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Conceptual hydrological modeling of the soil-bedrock interface at the bottom of the pyroclastic cover of Cervinara (Italy)

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Abstract

On the basis of the data collected by a monitoring station, a simplified mathematical model of the hydrological behavior of the layered pyroclastic cover of the slope of Cervinara (southern Apennines) has been developed. The model considers a single homogeneous soil layer, for which effective hydraulic characteristic curves have been defined. The top boundary condition accounts for the effects of evapotranspiration. The bottom boundary condition conceptually simulates, by means of a linear reservoir model, the hypothesized effects, on the soil water potential at the soil-bedrock interface, of the fluctuations of the water table of an ephemeral aquifer stored in the underlying fractured limestone. Despite its simplifying assumptions, the model satisfactorily reproduces the observed soil water potential at all the monitored depths. The obtained results indicate that even the highest rainfall intensity can pass through the highly conductive unsaturated soil cover, and leak through the fractured bedrock. Only when the water level in the underlying aquifer is high, as it happens after long lasting periods of rainfall, the establishment of the vertical water potential gradients, needed for the leakage of high infiltration peaks, leads to soil saturation at the bottom of the cover. Such a picture provides a possible interpretation of the triggering mechanism of the landside occurred in 1999 along the slope.

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Keywords: Volcanic ashes; hydrological modelling; unsaturated soil; ephemeral aquifer; fractured bedrock.

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1. Introduction

Large mountainous areas surrounding the city of Naples (southern Italy) are characterized by the presence of slopes covered with few meters of loose pyroclastic materials lying upon a fractured limestone bedrock. The covers are constituted by alternating layers of ashes (silty sands, with porosity between 0.7 and 0.75) and pumices (silty gravels), which in some cases have been subjected to weathering and/or erosion. At the soil-bedrock interface, sometimes a layer of weathered ashes is found, characterized by finer texture (in some cases clay content reaches 30% in weight) and a porosity around 0.6[1,2,3]. The equilibrium of the steepest slopes, with inclination angles larger than the friction angle of the ashy deposits (usually around 38°) is ensured, in unsaturated conditions, by the contribution to shear strength offered by soil suction. Wetting of the soil cover during rainfall infiltration may therefore cause the triggering of shallow landslides, sometimes developing in form of fast and destructive flows of mud and debris.

Since the deadly slides of Sarno (May 1998) and Cervinara (December 1999), the hydrologic and geotechnical behavior of the pyroclastic covers of Campania have been deeply studied, and various possible triggering mechanisms have been hypothesized.

Some authors suggested that unsaturated coarse-textured layers, often observed owing to the presence of layers of pumices within the pyroclastic cover profile, can act as a capillary barrier, delaying or even impeding the advancement of the infiltration front. Consequently, infiltrating water remains confined in the uppermost part of the soil cover, until the attainment of failure conditions. This triggering mechanism explains the cases in which the landslide involved only the shallowest part of the soil cover, with the failure surface located at the interface between ashes and pumices[4,5,6].

In many cases, however, the observed landslides involved the entire soil cover, leaving uncovered the soil-bedrock interface or the layer of altered ashes, when present. Some authors supposed that the attainment of triggering conditions at the bottom of the soil cover may be favored by the low hydraulic conductivity of the altered ashes, which impede the infiltration of water through the soil-bedrock interface[7]. Conversely, others suggested that soil wetting at the bottom of the cover may be caused by the formation of temporary springs at the soil-bedrock interface[8], due to the raising of the water level in ephemeral aquifers often observed in the fractured limestone[9].

Recognizing the actual triggering mechanism is indeed difficult, because also other factors concur to the establishment of local failure conditions, such as stratigraphical[10] or geometrical discontinuities, e.g. scarps and road cuts[11], as well as flow accumulation due to slope and bedrock morphology.

In this paper, the information, provided by the data collected by a monitoring station operating since 2009 at the slope of Cervinara, around 40km northeast of Naples (Italy), is exploited to formulate a simplified conceptual model of the hydraulic behaviour of the soil-bedrock interface. Such a model, which simulates the possible interaction between the unsaturated soil cover and an ephemeral aquifer stored in the fractured limestone bedrock, represents a possible compromise between approaches ascribing landslide triggering only to the hydraulic properties of the unsaturated layers, and those which mainly focus on the role played by processes occurring at the soil-bedrock interface.

