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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Effects of the vegetation on the hydrological behavior of a loose pyroclastic deposit

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Abstract

The effects of the vegetation cover are introduced into a simplified hydrological model of a slope covered with pyroclastic materials, located in Cervinara, in the Apennines of Campania (southern Italy). The vegetation consists of deciduous chestnut trees (*Castanea sativa*) with a dense seasonal understory, mainly constituted by ferns (*Pteridium aquilinum*) and other shrubs. The brushwood grows during late spring and summer, while it is nearly absent during the rest of the year. Approximately in the same period, from May to September, the chestnut trees have deep foliage, while in October the leaves dry and fall. Such seasonal vegetation cover affects rainfall infiltration, as indicated by soil water potential data collected by a hydrological monitoring station operating since 2010 at the slope. The effects of the vegetation are introduced in the hydrological model in two ways: interception of the precipitation, and a root water uptake model which distributes the total evapotranspiration flux over the root depth, according to the local value of soil water potential. The presented results show that the introduction of seasonally variable values of leaf area index and interception capacity ensures good performance of the hydrological model. The results also show that, through rainfall interception and root water uptake, the vegetation cover has positive effects on slope equilibrium, by keeping soil suction high enough to prevent the establishment of the conditions which lead to slope failure.

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Keywords: Leaf area index; interception capacity; hydrological modeling; rainfall-induced landslides

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1. Introduction

The slopes of large areas of Apennines of Campania (Southern Italy) are constituted by loose granular pyroclastic soils originated by a number of eruptions of the volcanic complexes of Somma-Vesuvius and Phlegrean Fields occurred during the last 50000 years. Such deposits usually form a shallow (few meters) unsaturated layer laying upon a fractured calcareous bedrock. Along steep slopes, with inclination comparable or larger than the internal friction angle of the pyroclastic soil (around 38°), the equilibrium of such layer is possible thanks to the contribution to the shear strength offered by soil suction in unsaturated conditions [1]. Therefore, rainfall infiltration processes, leading to the decrease of suction, are known to affect the equilibrium of such slopes: indeed, during the last decades, a number of shallow landslides have been triggered by heavy and long-lasting rainfall events. Many of such landslides caused catastrophic effects, because the sliding mass moves like a fluid, covering large distance at high velocity, in some cases hitting towns located near the foot of the mountains, where heavy damages and victims have been reported.

This kind of landslides, in the following indicated as flowslides, are sudden and not preceded by warning signs, such as small movements or formation of cracks. Thus, in most cases the prediction of landslide triggering is carried out by coupling an hydrological model with a slope equilibrium model allowing the safety factor to be evaluated [2, 3, 4, 5, 6].

As landslide triggering occurs when soil suction decreases, the water uptake by roots can play a positive role in preventing the establishment of the conditions for slope failure. Indeed, it is known by far that the presence of vegetation modifies the hydrological balance of a slope: root water uptake deeply affects water movement through the unsaturated zone of soil [7], and canopy is capable of intercepting a significant amount of precipitation [8]. In fact, in presence of seasonally variable vegetation, such as woods of deciduous trees, landslides usually occur when the trees are leafless and the understory is less dense. Nonetheless, still few are the examples of hydrological models used for landslide prediction accounting for the effects of vegetation [9, 10, 11].

In this paper, the results of field monitoring carried out at Cervinara, in the Apennines of Campania (southern Italy), are presented, indicating that the seasonally varying vegetation cover deeply affects rainfall infiltration. Based on the experimental data, a simple hydrological model is developed, in which the effects of vegetation are accounted for through seasonally variable interception capacity and root uptake. The obtained results show that the model well reproduces the suction of the upper soil layers, particularly during spring and summer, when the vegetation cover grows more.

2. Slope monitoring data

The experimental site is located along the slope of Cervinara, in the mountainous area 50km northwest of Naples, southern Italy. There, in the night between 15th and 16th December 1999, along the northeast slope of Mount Cornito, fairly regular with inclination around 40°, a flowslide was triggered after a rain event lasting more than 24 hours. Geological surveys have shown that the pyroclastic cover involved in the flowslide had a thickness of around 2.5m. It consisted of an alternation of loose volcanic ashes and pumices, with very high porosity, ranging between 0.65 and 0.75, laying upon a fractured limestone bedrock. As it is often found in the calcareous mountains of southern Apennines, an aquifer is found in the fractured rock, which supplies semi-perennial springs at the foot of the mountain. Fluctuations of the free surface of the aquifer affect the suction regime of the overlying soil cover.

