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

Inferring the hydraulic properties of a historical soil: A revisiting of Perrault's experiments

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Abstract

In his classical work published in 1674, Pierre Perrault presented four sets of experiments about the water circulation in the subsoil, which are recognized as one of the seminal contribution to the experimental hydrology. With the aim of deepening the knowledge of Perrault's experiments, and of testing the performance, in scarcity of experimental data, of a water flow conceptualisation based on the Richards equation and on soil—water constitutive laws, one of the reported experiments, the richest in quantitative details, was numerically re—analysed. As a result of the deductions inferred from the data and of the simulations, estimates of the hydraulic properties of Perrault's soil are provided.

Keywords: Perrault's experiment; soil hydraulic properties; Richards equation;

1. Introduction

In the second half of the XVII century the hydrological knowledge was at a crucial turning point of its history. An exogenous engine (the Sun) was in fact about to be recognized as the engine of the hydrological cycle, instead of an endogenous one, placed in the depths of the Earth. Even if the importance of the Sun for the hydrological cycle had already been recognized by some investigators in the ancient Greek culture (e.g [1], p.560), their conclusions were neglected for more than fifteen centuries in favor of the acceptance of an endogenous engine, in agreement with the Hermetic (symbolic) correspondence between the Man (the microcosms) and the Universe (the macrocosms). The crisis, in the XVII—century European culture, of a symbolically based description of natural phenomena, jointly with

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the diffusion of the scientific method and of the availability of the first experimental data on the water balance [2] reopened the debate on the hydrological cycle.

Perrault contributed to this debate with his classical book of 1674 about the origin of springs (*De L'origine des Fountaines*) [3], which is recognized as one of the seminal works of the experimental hydrology [2,4,5] and the first rigorous attempt to explain the groundwater circulation [6]. In this book, he reports details about observations and experiments which he performed both to assess the water balance at the basin scale, and to understand the behavior of the soil—water movement during infiltration and redistribution. Here we will focus on these latter experiments. Perrault, aiming at understanding (1) whether the water could spontaneously rise within the soil and originate springs, and (2) how the rainfall could percolate through the soil to form the groundwater, took an empty pipe, 65 cm long, filled it with different soils and observed its behavior against imbibition *per ascensum*, infiltration, percolation and water—content redistribution. Finally he concluded that the precipitation cannot deeply percolate to onset permanent springs, as the soil can be crossed by water only if it has already been wetted. Even if some of his conclusions in this field went in the direction of the ancient opinion, the report is very modern as most of the details are precisely described and some of them are also quantitatively provided.

With the aim of deepening the knowledge of Perrault's experiments, and of testing the performance, in scarcity of experimental data, of a water flow conceptualization based on the Richards equation and soil—water constitutive laws, we numerically re—analyzed one of the reported experiments, which is the richest one in quantitative details. After a description of the source and of the historical experiment (Section 2), the theoretical framework and the main hypotheses are reported (Section 3) and, as a result of the deductions inferred from the data and of the simulations, the estimates of the hydraulic properties of Perrault's soil are presented and discussed (Section 4).

2. Perrault's opus and experiments

Two early versions of Perrault's opus are now easily available. One is the electronic version of that imprinted in 1674 in Paris, at Pierre le Petit's [3], now available on line, and the other is the Nabu reprint of that imprinted in 1678 in Paris, at Jean & Lourent d'Houry's [7]. Both are based on an original work dated by the Author at the end of July 1672 (p.353, in both the sources) which was firstly published in September 1674, as it is reported in the second page of the *Privilege du Roy* (page without number, same position in both the sources). Particularly the 1678 edition seems to be just a reprint of the 1674 one, with marginal changes in the decorative apparatus, but with the same pagination and also the same list of *errata* at the end of the *Table des Matieres* (last page, without numbers). In the following, if not differently specified, we will refer to the 1674 edition. Two different measurement systems were used in France in second half of XVII century: the *Toise de l'Ècritoire* which was in course until 1667, and the *Toise du Châtelet* which came into course in 1668 [8]. The main measurement units of interest for our purpose are reported in Table 1. As the first edition of the book belongs to 1674 we will refer to the *Toise du Châtelet* system.

In his book, after a literature review of previous Authors' opinions (First part, pp.8—146), Perrault states his thesis (the *Opinion de l'Auteur*, beginning of the Second part, pp.148—150), according to which the precipitation is not able to deeply percolate within the soil, but remains in the upper layers, directly contributes to the evaporation and, marginally, to recharge and modulate the springs. He states his thesis in contrast with other Authors' theses (which are referred to as the *Opinion Commune*, pp.150—152), according to which the precipitation can slowly percolate until it reaches an impervious layer of *terre grasse* or rock, and then flow along this layer until it forms a spring. He identifies two major difficulties rising from the *Opinion Commune* (p.153—154), i.e. (1) whether the precipitation could really leach the soil and (2) whether the soil—water could spontaneously originate springs, once it reached deep soil layers. In order to assess such issues he then performed four sets of experiments, which he reports in the following pages (pp.154—160).