Table 1. Main physical properties of the soils of the slope of Cervinara.

Soil material	d_{max} (mm)	γ_s (kNm^{-3})	γ (kNm^{-3})	porosity	cohesion (kPa)	friction angle (°)
Coarse pumices	20	23	13	0.50-0.55	0	45
Volcanic ashes	10	26	14	0.68-0.75	0	38
Pumices	20	26	14	0.50-0.70	0	40
Weathered ashes	10	26	16	0.60	2	38

2. Field monitoring at the slope of Cervinara

The experimental site is located along the northeast slope of Mount Cornito, near the town of Cervinara, about 50km northwest of Naples, southern Italy, just besides the location where, in the night between 15th and 16th December 1999, a flowslide was triggered after an intense rain event lasting more than 24 hours[1].

The monitored slope, at an elevation between 550m and 760m above the sea level, has an average inclination of 40°, locally reaching 50°. The pyroclastic cover has a thickness between 1.8 and 2.5m and consists of an alternation of loose volcanic ashes, with porosity ranging between 0.70 and 0.75, and pumices laying upon a fractured limestone bedrock. At the base of the soil cover, a layer of weathered ashes with lower saturated hydraulic conductivity is often found. An example of the layered soil cover typically observed along the slope is given in Figure 1.

Such layered profile is the result of the deposition of materials originated by several eruptions of the two main volcanic complexes of Campania (the Somma-Vesuvius and the Phlegrean Fields) occurred during the last 40000 years[12,13]. The main physical properties of the soils of the layered profile found at Cervinara are given in table 1.

The slope is covered with woods, mainly deciduous chestnuts. From May to late September, when the foliage of the trees is present, a dense understory grows, mainly formed by ferns and other seasonal shrubs. Few areas at the upper part of the slope are not covered with woods and the vegetation consists only of shrubs and grass. Visual inspection in trenches showed that roots usually extend across the entire soil depth, with a maximum density in the upper 0.40m, becoming sparse below 1.50m depth.

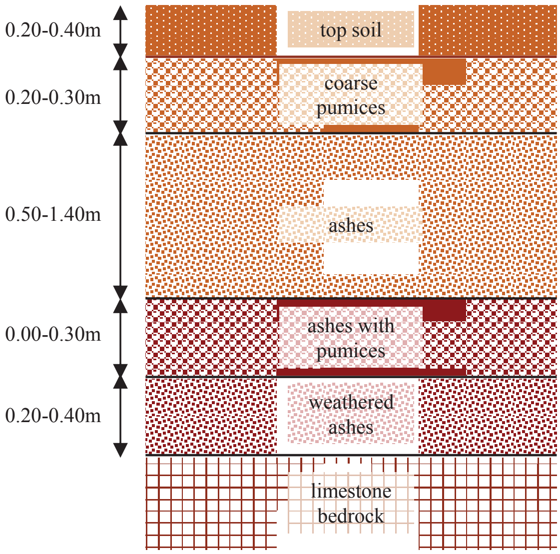

Fig. 1. Typical layered soil profile of the slope of Cervinara.

Manual monitoring of soil suction by tensiometers has been carried out at various locations along the slope since late 2001[1]. In August 2009 an automatic hydrological monitoring station at high temporal resolution was installed[14,15]. Since then, measurements of volumetric water content by Time Domain Reflectometry (TDR) and capillary tension by jet-fill tensiometers have been acquired at various depths and locations every two hours. In addition, a rain gauge for automatic acquisition of rainfall height was installed. More details about the monitoring at the slope of Cervinara can be found in other papers by the authors[1,15].

Examples of soil suction, observed at various depths during two years, are given in figure 2, plotted together with the corresponding daily hyetograph.