Along the slope, the vegetation cover is constituted by deciduous chestnut woods (*Castanea sativa*). From May till the end of September a dense understory grows, mainly formed by ferns (*Pteridium aquilinum*) and other shrubs.

In August 2009 an automatic monitoring station at high temporal resolution has been installed. Since then, measurements of volumetric water content by Time Domain Reflectometry (TDR) and capillary tension by tensiometers are taken every two hours. In addition, a rain gauge for hourly automatic acquisition has been installed, with sensitivity to rainfall increments of 0.2mm. The monitoring station includes eight tensiometers and seven metallic probes for TDR measurements of soil water content.

The eight installed tensiometers are jet-fill type, equipped with a suction tension transducer with solid-state circuit, and are placed at various depths between 0.60 and 1.75m. The seven TDR probes, of various lengths between 10 and 40cm, are connected through coaxial cables and a multiplexer to a Campbell Scientific Inc. TDR-100 reflectometer. All the probes are buried vertically in the soil at different depths, to retrieve a continuous profile of moisture throughout the investigated soil depth. The probes are disposed in the immediate proximity of the ceramic tips of the tensiometers, so to allow coupling water content and capillary tension measured at the same depth. To ensure reliable soil water content estimates, a specific TDR calibration relationship, linking bulk dielectric permittivity and volumetric water content has been experimentally determined, for both pumices and ashes, over reconstituted samples taken at Cervinara, close to the monitoring station [12].

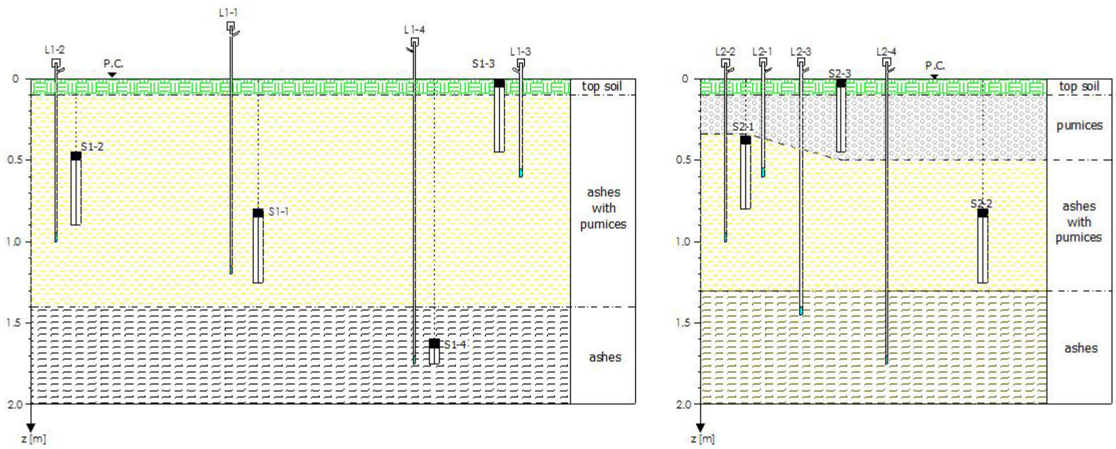

Fig. 1. Sketch of the instruments installed at the field monitoring station: L=tensiometers; S=TDR probes (the shown vertical section is orthogonal to the direction of slope maximum inclination).

For the automatic acquisition and storage of the monitoring data, all the transducers are connected to a Campbell Scientific Inc. CR-1000 Data Logger. All the installed equipments are powered by a 12V battery connected to a solar panel. A sketch of the entire monitoring station is given in Figure 1.

Figure 2 shows the soil suction and volumetric water content measured at four depths between 01.01.2011 and 30.07.2011, together with the corresponding daily hyetograph.

