, consisting of highly
112 weathered reddish-brown ash (silty sand), with a clayey fraction, has a very variable thickness
113 (0.20–1.20 m), and in some areas of the test site is discontinuous.

114

115 **2.1 Soil physical properties**

116 Grain size analyses, according to the Unified Soil Classification System³³ were carried out on samples
 117 taken in all the layers of the soil cover at the test site (Figures 1f-i). The shallower soils, layers A1 and
 118 A2, were classified as silty sand with gravel and silty gravel with sand, respectively; layer B as well-
 119 graded gravel with sand; the bottom soils, C1 and C2, as sandy silts.

120 The values of soil physical properties determined on the undisturbed specimens used for hydraulic
 121 characterization are reported in Table 1. Only ash layers in the cover were investigated: topsoil, layers
 122 A1 and A2, and bottom soil, layers C1 and C2. In addition, some specimens were collected at the
 123 ground surface in order to better characterize the roots effect of on hydraulic properties. Hereafter this
 124 layer, whose thickness is 0.10 m, will be called A1sup. Specific gravity of soil particles (G_s) was
 125 obtained according to ASTM standard³⁴; G_s values ranges from 2.52 to 2.69 along the vertical soil
 126 profile (Table 1). Fines fraction presents in soil layers A and B was not plastic. Instead fine fraction in
 127 soil C2 provided a plastic limit varying between 23% and 60 % and a plasticity index ranging between
 128 3% and 17 %, thus, this soil is classified as medium and high compressibility silt³⁵.

129

130 **Table 1. Soil physical properties and root information of each tested specimen: sampling depth (z), soil**
 131 **particle specific gravity (G_s), soil dry density not accounting for the presence of roots (γ_d), soil porosity of**
 132 **bare soil (n_0), root dry biomass (M_{roots}), root volume ratio (R_v), and root-permeated soil porosity (n).**

Soil layer	Sample no.	z [m]	G_s [-]	γ_d [g cm ⁻³]	n_0 [-]	M_{roots} [g]	R_v [-]	n [-]
A1sup	N1	0.05	2.580	0.8935	0.654	0.484	0.00503	0.649
A1sup	N2	0.05	2.580	0.8020	0.689	0.340	0.00352	0.686
A1sup	R1	0.05	2.515	0.7393	0.713	2.471	0.02521	0.688
A1sup	R2	0.05	2.580	0.7760	0.699	1.176	0.01206	0.687
A1sup	R3	0.20	2.580	0.8193	0.682	0.962	0.00988	0.673
A1sup	R4	0.00	2.580	0.7469	0.711	1.840	0.01869	0.692
A1sup	R5	0.00	2.580	0.6556	0.746	4.630	0.04617	0.700
	mean	0.06	2.570	0.7761	0.699	1.700	0.01722	0.682
	std. dev.	0.07	0.025	0.0742	0.029	1.491	0.01484	0.017
A1	1.11.1	0.50	2.603	0.9265	0.644	0.274	0.00286	0.641
A1	1.11.2	0.50	2.603	1.0017	0.615	0.056	0.00059	0.615
A1	1.6.2	0.80	2.688	0.8690	0.677	0.098	0.00102	0.676
A1	1.7.2	0.80	2.580	0.9950	0.614	0.133	0.00138	0.613
A1	1.9.1	0.50	2.580	0.8217	0.681	1.337	0.01371	0.668
A1	1.9.2	0.50	2.580	0.8937	0.654	0.627	0.00648	0.647
	mean	0.60	2.606	0.9179	0.648	0.421	0.00434	0.643
	std. dev.	0.15	0.042	0.0711	0.029	0.495	0.00507	0.026
A2	1.1.1	1.65	2.688	0.8053	0.700	0.072	0.00074	0.700
A2	1.2.1	1.65	2.688	0.7379	0.725	0.128	0.00132	0.724
A2	1.4.1	1.65	2.688	0.9838	0.634	0.052	0.00054	0.633
A2	1.5.1	0.95	2.688	0.7731	0.712	0.071	0.00073	0.712
A2	1.5.2	0.95	2.688	0.8630	0.679	0.049	0.00051	0.678

A2	1.6.1	0.80	2.688	0.8075	0.700	0.098	0.00102	0.699
A2	1.7.1	0.80	2.688	0.7650	0.715	0.086	0.00089	0.714
	mean	1.21	2.688	0.8194	0.695	0.079	0.00082	0.694
	std. dev.	0.42	0.000	0.0827	0.031	0.028	0.00028	0.031
C1	2.12.1	1.45	2.666	0.6654	0.750	-	-	0.750
C1	2.12.2	1.45	2.666	0.7143	0.732	0.360	0.00371	0.728
C1	2.13.1	1.30	2.646	0.6413	0.758	0.077	0.00080	0.757
C1	2.15.1	1.30	2.666	0.6701	0.749	0.098	0.00102	0.748
C1	3.16.1	1.10	2.624	0.9840	0.625	-	-	0.625
	mean	1.32	2.656	0.7350	0.723	0.178	0.00184	0.722
	std. dev.	0.14	0.019	0.1417	0.055	0.158	0.00162	0.055
C2	1.1	1.80	2.528	0.8064	0.681	0.064	0.00066	0.680
C2	1.2	1.80	2.455	0.9036	0.643	0.951	0.00984	0.633
C2	1.3	0.80	2.528	0.7831	0.690	0.386	0.00399	0.686
	mean	1.47	2.500	0.8310	0.671	0.467	0.00483	0.666
	std. dev.	0.58	0.042	0.0639	0.025	0.449	0.00465	0.029

133

134 The investigated deposits presented high porosities (n_0), ranging from 0.61 to 0.76 (Table 1).
135 Additionally, the specimens were extremely permeated by roots; the roots present in the samples were
136 dead and unable to affect the soil matric suction through transpiration. Hence, the model of Ng et al²⁴
137 was adopted to better estimate soil porosity as the solid phases in the samples was composed by soil
138 particles and roots characterized by two different densities. Hence the root-permeated soil porosity n
139 was estimated as:

$$140 \quad n = n_0 - R_v \quad (1)$$

141 where n_0 is the porosity of bare soil, and R_v is the root volume ratio (Table 1). The root volume ratio
142 (R_v) is defined as the ratio between the volume occupied by roots in a root-permeated soil specimen
143 and the total volume of the specimens itself. In this case, R_v was estimated for each cylindrical soil
144 sample (diameter = 71.5 mm; height = 60 mm; volume = 240.90 cm³) recovered in situ. First of all, the
145 dry biomass in each soil sample (M_{roots}) was determined by collecting individually the roots after
146 oven-drying the rooted samples at 105 °C for 24 h and measuring their weight in a precision scale with
147 an accuracy of 0.001 g. Then, the volume occupied by roots was calculated as the ratio between M_{roots}
148 and the specific gravity of roots.

149 The specific gravity³⁵ of the roots of *C. sativa* was first determined³⁵: analyses of the digital images of
150 roots were carried out with the software WinRHIZO (Regent Instruments, Inc) to estimate their
151 volume. The specific gravity of root wood depends on root moisture content³⁶. In the present study,
152 matric suction varied between 0 and 100 kPa, in this range wood moisture content would be equal to
153 about 23 % and root volume changes are not expected, according to Simpson and Ten

154 Wolde³⁶. Therefore, the root specific gravity is fairly constant in the matric suction range experienced
155 by soil samples and it resulted equal to 0.399.

156 Soil porosity value estimated according to equation 1 is about 2.5% lower than that estimated by
157 neglecting the pore volume occupied by roots in the surficial layer A1sup. The difference between the
158 two porosity values is lower in the remaining soil layers.

159 **3 Methods**

160 **3.1 Experimental procedure**

161 The experimental procedure consisted of a sequence of laboratory tests to collect data about: a)
162 saturated hydraulic conductivity; b) development over time of soil response during evaporation and
163 imbibition processes, at both (b1) low to medium matric suction values (i.e. from 0 to 80 kPa, largely
164 bounding the expected AEV of tested soils,), and (b2) high matric suction values (i.e. corresponding to
165 water content values close to the residual one, with matric suction values from 800 kPa up to 1.0 MPa).
166 Data indicated in point b) were obtained using two different laboratory devices: a ku-pf MP10
167 apparatus for low to medium matric suction values (b1) and a pressure plate for high matric suction
168 values (b2). The results of both drying and wetting tests carried out in the b-range were used to
169 calibrate a K-P-S (hydraulic conductivity – pore pressure – saturation) hysteretic model.

170 Each soil specimen was trimmed from an undisturbed and unsaturated soil core directly into a
171 cylindrical stainless-steel sleeve (whose diameter and length were respectively 71.5 mm and 60.0 mm)
172 and weighed to record its initial state (i.e., water content and porosity). The device used to perform
173 permeability tests (phase a) was equipped with: (i) pressure probes, to measure pore water pressure at
174 the bottom and top of the specimen, (ii) two water reservoirs with pressure regulators, and (iii) two
175 burettes to control the water volume flowing through the specimen. Distilled water was flushed
176 upwards through the specimen by applying 10 kPa and 5 kPa in the lower and upper reservoir,
177 respectively. Volumes of water flowing into and out of the soil specimen were monitored over time. At
178 the steady state, when inflow and outflow rates became equal, full saturation of the specimen was
179 supposed to be attained. At least four flushing cycles were repeated per test. The permeability of the
180 soil specimen inferred from data collected during the steady phase of the test was considered a good
181 estimate of the saturated permeability.