During the rainy season (from late October till early May), even after the heaviest rainfall events, the soil never approached saturated conditions. The observed soil suction and water content fluctuations, due to rainfall infiltration, result more smoothened, the deeper is the considered measuring point. In particular, the measurements taken by means of the deepest tensiometer, placed near the bottom of the soil cover show that during the rainy season the water potential at that depth is always between -0.2m and -0.5m. Such feature suggests that, at some depth, soil suction (and similarly soil water content) remains nearly constant for the entire rainy season.

Conversely, during the dry and warm season, the steepest increase of soil suction, as well as the corresponding steepest decrease of water content, is observed at the deepest probes, indicating that the soil cover is drained from the bottom, through the pervious soil-bedrock interface. Indeed, the water potential vertical gradients, estimated by means of soil suction measurements taken by tensiometers placed at adjacent depths, result always positive, indicating that, at the investigated depths, the water flux is always directed downward. Evapotranspiration, which during such season should attain its maximum values, owing to the warm air temperature and the flourishing of vegetation, likely affects only the upper soil layer, and its effects are hardly distinguishable with the installed devices, the shallowest of which is buried at the depth of -0.60m below the soil surface.

One of the possible interpretations of such behavior is to assume that the water potential at the base of the soil cover is affected by the fluctuations of the water level of an aquifer located in the underlying fractured limestone. Indeed, ephemeral aquifers, sometimes drained by temporary springs, are often observed in the fractured calcareous rocks of Apennines[9]. The water table of such aquifers rises up at the beginning of the rainy season, and remains nearly stable for several months, during which the leakage from the overlying soil cover compensates the drainage of the aquifer. At the end of the rainy season, the water level quickly decreases, until the springs and creeks fed by its water dry out. Such water table fluctuations occur within the system of fractures and large voids, which constitute only a small fraction of the total porosity of the calcareous rock, the so-called *effective porosity*. The remaining porosity is represented by much finer pores of the karstified rock matrix, particularly developed in the upper part of the bedrock, where weathering phenomena take place. The hydraulic contact between the aquifer, located in the fractures, and the overlying unsaturated soil is ensured by capillarity in the fine pores of the weathered layer close to the soil-bedrock interface.

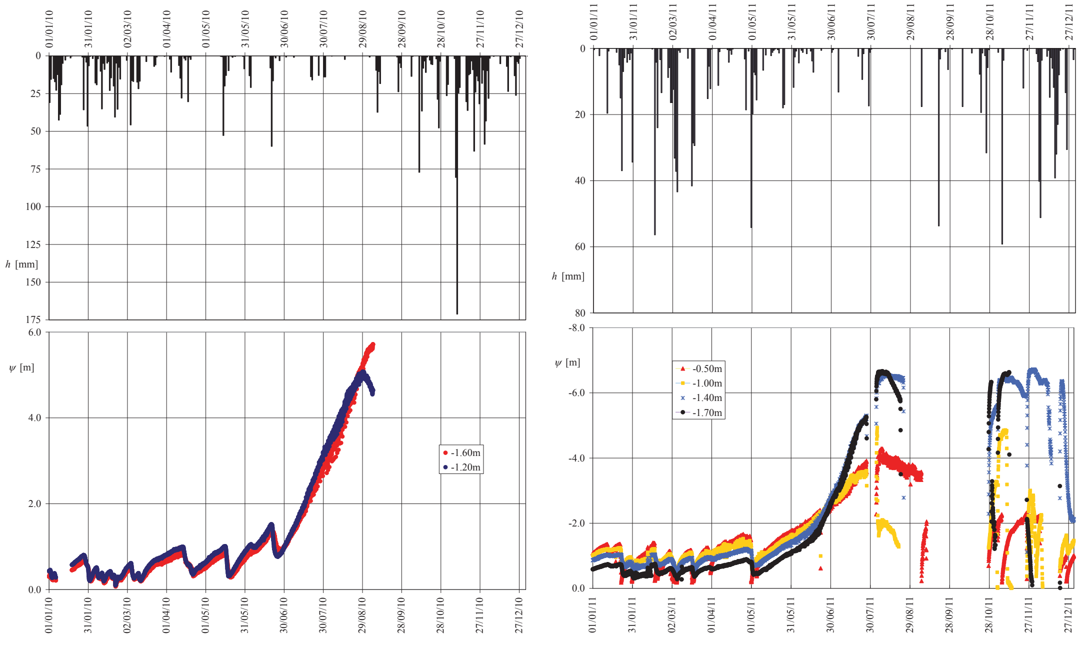

Fig. 2. Daily hyetographs and corresponding soil suction at various depths, observed during 2010 and 2011.