After more than two years of field monitoring, the following observations can be made:

- There is very little evidence of surface runoff.
- Volumetric water content rarely exceeded 0.40: i.e., the soil was always far from saturation.
- The vertical water potential gradient at all the investigated depths, which could be estimated by the differences between the suction measured at adjacent depths, was always downward directed, indicating that the water infiltrating in the soil cover was mainly drained towards the underlying aquifer.

- The constant increase of soil suction at all depths, observed every year from May on, can be interpreted as the consequence of the decrease of the water level in the aquifer, as it typically occurs in similar contexts [13, 14]; such interpretation is borne out by the readings of the two deepest tensiometers, where the suction increasing trend is steeper than above.
- In most cases, the precipitation events occurred after May hardly affect the suction measured at any depth; conversely, the soil suction was affected by events with similar rainfall height, reaching the soil with similar suction values, but occurring before May.

In particular, the seasonally variable response to precipitations seems clearly related to the seasonal variation of vegetation cover. Indeed, canopy interception capacity of precipitation is the sum of the contributions of tree foliage, understory and litter. In woods of deciduous trees, the first of the three contributions is obviously strongly related to the presence of leaves, with reported values of up to 5.0mm [15, 16]. Also the evapotranspiration is deeply affected by the development of vegetation, which sums its action to the seasonally variable climatic constraints.

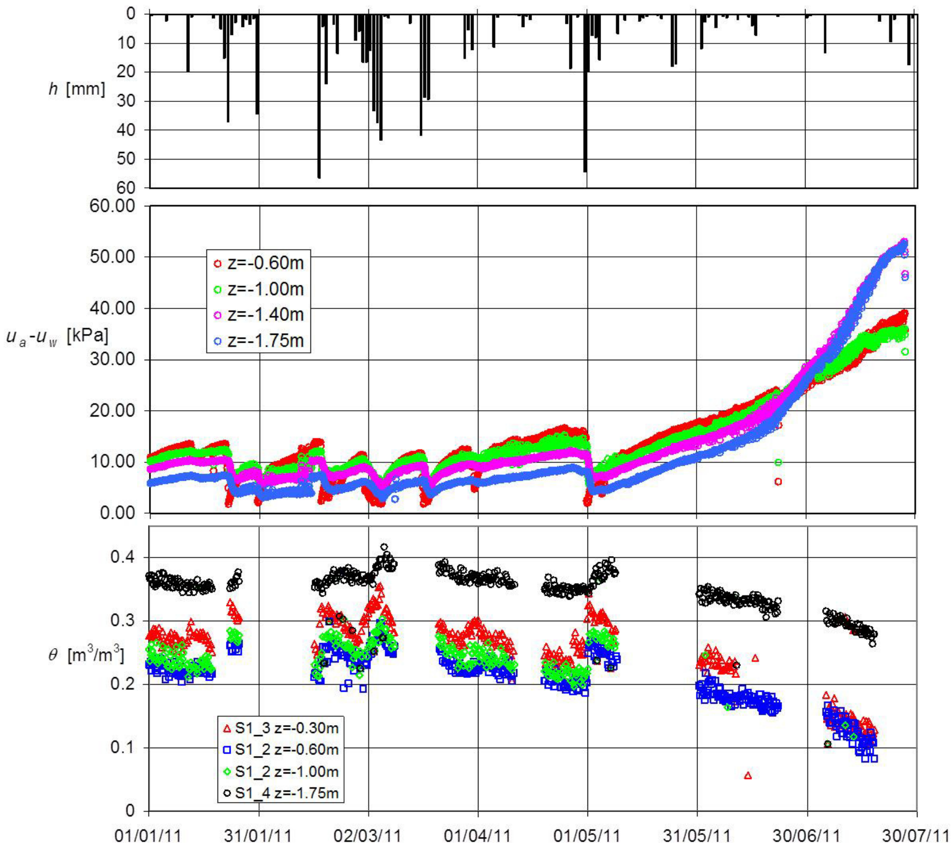

Fig. 2. Field monitoring data observed between 01.01.2011 and 30.07.2011. From top to bottom: daily rainfall height; soil suction; soil volumetric water content

Fig. 3 shows the scatter plot of soil water content and soil suction head measured at the same depths. The experimental points show that the alternation of ashy soil layers and soil layers rich of pumices causes different hydraulic behaviors, which can be fitted by different water retention curves.