182 At the end of the permeability test, the specimens still contained in the steel sleeve were moved for the
183 b1 phase to a ku-pf MP10 apparatus (Umwelt-Geräte-Technik GmbH, Figure 2), consisting of a star-

184 shaped sampler changer which managed up to ten stainless steel specimen rings, in order to monitor
185 matric suction and water content during evaporation and imbibition cycles.

186 A plastic paraffin film (parafilm M) was fixed at the bottom of the sample to prevent water evaporation
187 and drainage. The matric suction in each specimen was measured at two points (15 mm and 45 mm
188 below the top of the sample) by means of two mini-tensiometers, with a full-scale of 80 kPa and a
189 measurement resolution of 0.01 kPa. The mini-tensiometers were preliminarily saturated and calibrated
190 following standard procedures and then carefully installed in prearranged holes in order to ensure good
191 contact between the porous tip and the soil specimen. Each pair of tensiometers was connected to a
192 conditioning unit arranged upon each sample holder. The star-shaped changer periodically placed each
193 sample holder upon a precision balance (resolution of 0.01 g) and variations in total soil water storage
194 were determined from weight measurements. Matric suction and weight measurements were recorded
195 every 10 minutes throughout the entire test, i.e. wetting and drying phases. For more details about the
196 ku-pf apparatus readers can refer to Nicotera et al³⁰.

197 The saturated soil specimens contained in the rings were sealed also at the top end and were placed on
198 the specimen holders waiting for the hydrostatic condition to be reached. Hydraulic equilibrium was
199 checked via tensiometer readings, assuming that the equalization process was complete when the
200 difference between the top and bottom tensiometer measurements decreased to 0.3 kPa (i.e.,
201 corresponding to the hydrostatic matric suction profile).

202 The evaporation phase was initiated by removing the sealing cap and cling film from the top of the
203 sample: this way, water started to evaporate from the top surface of the sample. When the main drying
204 branch of the WRC had to be determined, drying process was stopped before tensiometers cavitation
205 (i.e. when matric suction readings reached the range between 70 kPa and 80 kPa) by covering the
206 sample with clinging film and a metallic cap. If the scanning paths were detected, the drying process
207 was stopped at reversal points corresponding to matric suction varying between 20 kPa and 50 kPa.
208 Subsequently, the soil sample was subjected to a series of wetting steps: distilled water was repeatedly
209 manually poured onto the top surface of the sample and infiltrated into the specimen, redistributing in
210 the soil. Different masses of water were used in each step: a larger mass of 5 g was added when the
211 matric suction values measured in the sample exceeded 15 kPa; a mass of 3 g of water was added,
212 instead, if the matric suction values were lower than 15 kPa. It was thus possible to obtain more refined
213 water retention data around the air-entry value (AEV) of the WRC, which ranged approximately from

214 6 kPa up to 12 kPa³⁰. During each step of wetting, the soil sample top surface was covered with a
215 clinging film and a cap to prevent evaporation as much as possible. Each new wetting step started after
216 the attainment of hydrostatic condition in the sample and lasted at least two hours. In this regard, it is
217 useful to highlight that two hours was the minimum necessary time to reach the equilibrium in a
218 wetting step. Indeed, the equilibrium was reached quickly when the sample was close to saturation
219 because the hydraulic conductivity was high and a quick movement of water inside the sample
220 occurred. Furthermore, the height of samples was small (60 mm) and small quantities of water were
221 added in the low suction range (3g). However, the hydrostatic conditions can take as much as three
222 days to be reached when suction is high.

223 In the range of residual saturation, there is a significant change in the gradient of the WRC: large
224 increases in matric suction produce small decreases in water content³⁷. Investigation of the water
225 retention properties in this region requires measurement of matric suctions significantly higher than
226 80 kPa and hence well above the full-scale value of the ku-pf mini-tensiometers. A pressure plate
227 apparatus was used to determine water contents along the main drying branch in the range of residual
228 saturation by applying matric suction values of 600 kPa or 850 kPa through the axis translation
229 technique (b2 phase). In the present work, only one point of the WRC per tested specimen was
230 determined by means of the pressure plate in accordance with the procedure suggested by Nicotera et
231 al³⁰. The samples were removed from the baskets of the ku-pf apparatus after the end of the last drying
232 phase. The bottom surface of the samples was placed on the porous stone of the pressure plate assuring
233 good contact. The weight of the samples was recorded using a balance. The experimental procedure was
234 concluded by oven-drying the sample to determine water content, porosity and root dry biomass.

235 The procedure discussed in this study does not involve measurements of soil volume variation.
236 However, the volume changes due to water content variations in pyroclastic soils of this region, at least
237 for the surficial layers (A), are expected to be non-significant according to previous experimental work
238 on pyroclastic soils of the same region^{38,39}.

239

240 **3.2 Evaluation of the parameters of the hydraulic hysteretic model**

241 The hysteretic model adopted herein was proposed by Lenhard et al⁴⁰ and is implemented in
242 HYDRUS-1D software⁴¹. The relationship between the volumetric water content (θ) and the matric
243 suction (s) is described by the classical van Genuchten⁴² equation. However, two different sets of

244 values of the fitting parameters are required to describe WRC along main-drying and main-wetting
 245 represented by Equation 2 and 3, respectively:

$$246 \quad \theta(s) = \theta_r + (\theta_s^d - \theta_r) / \{ [1 + (\alpha^d s)^{n_v}]^{1-1/n_v} \} \quad (2)$$

$$247 \quad \theta(s) = \theta_r + (\theta_s^w - \theta_r) / \{ [1 + (\alpha^w s)^{n_v}]^{1-1/n_v} \} \quad (3)$$

248 where the superscripts d and w refer to the main drying and main wetting curves, respectively; θ_r is the
 249 residual volumetric water content; α and n_v are fitting parameter of the van Genuchten equation;
 250 θ_s represents the volumetric water content at saturation.

251 In this study the WRC and HCF have been assumed unimodal for each layer. However, in the last
 252 findings of Jotisankasa et al²⁹ on the effects of Vetiver grass on the hydraulic behaviour of clayey sand,
 253 the HCF shows a bi-modal trend probably due to the plant variation.

254 The differences between the two curves are related to the maximum value θ_s of the volumetric water
 255 content and to the matric suction scaling parameter (α). Two different values for both parameters are
 256 considered for drying and wetting, respectively θ_s^d and θ_s^w and α^d and α^w . The fitting parameter n_v and
 257 the residual water content (θ_r) are the same for both branches.

258 The scanning paths are scaled from the main branches following the method presented by Parker and
 259 Lenhard³¹, characterized by a closed hysteretic loop. In particular, drying scanning curves are scaled
 260 from the main drying curve, and wetting scanning curves from the main wetting curve. The scaling
 261 procedure is well documented in Rianna et al²⁰ and Vogel et al⁴³. Compared to other models based on a
 262 scaling procedure, this model allows prevention of the artificial pumping error, that is, the non-closure
 263 of the scanning loops in simulated cyclic paths, which is considered to be an aberration rather than a
 264 soil property. This is avoided by collecting in the model all the reversal points experienced by the soil.
 265 Preserving the “memory” of the various wetting–drying cycles to which the sample has been subjected
 266 allows paths to draw closed scanning loops.

267 The HCF is modelled in HYDRUS-1D according to Vogel et al⁴³. It is described by Equation 4, where
 268 K is the soil hydraulic conductivity, l and m are fitting parameters, in which $m = 1 - 1/n_v$, S is the
 269 effective degree of saturation (Equation 5), and K_{sat} is the saturated hydraulic conductivity^{42,44}.

$$270 \quad K(S) = K_{sat} S^l [1 - (1 - S^{1/m})^m]^2 \quad (4)$$

$$271 \quad S = (\theta - \theta_r) / (\theta_s - \theta_r) \quad (5)$$

272 The model parameters were estimated via inverse analysis of the experimental measurements.
 273 According to Nicotera et al³⁰, application of the inverse method consists of a numerical analysis

274 simulating a lab test, and determination of the values of the model parameters for which differences
275 between observed and simulated flow variables are minimized; the estimated values of the parameters
276 are those that optimize the model response⁴⁵. This procedure was carried out in this research through
277 the software HYDRUS-1D in which an objective function was minimized by using the Levenberg-
278 Marquardt non-linear method⁴⁶.

279 The fitting of the hysteretic model was subdivided into two subsequent phases: the first consisted of
280 fitting the parameter vector associated to the main drying branch ($\theta_s^d, \theta_r, \alpha^d, n, l$); the second phase
281 was devoted to estimating the remaining parameters associated to the main wetting branch (θ_s^w, α^w).