3. The hydrological model of the soil cover of the slope of Cervinara

A simplified mathematical model capable of reproducing the main features of the observed hydraulic behavior of the soil cover at the monitoring station of the slope of Cervinara has been developed[14,15]. The main simplifying assumptions are: the layered soil cover has been substituted, in the model, with a single homogeneous soil layer; the unsaturated flow of water through the soil cover is assumed to be one-dimensional.

In particular, the model consists of the classical 1D Richards equation with a root water uptake term:

$$\frac{\mathrm{d}\theta}{\mathrm{d}\psi}\frac{\partial\psi}{\partial t}=\frac{\mathrm{d}k}{\mathrm{d}\theta}\frac{\mathrm{d}\theta}{\mathrm{d}\psi}\frac{\partial\psi}{\partial z}+\frac{\partial}{\partial z}\left(k\frac{\partial\psi}{\partial z}\right)-q_r \tag{1}$$

The root water uptake q_r has been modelled by linearly distributing along the root depth the total evapotranspiration flux[16]. The latter has been expressed as a fraction, depending on soil water potential, of the potential evapotranspiration[17], in turn evaluated by means of the Penman-Monteith equation, taking into account the aerodynamic resistance to upward vapor diffusion, as well as the surface resistance to vapor emission by the stomata of the leaves[18].

The hydraulic behavior of the soil is described by introducing, in equation (1), the expression proposed by Van Genuchten[19] for the water retention curve $\psi(\theta)$ and by Brooks and Corey[20] for the hydraulic conductivity function $k(\theta)$.

Equation (1) is completed with the boundary conditions imposed at the top of the soil cover, soil surface, and at the soil-bedrock interface.

In particular, the water balance of the upper soil layer of thickness dz is written at the top surface. During rainfall, only the potential infiltration, depending on the hydraulic properties and on the conditions of the top soil, is allowed, while the exceeding rainfall intensity is removed by surface runoff.

At the soil-bedrock interface, as already pointed out, the water potential is supposed to be affected by the fluctuating water level of the aquifer located in the underlying fractured limestone. Therefore, the boundary condition at the bottom of the soil cover is conceptualized by introducing a linear reservoir model, simulating the aquifer supplied by water leaching through the soil-bedrock interface, and at the same time drained by a temporary spring, as sketched in figure 3.

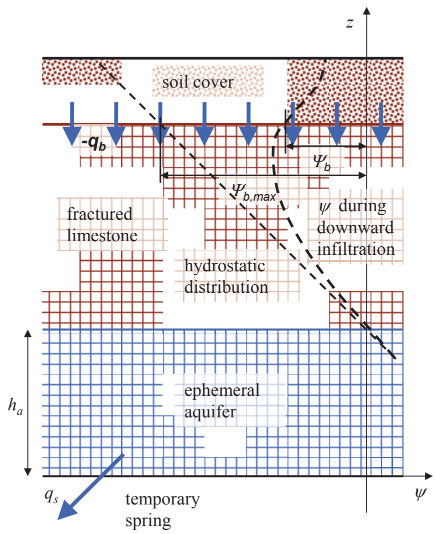

Fig. 3. Sketch of the conceptual model of the aquifer located in the fractured bedrock.