3. The hydrological model

The proposed hydrological model aims at highlighting the role played by vegetation-related hydrological processes in the definition of the hydrologic balance of a slope. Thus, although layers with differences in textures and hydraulic behavior can be distinguished within the soil profile, the simplified assumption of a single homogeneous layer is made. Furthermore, since no significant difference in the response of tensiometers, as well as of TDR probes, buried at the same depth at different locations along the slope is observed, the 1D Richards equation along the vertical direction z (positive upward) is written to model soil water potential, h:

$$\frac{d\theta}{dh}\frac{\partial h}{\partial t} = \frac{dk}{dh}\frac{\partial h}{\partial z} + \frac{\partial}{\partial z}\left(k\frac{\partial h}{\partial z}\right) - S_r \tag{1}$$

In equation (1) θ represents soil volumetric water content; k is the hydraulic conductivity of the unsaturated soil; S_r is a sink term accounting for the uptake of water by roots. The hydraulic behavior of the soil is described by means of the water retention curve $\theta(h)$, for which the van Genuchten expression has been adopted [17], and of the hydraulic conductivity curve $k(h)$, which has been modeled with the Brooks and Corey expression [18].

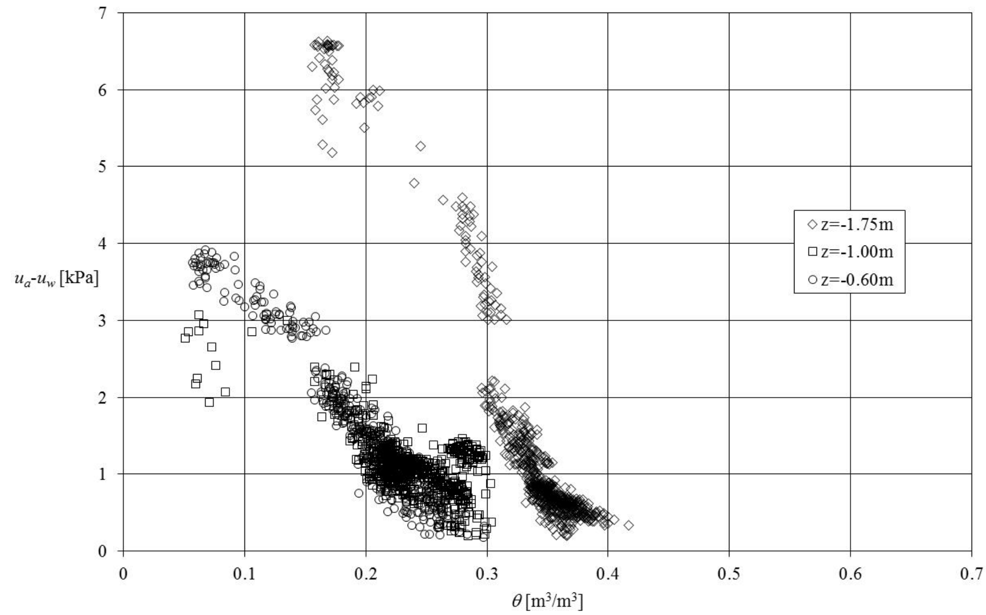

Fig. 3. Water retention data at various depths from field monitoring

The uptake of water by roots is assumed to be maximum at the soil surface and to linearly decrease with depth until the maximum root depth, d_r, where it becomes null. The total uptake of water along the entire root depth equals the actual evapotranspiration rate, *ET*, which is evaluated multiplying the maximum evapotranspiration, $ET_{\max}$ (calculated with the Penman-Monteith equation [19], in which monthly means of climatic variables have been introduced) by a reducing factor, λ, depending on the soil water potential [11]:

$$S_r = \frac{2\lambda ET_{\max}}{d_r}\left(1 + \frac{z}{d_r}\right) \tag{2}$$

The reducing factor assumes the following expression, in which is $h_1 > h_2 > h_3 > h_4$ [7]:

$$\begin{array}{ll} h > h_1 & \lambda = 0 \\ h_1 \geq h > h_2 & \lambda = \dfrac{h_1 - h}{h_1 - h_2} \\ h_2 \geq h > h_3 & \lambda = 1 \\ h_3 \geq h > h_4 & \lambda = \dfrac{h - h_4}{h_3 - h_4} \\ h_4 \geq h & \lambda = 0 \end{array} \tag{3}$$