282 The fitting of the main drying curve followed the procedure defined by Nicotera et al³⁰. In particular,
283 the data sets in the objective function were composed by: (i) the matric suction values measured by the
284 two mini-tensiometers during the evaporation process; (ii) a data pair (s, θ) obtained from the final
285 readings in the pressure plate; and (iii) a data pair (s, θ) corresponding to AEV. AEV was identified as
286 the point of maximum curvature on the WRC curve preliminarily obtained by coupling the arithmetic
287 mean of the two measurements of matric suction to the average water content of the whole soil sample.
288 Initial guesses of the parameters were determined by fitting the experimental points by the van
289 Genuchten equation using the Solver function of Excel in order to minimize the coefficient of
290 determination. In the inverse analyses, the parameters θ_s^d and θ_r were allowed to vary between 0 and 1,
291 the parameters α^d and n were allowed to vary between 0 and 10 (kPa⁻¹ in the case of α^d), and the
292 parameter l was allowed to vary between -10 and 10, as suggested by Nicotera et al³⁰.

293 Regarding the wetting branch, the data set in the objective function was composed of the matric suction
294 values measured by the two tensiometers over one drying-wetting cycle, as suggested in Dias³⁵. The
295 initial guess for α^w and θ_s^w were set equal respectively to $2\alpha^d$ and to the average water content of the
296 soil sample at the end of the wetting process as inferred from the weight of the sample itself. The
297 optimal values of θ_s^w and α^w were searched in the range from 0 to θ_s^d and from 0 to 100 kPa⁻¹,
298 respectively.

299

300 **3.2.1 Water capacity**

301 Once the fitting parameters had been determined, water capacity associated to the main loop was
302 determined. Water capacity (C), or water storage modulus, is the derivative of the WRC (Equations 2

303 and 3), resulting in the following general equation⁴⁷ valid for both drying and wetting branches
 304 according to the values assumed for parameters θ_s and α :

$$305 \quad C = d\theta/ds = \alpha(\theta_s - \theta_r)(n_v - 1)|\alpha \cdot s|^{n_v-1}(1 + |\alpha \cdot s|^{n_v})^{1/n_v-2} \quad (6)$$

306 Water capacity regulates the propagation velocity of the wetting front in the subsoil: the higher the
 307 water capacity, the slower is the wetting front movement. Indeed, Freeze⁴⁸ observed experimentally
 308 that, in sands, keeping the saturated permeability constant, higher water capacity results in less water
 309 flowing towards deep soils because a large amount of water needs to satisfy the storage demand by the
 310 soil.

311

312 **4 Results**

313 **4.1 Saturated hydraulic conductivity**

314 Saturated hydraulic conductivity, measured in the laboratory according to the previous procedure,
 315 varies by slightly above one order of magnitude along the vertical profile, ranging from $1.69 \times$
 316 $10^{-7}ms^{-1}$ to $8.09 \times 10^{-6}ms^{-1}$ (Table 2). These values compare well with those measured on
 317 pyroclastic soils sampled at other test sites in Campania^{30,49}. It is worth noting that permeability values
 318 determined at the end of the saturation phase reported in Table 2 should be considered only a lower
 319 limit for saturated permeability (K_s) because the full saturation of specimens was not always attained.

320

321 **Table 2. Values of Mualem–van Genuchten model parameters derived via inverse analysis of the first**
 322 **drying phase.**

soil	sample	z (m)	$K_{sat}^d (m s^{-1})$	θ_r	θ_s^d	α^d (kPa ⁻¹)	n_v	l	AEV (kPa)	R^2
A1 sup	R1	0.05	8.09E-06	0.160	0.677	0.1680	1.580	1.795600	2.5964	0.983
	R2	0.05	3.70E-06	0.139	0.635	0.1401	1.490	1.639600	3.0935	0.998
	R3	0.05	6.21E-06	0.117	0.625	0.1647	1.525	0.719800	2.5932	0.999
	N1	0.05	4.35E-07	0.120	0.610	0.0750	1.546	0.677320	5.7970	1.000
	N2	0.20	4.35E-07	0.132	0.588	0.1045	1.551	0.000103	4.1623	1.000
	mean	0.00	2.04E-06	0.134	0.627	0.1304	1.538	0.966485	3.648	
	std dev	0.00	-	0.017	0.033	0.0401	0.033	0.744795	1.3609	
A1	1.6.2	0.06	(4.35E-07)	0.143	0.569	0.1068	1.725	0.000001	4.1733	1.000
	1.7.2	0.07	2.93E-07	0.051	0.569	0.0533	1.515	2.398400	8.1397	0.999
	1.9.1	0.50	9.02E-07	0.161	0.644	0.1109	1.772	0.038050	4.0539	0.999
	1.9.2	0.50	6.02E-07	0.089	0.606	0.0874	1.424	1.451900	4.9648	0.997
	1.11.2	0.80	(4.35E-07)	0.105	0.521	0.0883	1.492	1.197200	4.9086	0.998
	mean	0.80	4.96E-07	0.110	0.582	0.0893	1.586	1.017110	5.2480	

	std dev	0.50	-	0.044	0.046	0.0228	0.153	1.015198	1.6686	
A2	1.1.1	0.50	(1.43E-06)	0.080	0.597	0.1315	1.510	-0.466950	3.2983	1.000
	1.2.1	0.60	(1.43E-06)	0.104	0.580	0.1192	1.585	0.217510	3.6614	0.999
	1.4.1	0.15	1.43E-06	0.120	0.453	0.0604	1.768	0.933960	7.4378	0.998
	1.5.1	1.65	5.94E-06	0.082	0.549	0.0940	1.571	3.114900	4.6360	0.999
	1.6.1	1.65	(6.75E-07)	0.098	0.554	0.1784	1.531	0.290140	2.4342	1.000
	1.7.1	1.65	1.43E-06	0.115	0.594	0.1241	1.546	3.873900	3.5034	1.000
	mean	0.95	1.60E-06	0.100	0.554	0.1179	1.585	1.327243	4.3346	
std dev	0.95	-	0.016	0.054	0.0394	0.094	1.752830	1.9023		
C1	2.12.2	0.80	2.06E-06	0.261	0.660	0.0889	1.726	0.000108	5.0088	0.999
	2.13.1	0.80	4.88E-06	0.249	0.690	0.1141	1.778	0.006155	3.9448	0.999
	2.15.1	1.21	(6.62E-07)	0.262	0.700	0.1057	1.838	0.578340	4.3088	0.999
	mean	0.42	1.88E-06	0.257	0.683	0.1029	1.781	0.194868	3.8999	
	std dev	1.45	-	0.007	0.021	0.0128	0.056	0.332111	1.1809	
C2	1.1	1.45	5.24E-07	0.230	0.643	0.0445	1.572	0.000344	9.5787	0.997
	1.2	1.30	4.96E-07	0.103	0.630	0.0111	1.486	7.634200	39.0419	0.999
	1.3	1.30	1.69E-07	0.225	0.654	0.0242	1.667	-1.511200	18.2387	0.999
	mean	1.30	3.53E-07	0.189	0.651	0.0268	1.581	0.589181	14.3880	
	std dev	1.10	-	0.067	0.007	0.0166	0.081	2.448492	15.2495	

323

324 The negative logarithm of saturated permeability (which expresses its order of magnitude), root dry
325 biomass, mass fraction of silt, and soil porosity of each lithotype are shown in Figures 3a-d. In Figure 3
326 (box and whiskers plot), each box contains the second and third quartile of the represented properties;
327 the median value is represented by the horizontal line, the average value is indicated by an “x”, and the
328 minimum and maximum values excluding outliers are indicated by whiskers. The soil characterized by
329 the highest mean value of permeability is A1sup, the least pervious is C2 (Table 2, Figure 3a). The
330 saturated permeability of A1sup soil is on average one order of magnitude higher than that of A1 soil,
331 although they have the same grain size distribution. In addition, A1sup layer presents both higher dry
332 root biomass and higher porosity than A1 (Figure 3b). A2 layer is more permeable on average than A1,
333 it contains a larger quantity of pumices (Figures 1f-g) but contains less dry biomass than soil A1
334 (Figure 3b). Therefore, the differences in terms of saturated hydraulic conductivity could be due to a
335 combination of particle size distribution and root biomass effects. C2 layer is the least permeable on
336 average among all the tested soil layers because of a high silt fraction and low porosity (Figures 3a-d).