The water potential at the bottom of the soil cover is thus linked to the water level in the reservoir, assuming that ψ_b, the water potential at the soil-bedrock interface ($z=z_b$), directly follows the fluctuations of the water table of the underlying aquifer, located in the fractures of the limestone bedrock. Thus, in the water mass balance equation of the unit horizontal surface of the aquifer, which is schematized with a linear reservoir model, the derivative of ψ_b with respect to time can substitute that of the water table level $h_a=\psi_b+z_b$, leading to the following equation:

$$n_a \frac{\mathrm{d}h_a}{\mathrm{d}t} = i_b - q_s = i_b - \frac{h_a}{K_a} \Rightarrow n_a \frac{\mathrm{d}\psi_b}{\mathrm{d}t} = k_{z=z_b}\left(1 + \left.\frac{\partial \psi}{\partial z}\right|_{z=z_b}\right) - \frac{\psi_b + z_b}{K_a} \quad (2)$$

In equation (2) n_a is the effective porosity of the fractured limestone; i_b is the vertical infiltration through the soil-bedrock interface; q_s is the discharge of the spring draining a unit horizontal surface of the aquifer; K_a is the time constant of the linear reservoir model of the aquifer; the vertical elevation z, assumed positive upward, is set equal to 0 at the level of the water table of the aquifer, below which the temporary spring dries out.

Most of the parameters of the model have been measured or have been assigned according to indications from the literature, while only few of them have been estimated by means of model calibration against soil suction and water content data collected during the monitoring activity. In particular, the parameters of the linear reservoir model introduced as bottom boundary condition, given in table 2, have been identified through model calibration based on the experimental data of soil suction and water content collected by the monitoring station between 2009 and 2011. More details about the above described mathematical model and the estimation of the parameters can be found in Greco et al. (2013)[15]. The calibrated model has been also applied to the simulation of the hydrological response of the soil cover to the rainfall data of 1999, when, as already pointed out, a catastrophic slide was triggered very close to the location of the monitoring station. The rainfall data used for such a simulation have been provided by the nearby rain gauge of S. Martino Valle Caudina.

Table 2. Parameters of the linear reservoir model of the aquifer stored in the fractured limestone bedrock.

Parameter	Symbol	Value
Soil-bedrock interface elevation	z_b (m)	7.97
Effective porosity	n_a	0.005
Time constant	K_a (days)	871

4. Results and discussion

An example of the agreement between simulated and observed soil water potential is given in figure 4, indicating that, despite the introduced simplifying assumptions, the proposed model is capable of satisfactorily reproducing the observed water potential trends at all the monitored depths, either during the rainy season, or during the dry season.

A qualitative sensitivity analysis of the model results to the variations of the parameters has been carried out. It shows that, among the parameters of the hydraulic characteristic curves, the most important is the saturated hydraulic conductivity, which has been assumed as large as $8.0\times10^{-5}\mathrm{ms}^{-1}$. Such a high value is needed to reproduce the fast response of water potential and water content, even at the highest monitored depth, to rainfall events.

About the top boundary condition, the sensitivity analysis indicates that variations of the parameters accounting for the vegetation effects have little influence on soil water potential at the monitored depths. Only during the vegetation flourishing season (from May till September), canopy interception and root water uptake are probably responsible for the ineffectiveness of rainfall events to induce changes of soil suction and water content below the depth of -0.60m.

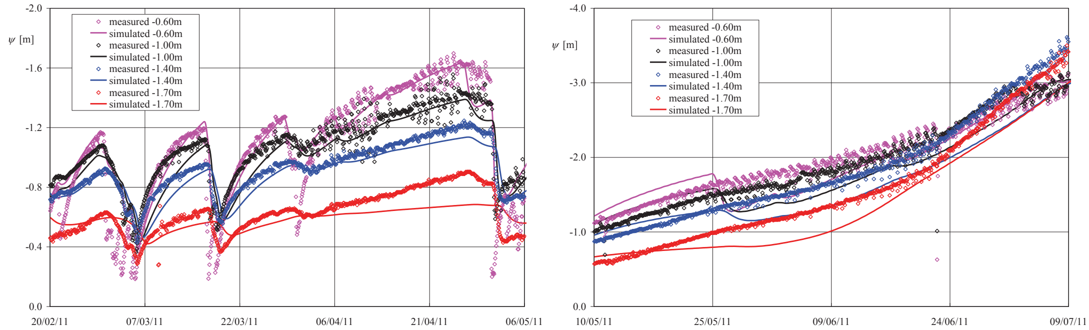

Fig. 4. Examples of the capability of the calibrated model to reproduce the observed soil suction at various depths.