Equation (1) must be completed with two boundary conditions, one written at the top soil surface, the other at the interface between soil cover and bedrock. The following top boundary condition is assumed:

$$i_0 = R - \frac{\mathrm{d}I}{\mathrm{d}t} \tag{4}$$

In equation (4), i_0 represents the infiltration rate per unit top soil surface; *R* is the rainfall intensity; *I* is the rainfall height intercepted by canopy per unit surface. The interception rate $\mathrm{d}I/\mathrm{d}t=R$ is assumed until the maximum interception capacity $I_{\max}$ is attained. Afterwards, $\mathrm{d}I/\mathrm{d}t$ is set to zero until rain stops.

At the bottom of the soil column, below the soil-bedrock interface, it is assumed hydrostatic pressure distribution down to the free surface of the underlying aquifer located in the fractured limestone, The latter is described by means of a linear reservoir model, so that the bottom boundary condition reads:

$$n_a \frac{dh_b}{dt} = i_b - q_s = i_b - \frac{h_b + Z_a}{K_a} \tag{5}$$

In equation (5), h_b is the water potential at the bottom of the soil column; i_b is the infiltration rate through the interface between soil and bedrock; n_a is the effective porosity of fractured limestone; q_s is the discharge supplied to the springs by a unit horizontal surface of the aquifer; Z_a is the aquifer bed depth; K_a is the time constant of the linear reservoir model of the aquifer.

4. Results and discussion

The model constituted by equations (1), (4) and (5) has been solved with an implicit finite differences scheme. The parameters of the model have been obtained by calibration against soil suction data at the depths of -0.60m, -1.00m, -1.40m, and -1.75m, measured between 01.01.2011 and 31.07.2011. The search of the parameters has been carried out by means of a genetic algorithm, allowing to constrain the variability of the unknown parameters to predefined intervals.

In particular, a saturated water content of 0.75 and a residual water content of 0.05 have been assumed (such values are derived from what measurements over undisturbed samples taken at the investigated slope); the other parameters of the van Genuchten water retention curve have been constrained so that the curve remained close to the field data plotted in fig. 3.

Table 1. Lower and upper constraints for the parameters during model calibration; best fit model parameters.

Model parameter	Lower limit	Upper limit	Best fit
Saturated water content θ_{sat}	-	-	0.75
Residual water content θ_{res}	-	-	0.05
van Genuchten parameter α (m^{-1})	12.0	17.0	13.7
van Genuchten parameter m	0.5	0.9	0.584
van Genuchten parameter n	0.7	1.1	0.895
Saturated hydraulic conductivity K_{sat} (ms^{-1})	5.0E-5	1.7E-4	9.55E-5
Brooks and Corey exponent δ	3.0	6.0	4.99
Maximum root depth d_r (m)	-	-	0.5
Summer leaf area index *LAI*	3.0	8.0	6.2
Summer maximum interception capacity I_{max} (mm)	7.0	20.0	18.8
Lower suction head for root water uptake h_1 (m)	0.0	0.2	-0.034
Lower suction head for maximum root water uptake h_2 (m)	1.0	2.0	-1.79
Upper suction head for maximum root water uptake h_3 (m)	2.0	5.0	-2.51
Upper suction head for root water uptake h_4 (m)	-	-	10.0
Aquifer bed depth Z_a (m)	8.0	11.0	10.1
Aquifer effective porosity n_a	0.02	0.1	0.01
Aquifer time constant K_a (days)	60	90	77.7

The constraints to the parameters describing the underlying aquifer located in the fractured limestone have been chosen in agreement with what could be found in the literature for similar contexts [13, 14].

About the parameters related to the vegetation cover, it has been assumed a maximum root depth of 0.5m [15]. The leaf area index, *LAI*, needed for the calculation of ET_{max}, has been assumed constant from the beginning of May till the end of September, while it has been considered negligible during the other months, when the trees are leafless and no understory is present. Similarly, it has been taken a maximum interception capacity I_{max}=0mm from the beginning of October till the end of April, while a constant value has been assumed during the rest of the year. The constraining intervals of *LAI* and I_{max} have been chosen according to the values found in the literature, while those of h_1, h_2, h_3 and h_4 of equation (3) have been chosen on the basis of what could be expected from the observed suction values.