337

338 4.2 Water retention curve and hydraulic conductivity function

339 Data collected during a test in the ku-pf apparatus on A2 soil (sample 1.4.1) are shown in Figure 4a as
340 an example of laboratory results. In this test the soil sample was subjected to an evaporation process
341 followed by two wetting-drying cycles. Matric suction increased during the drying phases as the water
342 content decreased. The wetting phases consisted of a sequence of steps initiated by an abrupt increase
343 in water content, inducing a sudden drop in matric suction measured by the top tensiometer. The
344 pressure distribution within the soil then tended to hydrostatic condition (Figure 4b), in which the
345 matric suction value measured by the top tensiometer (s top) was approximately 0.3 kPa higher than
346 that measured by the bottom tensiometer (s bot). However, the volumetric water content of the sample
347 during each wetting step remained constant but the water content distribution was not uniform within
348 the sample. A first estimate of the WRC curve preliminarily obtained by coupling the arithmetic mean
349 of the two measurements of matric suction to the average water content of the whole soil sample is
350 reported in Figures 5a,c. This representation of the experimental data is based on a rather crude
351 interpretation of data in which the laboratory specimen is assimilated to a *macroscopic volume element*
352 and spatial variations in water content and matric suction inside it are not taken into account. However,
353 experimental data represented in this way can be used to verify the accuracy of the inversion process.
354 Therefore, retention curves obtained by the numerical model associating the average value of the
355 matric suction to the average water content of the whole sample (by integrating on its whole volume
356 water contents simulated by the model itself) are reported in Figure 5. The drying-wetting cycles
357 measured are compared to the back-analyzed main drying and wetting branches of the WRC (Figure
358 5a); clearly the main loop envelops the experimental measurements. The main drying curve predicted
359 by the model also intercepts the AEV and the data points obtained from the pressure plate (PP)
360 (triangle and circle symbols in Figure 5a). Fitted main drying and main wetting of HCFs are reported in
361 Figure 5b with the value of saturated hydraulic conductivity measured in the laboratory. The model
362 satisfactorily reproduced the cycles determined experimentally: the scanning curves of the model were
363 in good agreement with the experimental data, this also emerges from the comparison between the
364 matric suction measurements and the values predicted over time (Figure 5c, d).

365 The Mualem–van Genuchten model parameters, as derived from the results of the optimization process
366 of the first evaporation phase, are reported in Table 2. The coefficient of determination (R^2) ranges
367 between 0.98 and 1.00. All the investigated soils behave like coarse-grained materials apart from C2

368 soil, AEV ranges from 2 kPa to 8 kPa (α^d varies between 0.075 and 0.17 kPa⁻¹ except for soil C2;
 369 Figure 6c)⁵⁰. The AEV is higher than 20 kPa only for C2 layer due to its fine texture (α^d varies
 370 between 0.01 and 0.04 kPa⁻¹; Figure 6c). The residual volumetric water content (θ_r) ranges
 371 approximately between 0.07 and 0.16 in soil A and between 0.10 and 0.27 in C (Figure 6a). The
 372 volumetric water content at saturation (θ_s^d) is lower in soil A than in soil C (Figure 6b) mainly due to
 373 the higher porosity. The value of parameter n_v , which affects the slope of the WRC, varies from 1.45
 374 to 1.75 for all the soils except for C1, for which it is larger (Figure 6d). Parameter l ranges from 0.20
 375 up to 3.00 in soils A and C1, while ranging from -1.5 to 7.00 in C2, presenting very high variability
 376 (Figure 6e).

377 The Mualem–van Genuchten model parameters of the MWC, as derived from the results of the
 378 optimization process, are reported in Table 3. The value of the coefficient of determination ranges from
 379 0.85 to 0.99. Parameter θ_s^w is lower on average in soil A than in soil C (Figure 6f). The θ_s^w/θ_s^d ratio,
 380 which is an indicator of the fraction of entrapped air in the subsoil, varied from 0.84 to 1.00. The range
 381 of this ratio agrees with those reported in the literature for pyroclastic layers in other geological
 382 contexts in Campania^{51,52}: 0.78-0.95. However, the air volume that remains entrapped in the voids
 383 during the wetting process depends on a multiplicity of factors such as pore-size distribution, history of
 384 drying and wetting cycles, and water supply rate⁵². In addition, it is worth pointing out that although
 385 the wetting processes in the laboratory and in situ are both directed downwards, a higher fraction of air
 386 could remain entrapped in the voids in situ, not being able to escape through the soil surface due to the
 387 higher velocity of the water infiltrating from the ground surface⁵³. Among all the layers, soil A presents
 388 a higher mean value of α^w with respect to soil C (Figure 6g). The α^w/α^d ratio varied from 1.01 to
 389 3.97 (Table 3), which is a wider range than that reported by Kool and Parker⁴⁷, which is 2.08±0.46 on
 390 average, 1.88±0.40 for undisturbed soil and 2.29±0.47 for compacted samples.

391

392 **Table 3. Values of Mualem–van Genuchten model parameters of the main wetting curve derived via inverse**
 393 **analysis.**

soil	sample	z (m)	θ_s^w	θ_s^w/θ_s^d	α^w (kPa ⁻¹)	α^w/α^d	R^2	K_{sat}^w (m s ⁻¹)
A1 sup	R1	0.05	0.565	0.84	0.1700	1.01	0.953	2.85E-07
	R2	0.05	0.598	0.94	0.2956	2.11	0.987	5.28E-07
	R3	0.05	0.607	0.97	0.2822	1.71	0.994	1.79E-06
	N1	0.05	0.610	1.00	0.2218	2.96	0.991	4.35E-07
	N2	0.20	0.587	1.00	0.2587	2.48	0.990	3.24E-07
	mean	0.00	0.593	0.95	0.2456	2.05		5.20E-07

	std dev	0.00	0.018	0.07	0.0507	0.74		
A1	1.6.2	0.06						
	1.7.2	0.07	0.569	1.00	0.2114	3.97	0.988	2.93E-07
	1.9.1	0.50	0.619	0.96	0.2926	2.64	0.996	3.37E-07
	1.9.2	0.50	0.520	0.86	0.2011	2.30	0.851	2.02E-08
	1.11.2	0.80						
	mean	0.80	0.569	0.94	0.2350	2.97		2.17E-07
	std dev	0.50	0.049	0.07	0.0501	0.88		
A2	1.1.1	0.50						
	1.2.1	0.60	0.580	1.00	0.2706	2.27	0.986	1.43E-06
	1.4.1	0.15	0.440	0.97	0.1443	2.39	0.986	5.84E-07
	1.5.1	1.65	0.549	1.00	0.2195	2.34	0.964	5.94E-06
	1.6.1	1.65						
	1.7.1	1.65	0.548	0.92	0.2146	1.73	0.991	7.10E-07
	mean	0.95	0.529	0.97	0.2122	2.18		2.17E-06
	std dev	0.95	0.061	0.04	0.0519	0.31		
C1	2.12.2	0.80	0.620	0.94	0.1500	1.69	0.991	4.56E-07
	2.13.1	0.80	0.675	0.98	0.2000	1.75	0.982	2.21E-06
	2.15.1	1.21						
	mean	0.42	0.647	0.96	0.1750	1.72		1.33E-06
	std dev	1.45	0.039	0.03	0.0354	0.05		
C2	1.1	1.45	0.618	0.96	0.0800	1.80	0.985	1.28E-07
	1.2	1.30						
	1.3	1.30						
	mean	1.30	0.618	0.96	0.0800	1.80		1.28E-07
	std dev	1.10						

394

395 The main loops (MDC and MWC) of each specimen, derived from the results of inverse analyses, are
396 represented in Figures 7a-j. These detect the size of the hysteretic domain, where the paths of matric
397 suction and water content measured in situ are usually observed¹⁰. Some variability is also observed
398 among samples of the same soil.

399 However, during the first evaporation phase after the permeability test the state of the soil does not
400 always follow the primary drying retention curve (corresponding to a drying process starting from
401 perfectly saturated conditions). Hence the obtained hydraulic parameters could refer to a secondary or
402 intermediate drying curve. In fact, fully saturation of soil specimens in the permeameter was very
403 difficult; even after several flushing cycles, isolated air bubbles could be entrapped in the soil sample
404 before the evaporation starts in the ku-pf apparatus. Therefore, the value of θ_s^d of the main drying
405 curve (starting point) often was lower than the soil porosity determined on the same soil specimen,
406 thus, the first drying did not correspond to the main drying curve. This observation is in agreement

407 with findings of Nicotera et al.³⁰ that tested the pyroclastic soils sampled from a test site in Campania
408 Region with similar geological and geotechnical features to the test site studied here. The air
409 entrapment preventing the fully saturation of the soil samples was observed also by Hillel⁵¹, Lu et al.⁵⁴
410 and Jotisankasa and Sirirattanachat²⁹.

411

412 **4.2.1 Discussion of the experimental results**

413 The experimentation carried out was much more demanding than usual: the testing time required to
414 obtain a scanning wetting curve was four times longer than the time necessary for the main drying
415 curve.

416 The soil tested presented marked hydraulic hysteresis. The main wetting curve modelled by the van
417 Genuchten model can be derived from the main drying curve by modifying only two parameters: α^w
418 and θ_s^w . In particular, the value of α^w ranges between 1.01 and 3.97 α^d (see Kool and Parker⁴⁷), while
419 the value of θ_s^w ranges between 0.84 and 1.00 θ_s^d in accordance with those found elsewhere for such
420 soils (Figure 6). Each parameter values are plotted as function of each other in the diagrams of Figure 8
421 in order to identify possible interplay between them. Figures 8p, r, l seem to indicate that a correlation
422 exists between θ_r , θ_s^d and n_v in agreement with Nicotera et al.³⁰; Figures 8n, j confirm the existence of
423 a correlation between θ_s^d and θ_s^w and between α^d and α^w . Similarly, some insight of the interplay
424 between roots amount and physical and hydraulic soil properties can be inferred from Figure 9, where
425 n , K_{sat}^d , M_{root} , θ_s^d , and AEV are plotted each against each other. The clear dependence of the saturated
426 hydraulic conductivity on soil porosity, as expected, emerges in Figure 9g. Indeed, θ_s^d trivially
427 increases with soil porosity but it almost always results lower due to air entrapment (Figure 9i); the
428 AEV increases with decreases of porosity (Figure 9j) in agreement with the results reported in
429 literature^{55,56}.