Conversely, the bottom boundary condition strongly affects soil suction of the deepest layers of the soil cover. In fact, during the rainy season, the water potential at the soil-bedrock interface undergoes small fluctuations. Therefore, the interface behaves as an open boundary, through which water leaks downward, without significantly affecting soil water potential. During the dry season, instead, the water potential at the interface decreases faster than in the upper soil cover, indicating that the soil cover is mainly drained from the bottom. Such feature is interpreted as the result of the decrease of the water level of the aquifer, stored in the fractured limestone, which causes an increase of soil suction at the soil-bedrock interface.

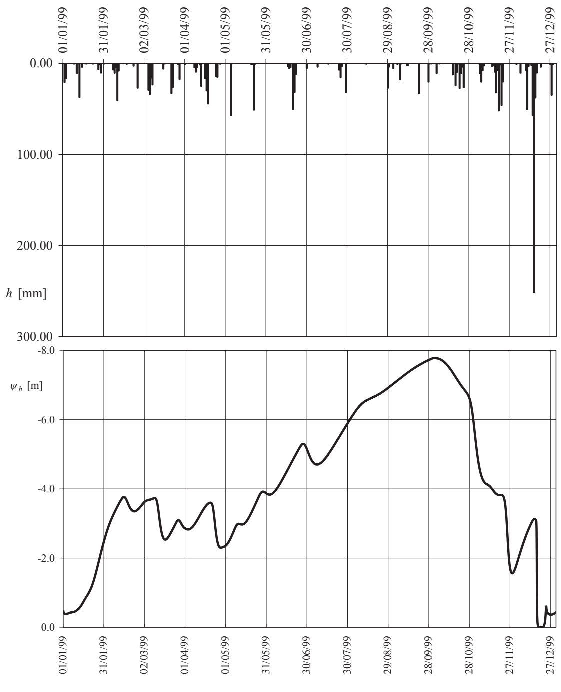

Fig. 5. Daily hyetograph (above) and simulated water potential at the soil-bedrock interface (below) during 1999.

Figure 5 shows the simulated variation of water potential at the soil-bedrock interface during 1999, together with the corresponding daily hyetograph. The minimum water potential, nearly -8.0m, was attained at the end of the dry season, when the water table in the underlying aquifer was the lowest. The obtained results should be interpreted keeping in mind that, despite the simplification of equation (2), which assumes that soil suction at the soil-bedrock interface, ψ_b, and the water table of the aquifer, h_a, undergo the same fluctuations, it is possible to demonstrate that, as long as there is a downward directed vertical flow, $q_a<0$, through the fractured limestone above the aquifer water table, it results $-\psi_b \leq h_a$. In fact, with the symbols shown in figure 3, it results:

$$\psi_b = \int_{h_a}^{z_b} \frac{\partial \psi}{\partial z} dz = -\int_{h_a}^{z_b} \left[1 + \frac{q_a(z)}{k_a(z)} \right] dz = h_a - z_b - \int_{h_a}^{z_b} \frac{q_a(z)}{k_a(z)} dz \tag{3}$$

In equation (3), k_a represents the hydraulic conductivity of the fractured limestone. Carbonate rocks often exhibit values of saturated hydraulic conductivities as high as 10^{-3}ms^{-1}. This feature depends on the bimodal distribution of pores dimensions, with the presence of large interconnected channels and fractures, representing only a small fraction of the total porosity (the so-called *effective porosity*, usually between 0.0001 and 0.001), through which the water flows easily[21]. The remaining matrix pores, representing nearly the total porosity (sometimes as high as 0.3), usually exhibit hydraulic conductivity as small as 1.0×10^{-8}ms^{-1}. Such an order of magnitude can be considered as the upper limit of the unsaturated hydraulic conductivity of the limestone. When the leakage from the upper soil cover is too high to be carried through the matrix pores, the matrix approaches saturation, and the excess water quickly percolates through the large channels, allowing a fast recharge of the underlying aquifer[21]. Therefore, it is possible to argue that most of the time it results:

$$-1 \leq \frac{q_a(z)}{k_a(z)} \leq 0 \tag{4}$$

Consequently, soil suction at the soil-bedrock interface results usually smaller than the depth of the water table below it:

$$0 \leq \frac{\psi_b}{h_a - z_b} \leq 1 \tag{5}$$

Therefore, the fluctuations of the water level of the aquifer are larger than the corresponding fluctuations of water potential at the soil bedrock interface. Indeed, aquifer water table excursions of tens of meters have been reported in similar contexts[9].