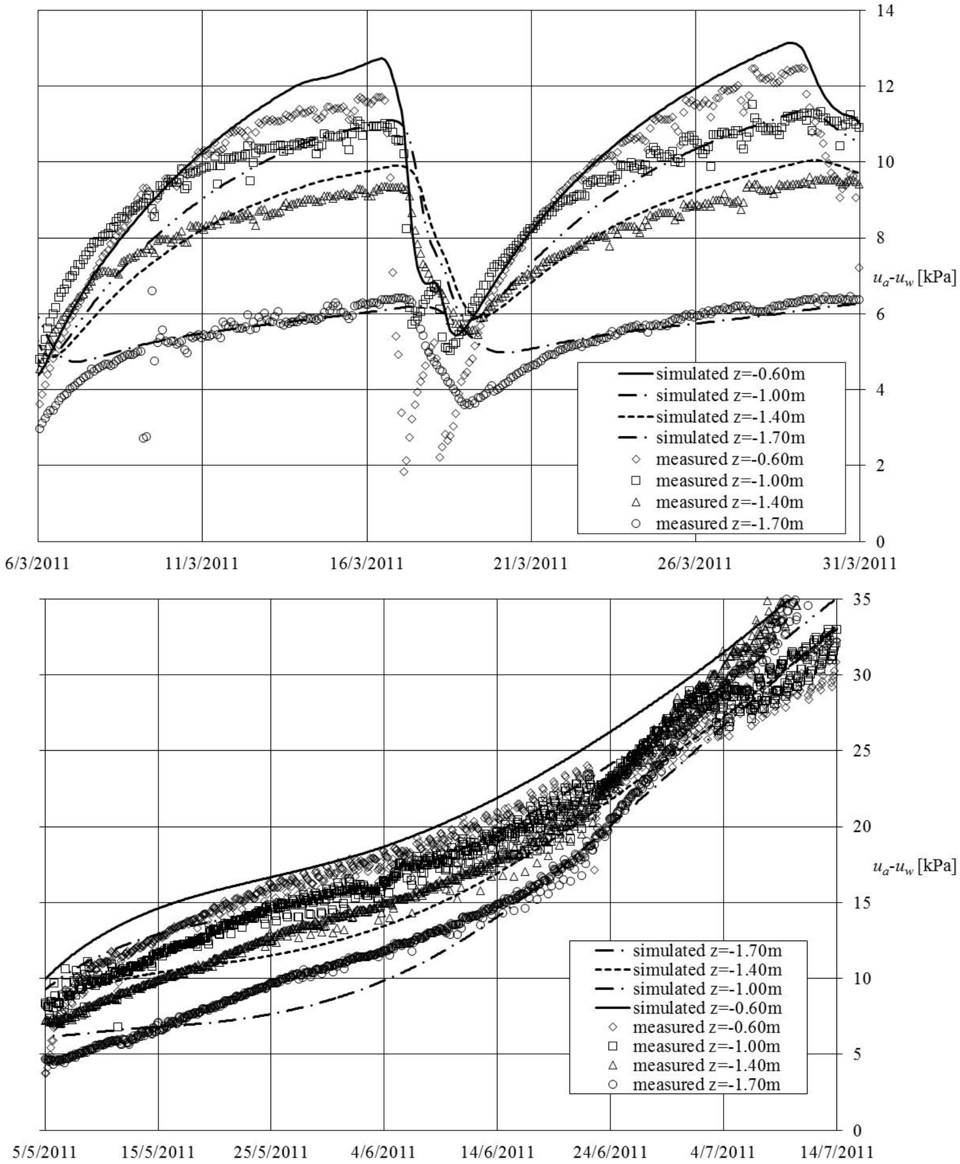

Fig. 4. Comparison between simulated and measured soil suction at various depths.

Table 1 gives the extremes of the intervals of variation of the parameters assumed during model calibration, together with the values providing to the best fit between model results and monitoring data.