430 In Fig. 9h porosity seems substantially independent of the M_{root} value, however the experimental data
431 seem to be insufficiently evenly distributed along the M_{root} axis in order to reach a definitive
432 conclusion. It is interesting to note the increase of saturated conductivity in top layer (A1 sup and A1)
433 with dry biomass, M_{root} . This could be due to preferential flow induced by drying and wetting cycles as
434 experienced during plant growth^{29,57,58}.

435 Again, M_{roots} is correlated to θ_s^d , at least in the top layers (Figure 9b); θ_s^d tends to increase with the
436 amount of dry biomass, this result is in agreement with previous findings^{29,59}. The θ_s^d increase with

437 root biomass may be attributed to the root exudation: the compound exuded around the roots tends to
438 increase the volumetric water content near saturation. Lastly, the M_{roots} affects the AEV: in top layer,
439 the AEV decreases (from 8 kPa to 2 kPa) with the root biomass increase (from 0.056 g up to 4.630 g).
440 The AEV decrease in rooted soil can be a consequence of some changes in soil structure caused by
441 roots and microbial activity in the rhizosphere because these are responsible for the formation of soil
442 lumps (commonly referred as aggregates in ecology studies) and preferential flow channels (continuous
443 macro-pores), so the coarse characteristics of the soil results to be amplified. An opposite trend appears
444 for soil layer C2 but this difference is a consequence of the fact that C2 is a silty sand with a clayey
445 fraction (more fine particles than the other soils), in addition C2 results to be the only layer for which
446 soil porosity shows a decrease with M_{root} . Therefore, AEV decreases with root biomass because more
447 pores are occupied by roots. Nevertheless, only three data points are available in layer C2 and hence
448 conclusions cannot be drawn in this case.

449 These features highlight that the plants change the soil hydraulic properties of the soil for their benefit.
450 The water storage capacity varies with matric suction, defining a curve decreasing towards the lower
451 matric suctions, whose maximum occurs at a matric suction between 1 kPa and 15 kPa. For values
452 estimated from the main drying branch, soils with lower AEV present higher water storage capacities
453 (Figure 10a). Along the main wetting branch, the water storage capacity curves present a higher
454 maximum (Figure 10b) with respect to the drying curves (Figure 10a). This is a consequence of the
455 decrease in AEV from main drying to main wetting curves, while the value of parameter n_v remains
456 constant⁶⁰.

457 The maximum values of water capacity estimated along both main drying and wetting branches for
458 A1sup and A1 soils are very similar. Therefore, the rate of wetting front movement is mainly
459 controlled by the saturated hydraulic conductivity, which is significantly different between these soils.
460 The wetting front is expected to move faster in soil A1sup because this presents a saturated hydraulic
461 conductivity one order of magnitude higher than A1.

462

463 **5 Potential effects of hydraulic soil behaviour on soil response to rainfall**

464 **5.1 Conditions of analysis**

465 A soil column with the hydraulic properties of the pyroclastic soil tested in this paper was modelled by
466 using the finite element code HYDRUS-1D⁴³. A series of simulations were performed to: (i) analyse

467 the effects of the presence of root-permeated soil on the propagation of the wetting front; and (ii)
 468 investigate the effects of hydraulic hysteresis considering scanning paths on the response of the soil
 469 column to heavy rainfall. The total length of the soil column was 0.90 m and the stratigraphy consisted
 470 of A1sup layer (0.10 m thick), A1 layer (0.20 m thick) and A2 layer (0.60 m thick) (Figure 11a).
 471 Four analyses, namely X1, X2, X3, and X4, were carried out by changing the hydraulic model
 472 (hysteretic and non-hysteretic) and the hydraulic properties (i.e. corresponding to rooted and non-
 473 rooted soil) of the most superficial layer of the soil column for a thickness of 0.10 m (Table 4). In the
 474 X1 analysis, the main drying curve (MDC) was considered operative for each layer and the hydraulic
 475 properties determined for A1 soil were also attributed to the upper 0.10 m of the soil column. In X2,
 476 MDC determined for the A1sup layer was assigned to the first 0.10 m to take into account the root
 477 presence. Hydraulic hysteresis was neglected in both analyses X1 and X2. In X3, the hydraulic
 478 hysteretic model (HHM) was adopted for all the layers, enclosing the upper 0.10 m of the soil column.
 479 Lastly, the combined effects due to the modelling of hydraulic hysteresis and the presence of the root-
 480 permeated soil (A1sup) were considered in analysis X4. The soil hydraulic parameters adopted to fit
 481 the MDC and the MWC were the mean values determined for each lithotype (Tables 2 and 3); the
 482 curves used are shown in Figures 11b-e.

483

484 **Table 4. Summary of the numerical simulations: soil profile, hydraulic model, initial conditions and**
 485 **simulation phases.**

Soil profile	Hydraulic model	Analysis	Initial conditions	Simulation phases
A1 (0.30 m) A2 (0.60 m)	MDC	X1	Hydrostatic pore water pressure distribution (s = 10 kPa at soil surface)	1) Preliminary transient simulation (1 January 2017 – 31 March 2017)
	HHM	X3		↓
	MDC	X2		2) Simulation of hydrological year (1 April 2017-1 April 2018)
A1sup (0.10 m) A1 (0.20 m) A2(0.60 m)	HHM	X4		↓ 3) 48h of intense rainfall starting on 4 th April 2018 and 21 st March 2018

486

487 Identical boundary conditions were applied in all the analyses. Rainfall and evapotranspiration flux
 488 measured at the test site for one year (1st April 2017 – 1st April 2018) were applied at the ground
 489 surface (Figure 9f) in order to investigate the soil response to seasonal meteorological cycles. Daily
 490 evaporation was calculated as the potential evapotranspiration (ET_0) given by Equation 7, where T_{max}

491 and T_{min} are the maximum and minimum daily temperatures, respectively, and R_a is the extra-
492 terrestrial radiation, whose variation during the year depends on the latitude of the study site⁶⁰:

$$493 \quad ET_0 = 0.0023(T_{max} + 17.8)(T_{max} - T_{min})^{0.5}R_a \quad (7)$$

494 The use of potential evapotranspiration over the dry period (June-October) leads to an overestimation
495 of water outflow from the ground surface. However, no data were available to determine the actual
496 value of evapotranspiration. The temperature measurements and variations of extra-terrestrial radiation
497 are reported in Dias³⁵.

498 In the analyses, evapotranspiration was stopped after one year: after this phase intense rainfall, whose
499 net intensity was equal to the saturated hydraulic conductivity of A1sup soil (the soil with the highest
500 saturated hydraulic conductivity: $3 \times 10^{-6} m s^{-1}$), was imposed at the top boundary of the soil column
501 for 48 hours. Note that, according to experience, continuous rainfall of $3 \times 10^{-6} m s^{-1}$ ($=13 mm h^{-1}$)
502 represents an intensity sufficient to trigger flowslides in the area close to the test site. Therefore, it was
503 used here to investigate the worst-case scenario in all carried out analyses^{14,16,53,62,63}. Occurrence of
504 water ponding was excluded, assuming that non-infiltrated water would move away as run-off. This
505 way, the boundary condition at the ground surface consisted of a film of water (a null pore water
506 pressure) applied during the whole duration of the heavy rainfall event.

507 According to Pirone et al¹⁰, the pumice soil layer generally lying at the bottom of the modelled
508 pyroclastic cover allows free drainage especially during the wet season (from November to May).
509 Therefore, a free drainage condition was imposed at the bottom of the soil column.

510 Hydrostatic pore water pressure distribution with a maximum value of matric suction at the ground
511 surface equal to 10 kPa was assumed as initial condition. This assumption was arbitrary; however, it
512 was observed that a three-month simulation period is long enough to sweep out the influence of initial
513 condition. Simplifying, meteorological conditions monitored at the test site from 1st January 2017 to 1st
514 April 2018 were simulated in order to detect the hydrological soil response. Then, 48 hours of virtual
515 intense rainfall were applied starting from two different profile of matric suction calculated on 4th April
516 2018 and on 21st March 2018. This was devoted to investigate the effect of initial matric suction on soil
517 response to intense rainfall event (Figure 11f). A summary of the carried out numerical analyses is
518 reported in Table 4.