Another significant feature of the simulated water potential at the bottom of the soil cover is that, between 18.12.1999 and 20.12.1999, a slight positive water pressure is attained. Such soil saturation is the result of the infiltration of the extreme rainfall event occurred between 14.12.1999 and 16.12.1999 (nearly 350mm in three days), which triggered a large flow-like landslide along the slope, not far from the location of the monitoring station. This event occurred when the water potential at the bottom of the cover was already larger than -3.0m, owing to the rain fallen during November and the first two weeks of December (295mm from 1st of November till 13th of December). It is worth noting that soil saturation corresponded to a fast rise of the leakage flow through the soil-bedrock interface, which reached the maximum value of nearly -1.0×10^{-6}ms^{-1} in the early morning of 17.12.1999, as shown in figure 6. It looks clear that soil saturation at the bottom of the cover was caused by the building of the water potential gradient needed to allow such a high peak discharge to leak through the underlying bedrock, in which a relatively high water potential had already established.

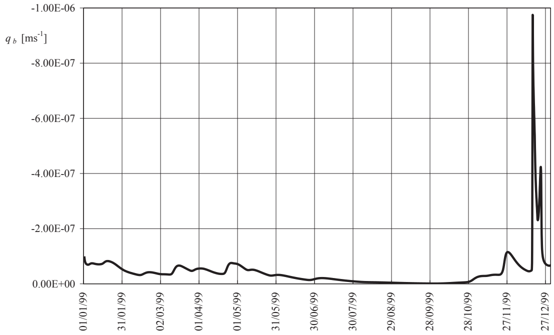

Fig. 6. Simulated water leakage through the soil-bedrock interface during 1999.

5. Conclusions

A simplified 1D mathematical model of the hydrological behavior of the pyroclastic soil cover of the slope of Cervinara (southern Apennines) has been developed. The model consists of a single homogeneous soil layer, for which the hydraulic characteristic curves have been defined on the basis of field data of soil water content and suction at various depths within the soil profile. Such data have been acquired by means of an automatic monitoring station operating since November 2009.

The model is completed with the boundary conditions. At the soil surface, the top boundary condition accounts for the effects of vegetation upon evapotranspiration fluxes, and transforms into surface runoff the rainfall intensity exceeding the potential infiltration of the top soil layer. At the bottom of the soil cover, the water potential at the soil-bedrock interface is linked to the fluctuations of the water table of the aquifer stored in the underlying fractured limestone. The aquifer is conceptually modeled as a linear reservoir.

The model, which satisfactorily reproduces the observed water potential at all the monitored depths, provides a plausible interpretation of the fact that, during all the monitoring activities, started since 2001, the soil cover never approached saturation at any depth: the unsaturated soil cover and the underlying fractured bedrock allow the fast infiltration and leakage of the highest observed rainfall intensity peaks. When the water level in the underlying aquifer is high, owing to the rainfall fallen in the preceding weeks, also the water potential at the bottom of the soil cover is high. In these conditions, if a high infiltration rate reaches the soil-bedrock interface, the establishment of the water potential gradient, needed to allow the leakage through the underlying bedrock, may lead to soil saturation at the bottom of the cover. According to the model simulations, this happened on the 15th of December 1999, when a large landslide was triggered by an extreme rainfall event, occurred after some weeks characterized by frequent and moderately intensive rainfall events.

The hypothesized mechanism is consistent with existing empirical models of landslide triggering in similar slopes, linking triggering to both recent and past rainfall[6,21].

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