Figure 4 shows the comparison between simulated and measured soil suction head during two periods of the year: from 06.03.2011 till 31.03.2011, when the vegetation-related model parameters were set equal to zero (fig. 4a); from 05.05.2011 to 14.07.2011, when they assumed the values *LAI*=6.2 and I_{max}=18.8mm, as resulted from model calibration (fig. 4b). During both the periods the model satisfactorily reproduces the observed soil suction trends.

The values of *LAI* and I_{max} obtained after model calibration are substantially in agreement with what indicated in the literature for deciduous forests with understory in temperate climate [15, 20].

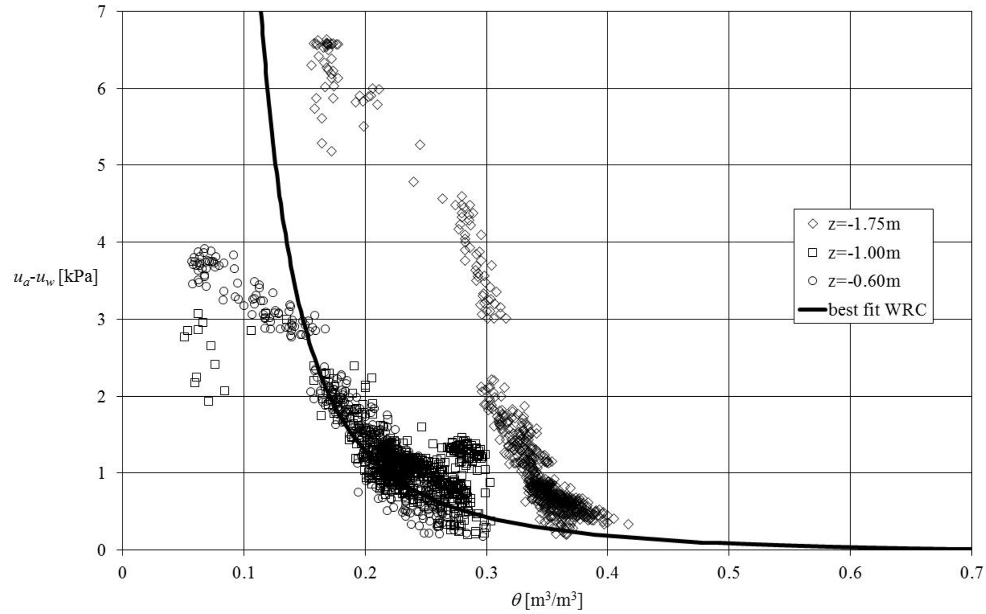

Fig. 5. Best fitting water retention curve compared with field monitoring data

Figure 5 gives the water retention curve obtained after model calibration. In the same graph the available experimental data are also plotted, showing good agreement with the obtained curve. The best fit saturated hydraulic conductivity results one order of magnitude larger than that measured in laboratory over undisturbed specimens. Such result was expected, since in the field the investigated soil has a well developed structure, that surely affects both the hydraulic characteristic curves close to saturation.

5. Conclusions

A simplified model of the hydrological behavior of a slope of pyroclastic granular soil laying upon a fractured limestone bedrock, covered with deciduous chestnut woods with a dense understory growing from May till September, has been developed on the basis of the data provided by a monitoring station operating at the slope during the last three years. The model adopts the 1D Richards equation along the vertical direction, and assumes the soil cover as being constituted by a single homogeneous layer. The bottom boundary condition accounts for the fluctuations of the free surface of an aquifer located in the fractured limestone, modeled as a linear reservoir. The top boundary condition accounts for the seasonal interception of precipitation by the chestnut woods canopy and by the understory. The evapotranspiration flux is introduced in the upper soil layer by means of a root water uptake model.

The model has been applied to the simulation of the soil suction at various depths along the slope of Cervinara, in the Apennines of Campania (southern Italy). The parameters of the model have been identified against the soil suction data measured at various depths during 2011. The model is capable of reliably reproducing the measured suctions with values of the parameters in agreement with literature indications, and confirms that during the periods when the vegetation cover grows (namely, late spring and summer), it exerts a positive effect upon slope equilibrium, by means of interception of precipitation and root water uptake, which keeps soil suction high enough to prevent the establishment of the conditions of slope failure even in presence of significant rainfall events.

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