519

520 **5.2 Results of numerical parametric analyses**

521 The vertical profiles of matric suction calculated by applying two days of intense rainfall starting from
522 4th April 2018 are reported in Figures 12a-d. The roots effect can be clearly identified by comparing
523 Figure 12a (analysis X1) to Figure 12b (analysis X2); the wetting front moved faster when the
524 properties of A1sup soil were assigned to the 0.10 m thick shallower layer of the soil column, taking
525 into account the vegetation cover. Indeed, the saturated permeability of A1sup is one order of
526 magnitude higher than that of soil A1. Positive values of pore water pressure established in the first
527 0.20 m of the soil column (Figure 12b) due to the permeability contrast between soils A1sup and A1. A
528 steady state condition (no matric suction variation in time) was reached after 24 h of rainfall if soil
529 A1sup was considered in the model (X2) and after 36 h if the root presence was disregarded (X1). To
530 appreciate the effect of the hysteretic model (HHM), Figure 12a (X1) should be compared to Figure
531 12c (X3). The wetting front moved slower when the HHM was adopted even if the difference between
532 the two models is not too big. Indeed, the water storage capacity was higher along the MWC than those
533 determined along the MDC. While the presence of roots produced an increase in the hydraulic
534 conductivity of the more superficial soil layer, and therefore contributed to increase the wetting front
535 advancement rate, the higher values of the water storage capacity associated with the imbibition
536 processes along scanning paths gave rise to a slowdown compared to what was expected considering
537 the MDC. Lastly, the profiles obtained from the X2 analysis (Figure 12b) are very similar to those
538 derived from X4 (Figure 12d) where both the presence of A1sup soil and hydraulic hysteresis were
539 considered.

540 Matric suction, volumetric water content and hydraulic conductivity calculated during 48 h of intense
541 rainfall at a depth of 0.50 m are plotted as a function of elapsed time in Figures 13a-c. First, matric
542 suction predicted by analysis X1 (continuous grey line) is to be compared with X3 (dashed black line)
543 to assess the relevance of adopting the hysteretic hydraulic model (Figure 13a). The initial value of
544 matric suction was 1 kPa lower (15 kPa in X1, 14 kPa in X3) when the HHM is adopted. However, the
545 model does not seem to play a major role in soil response during intense rainfall as the effects of HHM
546 on initial conditions were cancelled during the critical event. Indeed, after 12 h, when the effects of
547 rainfall reached the depth of 0.50 m, lower values of matric suction were predicted if water retention
548 was modelled by the MDC (analysis X1) than if HHM was considered (X3), but after 24 h this
549 relationship was reversed. This occurred because the steady state condition was reached later and at

550 lower values of matric suction when HHM was adopted. To address this issue, the paths detected at the
551 depth of 0.50 m in the X1 and X3 analyses are shown in Figures 14a and b. The continuous grey and
552 black lines (X3 and X1, respectively) represent paths experienced by the soil over one hydrological
553 year (1st April 2017 to 1st April 2018), whilst the triangle and square symbols (X3 and X1, respectively)
554 describe paths produced by the intense 48 h of rainfall. If the imbibition curve (analysis X3) was
555 followed instead of the MDC (X1), the soil was less permeable and the steady state conditions were
556 reached at lower values of matric suction. This presents implications on the minimal duration of
557 rainfall that may lead to failure of an infinite slope constituted by the same stratigraphy of the soil
558 column investigated here for which the rainwater infiltration is the main cause of instability. In fact, as
559 it was proved by processing the field data collected at some test sites assimilable to infinite slope in
560 Campania Region^{9,49}, the groundwater flow is predominantly vertical in the wet period, from
561 November to May. Therefore, HHM is able to predict a time to failure longer or shorter than the MDC
562 according to the duration of rainfall required to establish the critical matric suction value (i.e. the
563 matric suction value corresponding to the safety factor of 1). If matric suction values as low as 2 kPa to
564 3 kPa are required to maintain slope stability, HHM would predict that the rainfall event should last at
565 least two days to trigger a landslide. By contrast, the MDC model would never predict a failure because
566 the steady state condition corresponds to higher matric suction values. Then, the values of matric
567 suction calculated in X2 (dashed grey line) and X4 (continuous black line) (Figures 13a and d) are very
568 close to one another. This highlights the important effect of the roots that partially offsets hysteresis. In
569 any case, matric suction values predicted by considering root presence are always lower than those
570 predicted by neglecting it, regardless of the hydraulic model adopted. Disregarding the root presence in
571 the soil profile means overestimating matric suction values at each instant, hence overestimation of the
572 rainfall duration required to lead to slope failure.

573 Matric suction, volumetric water content and hydraulic conductivity calculated at a depth of 0.5 m
574 during a 48h rainfall event starting from 21st March 2018 are reported in Figures 13d-f. In this case, the
575 matric suction values ranged from 5.5 kPa to 7.5 kPa before the heavy rainfall event. Also, in this case
576 HHM (analyses X3 and X4 in Figure 13d) produced lower initial values of matric suction (the
577 difference was about 2-3 kPa), which in turn significantly affected soil response during the subsequent
578 intense rainfall. The matric suction predicted by HHM (X3 and X4) was always lower than those
579 calculated with the MDC (analyses X1 and X2), regardless of rainfall duration. However, the

580 volumetric water content varied slightly among all the analyses because the soil was close to saturation
581 (Figure 1-3e). Finally, time to failure during intense rainfall in winter (matric suction value is close to
582 AEV) is overestimated if the proper hydraulic properties for rooted soil and HHM are both overlooked.
583 In this case, accounting for hydraulic hysteresis plays a major role in suitable prediction of initial
584 distribution of matric suction and volumetric water content, because the soil keeps the memory of its
585 antecedent hydraulic history also during the critical rainfall event.
586 From field experience^{14,16,53,62}, the rainfall event able to trigger flowslides in the monitored area
587 amounts to a maximum of 200 mm day⁻¹. Therefore, rainfall intensity of 13 mm h⁻¹ (K_{sat} of the A1sup
588 layer) used in parametric analyses, with a duration lower than one day (18 h), represents a realistic
589 critical event. If 13 mm h⁻¹ for less than one day occurs in spring (when matric suctions in the subsoil
590 range between 10 and 20 kPa, see Figure 11a), the use of HHM predicts higher matric suction values
591 than those predicted by the MDC, and thus false alarms could be avoided. If the same rainfall event
592 occurs in winter for initial matric suction values lower than 10 kPa along the entire soil profile, the use
593 of HHM is always recommended because the matric suctions predicted are always much lower than
594 those predicted by adopting the MDC (Figure 10d). If the hydraulic soil model does not account for
595 hysteresis, it is always strongly recommended to adopt a curve that can represent the paths exhibited by
596 the soil in the field.

597

598 **6 Conclusions**

599 Soil hydraulic characterization greatly affects the results of physically based models used for predicting
600 flowslides. In this paper, an extensive hydraulic experimental investigation on pyroclastic soils of the
601 test site on Mt. Faito in Campania (Southern Italy) was presented. In this regard, the role of the root-
602 permeated soil and hydraulic hysteresis were analysed. The presence of roots was taken into account by
603 testing specimens collected from the upper 0.10 m of the soil profile, where the amount of biomass is
604 three times higher than that observed at greater depths. Hydraulic hysteresis was investigated by testing
605 cycles of imbibition and evaporation in a ku-pf apparatus. The hydraulic hysteretic model of Parker and
606 Lenhard³¹ was adopted to fit the experimental data via inverse analysis. The parameters of the van
607 Genuchten equation for main drying and main wetting curve were then obtained. Our main findings are
608 summarized below:

- 609 • the procedure proposed by Nicotera et al³⁰ was extended and modified. In particular, the
610 procedure to perform cycles of evaporation and imbibition in the ku-pf apparatus was
611 presented in order to allow successful calibration of the Parker & Lenhard³¹ hysteretic
612 hydraulic model through inverse analysis using the software HYDRUS-1D;
- 613 • the mean values of the main drying parameters of the Mualem-van Genuchten model were in
614 good agreement with those found for pyroclastic soils sampled in test sites in the same
615 regional context. All the investigated soils behaved like coarse-grained materials as the AEV
616 ranged from 2 kPa to 8 kPa, apart from soil layer C2. The measurements of saturated
617 permeability varied two orders of magnitude along the vertical profile ranging from $1 \times$
618 $10^{-7} m s^{-1}$ to $1 \times 10^{-5} m s^{-1}$. In particular, the saturated permeability determined on the
619 specimens collected in the top 0.10 m (soil A1sup) was one order of magnitude higher than
620 that estimated on specimens collected at 0.60 m of depth (soil A1).
- 621 • the hysteretic model only required two additional parameters (α^w and θ_s^w) in comparison to a
622 single curve model. The values of both parameters could be expressed in relation to those
623 determined along the drying curve: θ_s^w varied between 0.84 and $1.00 \theta_s^d$, indicating the
624 fraction of entrapped air in the soil pores; α^w varied on average between 1.01 and 3.97 (on
625 average 1.72 and 2.97) α^d . Therefore, in the absence of experimental data providing the
626 hysteretic loops, assigning α^w equal to $2\alpha^d$ and θ_s^w equal to $0.90 \theta_s^d$ were reasonable
627 assumptions.
- 628 • the dry root biomass, M_{root} , is correlated to hydraulic saturated conductivity: the soil specimen
629 with more roots show a higher hydraulic saturated conductivity. This behaviour has been
630 associated to preferential flow induced by drying and wetting cycles experienced during plant
631 growth. In the top layer A, the M_{root} also affects the θ_s^d and the AEV of WRC. The θ_s^d
632 increases with the root biomass because of production of the root exudation. Lastly, the AEV
633 decreases with the increase of M_{root} , due to formation of soil lumps and micro-cracks would
634 desaturate at a lower matric suction than the soil sample without.

635 The effects of hydraulic properties of root-permeated soil and hysteretic hydraulic models on the
636 simulation of the soil response to intense rainfall events were investigated through parametric analyses.
637 Two soil columns differentiated by the presence of roots in the shallower 0.10 m of soil were
638 considered in the analyses. The importance of the hydraulic model was also investigated by comparing

639 results obtained by representing the WRC with the main drying curve or with a hysteretic model. The
640 main findings of the numerical investigation were:

- 641 • The use of the proper hydraulic characterization for the first centimetres of the soil column is
642 essential to simulate the presence of roots properly because this soil layer regulates rainwater
643 infiltration at the ground surface;
- 644 • The use of HHM affects: (i) estimation of the initial distribution of matric suction and
645 volumetric water content before the simulation of a critical rainfall event; and (ii) the soil
646 response to intense rainfall. The first effect prevails largely over the second during the wet
647 period (October to February) when initial matric suction is lower than 10 kPa.

648

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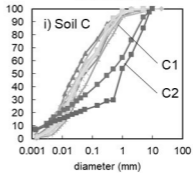
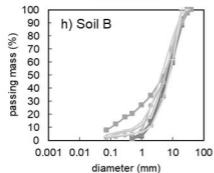
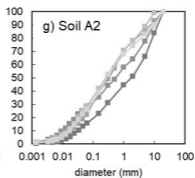
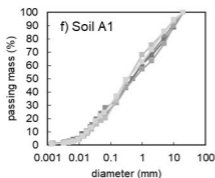
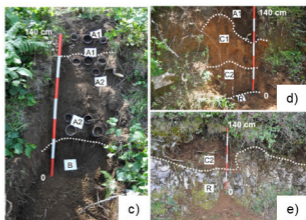
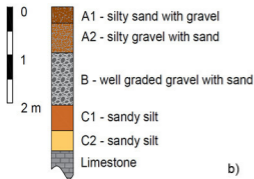
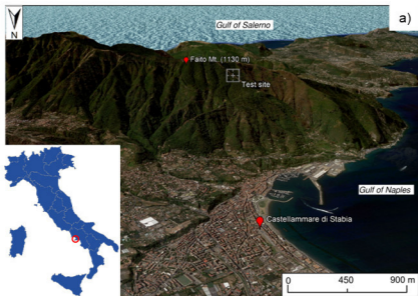
882 **List of symbols**

AEV	Air-entry value
C	Water storage capacity
ET ₀	Potential evapotranspiration
G _s	Soil specific gravity
HHM	Hydraulic hysteretic model
HCF	Hydraulic conductivity function
K	Soil hydraulic conductivity
K-P-S	Hydraulic conductivity – pore Pressure – Saturation
K _s	Actual saturated permeability
K _{sat}	Saturated hydraulic conductivity
K _{sat} ^d	Saturated hydraulic conductivity of the drying branch
K _{sat} ^w	Saturated hydraulic conductivity of the wetting branch
l	Fitting parameter of the HCF
m	Fitting parameter of the K-P-S model
MDC	Main drying curve
M _{roots}	Root dry biomass in each soil specimen
MWC	Main wetting curve
n _v	Fitting parameter of the van Genuchten equation
n ₀	Soil porosity ignoring the presence of roots
n	Root-permeated soil porosity
PP	Data point (θ,s) obtained from the measurements performed in the pressure plate
R _v	Root volume ratio
R _a	Extraterrestrial radiation
R ²	Coefficient of determination
S	Effective saturation
s	Matric suction
T _{max}	Maximum daily temperature
T _{min}	Minimum daily temperature

WRC	Water retention curve
z	Depth
α	Fitting parameter of the van Genuchten equation (in the main wetting or main drying)
α^d	Fitting parameter of the van Genuchten equation of the drying branch
α^w	Fitting parameter of the van Genuchten equation of the wetting branch
γ_d	Soil dry density
θ	Volumetric water content
θ_r	Residual volumetric water content
θ_s	Volumetric water content at saturation (in the main wetting or main drying)
θ_s^d	Volumetric water content at saturation of the drying branch
θ_s^w	Volumetric water content at saturation of the wetting branch

883

884



basket

rotating arms

monitoring

(a)



top tensiometer

bottom tensiometer

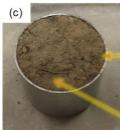
(b)



scale

cap and clinging film

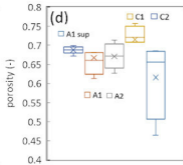
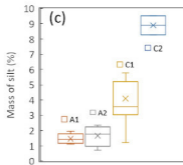
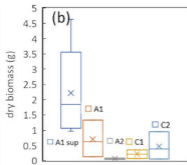
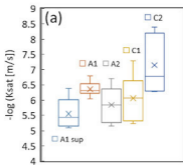
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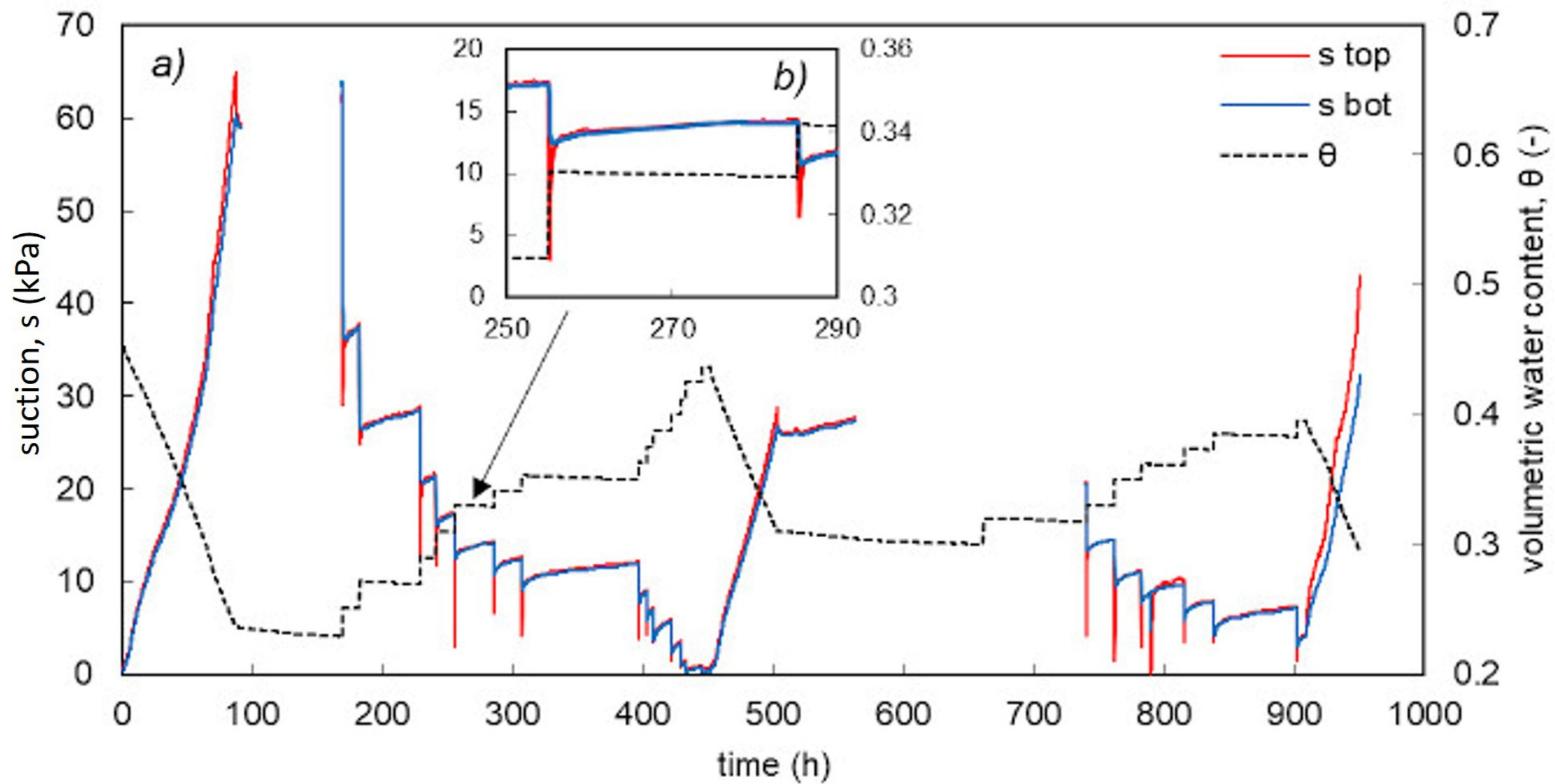


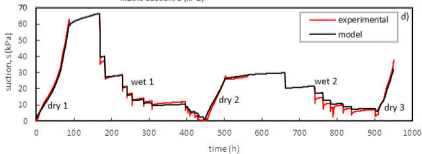
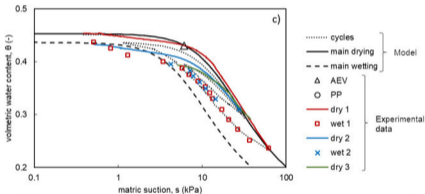
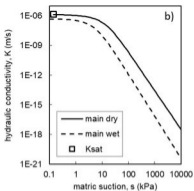
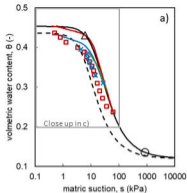
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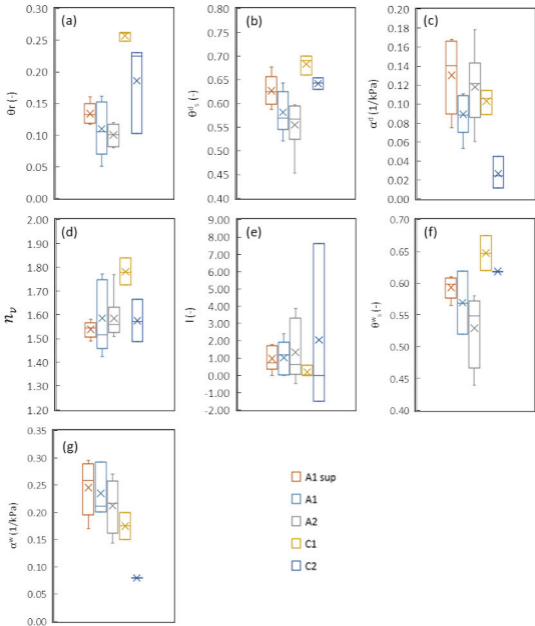
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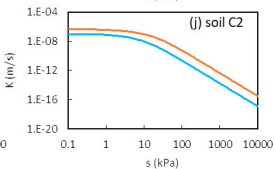
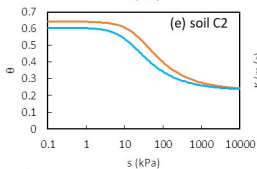
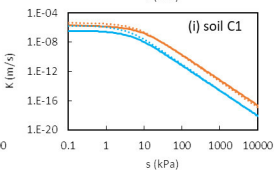
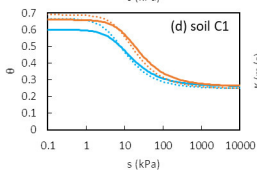
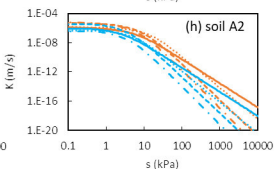
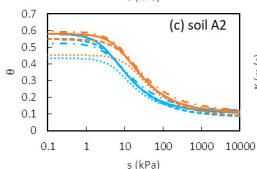
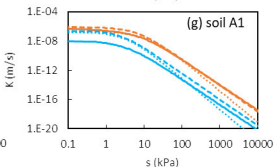
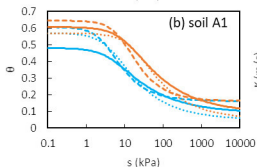
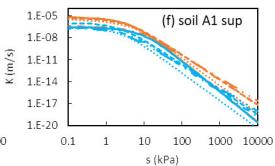
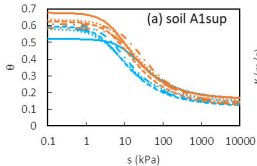
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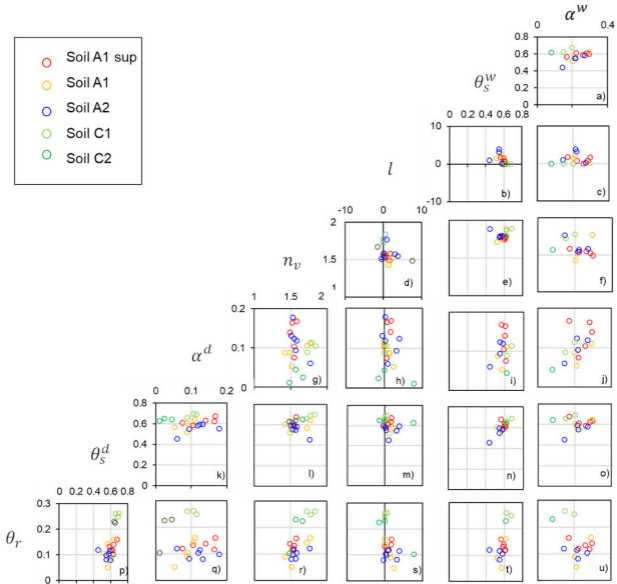
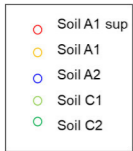


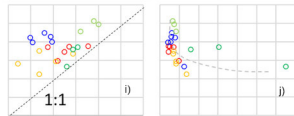
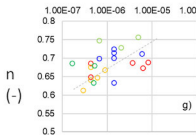
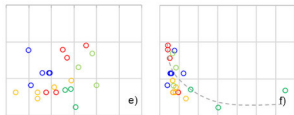
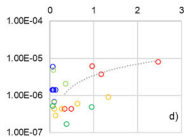
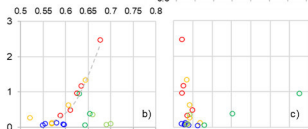
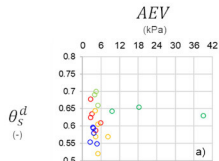
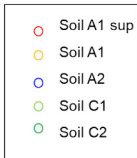


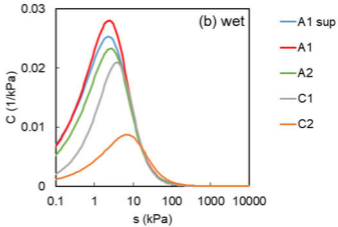
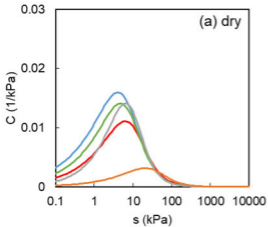




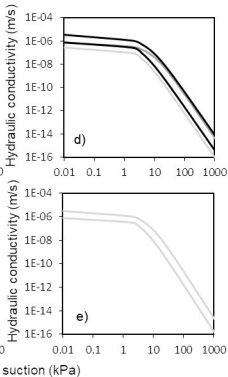
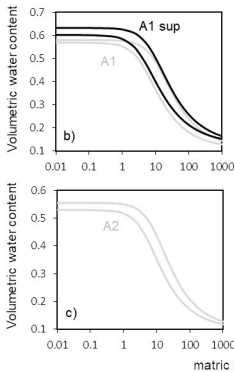
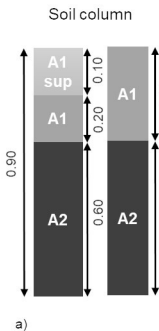




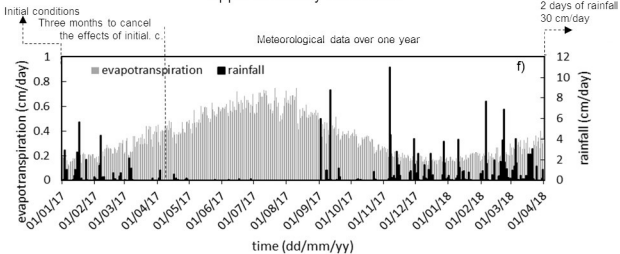


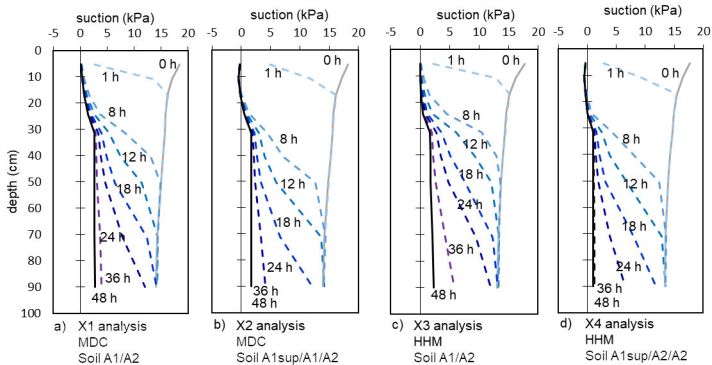


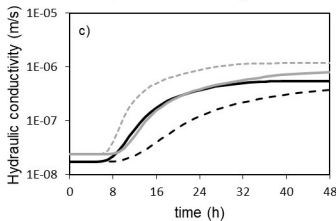
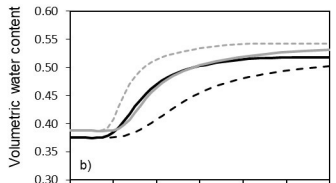
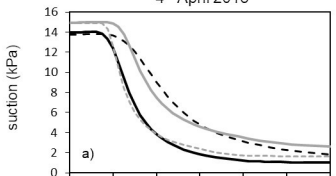
Hydraulic soil characterization



Upper boundary conditions





4th April 201821st March 2018