Table 1. Measurement systems in XVII-century France (see e.g. [8])

Name	*pied-du-roi*	*Toise de l'Ècritoire* (until 1667)	*Toise du Châtelet* (since 1668)
point	1/1728	0.189 mm	0.188 mm
ligne	1/144	2.268 mm	2.256 mm
pouce	1/12	2.722 cm	2.707 cm
pied-du-roi (*pied*)	1	32.660 cm	32.484 cm
toise	6	1.959 m	1.949 m

During the first set of experiments he filled with dried and sieved river sand a leaden pipe, 2 *pieds* long (65 cm) and with a diameter of 20 *lignes* (4.5 cm). He posed the bottom of the pipe within the water for a depth of 4 *lignes* (0.9 cm) and for a duration of 24 hours, afterwards he observed that the sand was wet for an height h_w = 18 *pouces* (48.7 cm). Then he tried to onset a spring by means of a little lateral opening 2 *pouces* (5.4 cm) above the surface of the water. As nothing happened, he suspended the pipe for a certain time, in order to let the water drop down. Also in this case no water dropped from the pipe. He then twice poured a certain amount of water (not detailed for this set) on the top of the pipe. The first time he recovered at the bottom of the column only three quarters of the poured water, while the second time all the poured water was collected. Finally he dropped the sand out of the pipe and verified that the soil was sodden in its lower part, but it was not so wet in its upper part, even if some water was poured above. He then concluded that the water can spontaneously rise within the soil only for a certain limited height, that it cannot spontaneously originate springs and that it can percolate only if the soil was previously thoroughly wetted. Afterwards the same protocol was applied to different soils observing analogous behaviors, but the report of this second set of experiments is much poorer in details.

The third set of experiments aimed at determining how much water should precipitate before it can percolate toward the deep soil. The same pipe, filled with dried and sieved sand, was suspended. Then he sometimes poured on the top of the soil column a certain amount of water, contained in "*une fiole de verre de la grosseur d'une moyenne balle de jeu de paulme que j'emplissois jusqu'au haut du goulet*"("a glass vial as big as a medium ball of the *jeu de paulme*, which I filled up to the height of the neck", p.159). The fourth time he recovered the third part of the vial, the fifth and the sixth time he recovered all the water and nothing more during further 18 hours, since that he concluded that that soil could be crossed by the precipitation only if previously wetted by a volume of water V_w = 3.5 *fioles*, quite contrasting with the previous observation that the soil was retaining 4 *fioles* minus one third of *fiole*. This volume corresponded to the third part of the h_w = 18 *pouces* of wetted soil which were observed to be necessary in order to onset percolation. He waited three days more, without recovering any more water, then he poured other 2 *fioles* of water on the top, and he recovered three quarters of the first (as the upper soil dried a little during that time) and all the second. Finally he performed a fourth set of experiments, which are briefly described, and during which he verified that salted water would have remained salted while rising within the soil. Perrault then summarizes the conclusions derived from the experiences (p.160 and followings), concluding that the water cannot easily leach the soil, which needs to be previously wetted with an equivalent amount of water to one third of its thickness.

The remaining part of the book is devoted to a general discussion about the hydrological cycle and the circulation of the water within the Earth. He proved that one sixth of the precipitation is enough to sustain the water flowing in the rivers (p.204 and followings), and accepted that the springs, that are sensitive to the rainfall and to the snowfall of the previous season, are related to a soil—water circulation in the upper soil, but remarked that the permanent springs should be caused by the condensation of water vapor flowing within the Earth (p.248 and followings).

3. Inference of Perrault's soil properties

3.1. Theoretical framework

In a physically based theoretical framework, according to a continuum approach, the dynamics of the water content in a Darcian soil can be described by the Richards equation [9]:

$$\frac{\partial}{\partial x}\left[K(\theta)\frac{\partial \Phi}{\partial x}\right]=\frac{\partial \theta}{\partial t}\,, \tag{1}$$

in which θ [L³/L³] is the volumetric soil water content, $K(\theta)$ [L/T] is the soil hydraulic conductivity and $\Phi = \psi + x$ [L] is the total hydraulic head, being $\psi(\theta) < 0$ the matric potential and x the gravimetric potential (x positive upward for our reference system). The effective saturation s is introduced as:

$$s=\frac{\theta-\theta_r}{\phi_e}\,, \tag{2}$$

being θ_r and ϕ_e [L³/L³] the residual water content and the effective porosity respectively. The effective porosity ϕ_e is defined as:

$$\phi_e=\theta_s-\theta_r\,, \tag{3}$$

being θ_s [L³/L³] the volumetric water content at saturation. With the coupled van Genuchten—Mualem approach [10,11], the soil—water constitutive laws are expressed by:

$$s=\left[1+\left(\psi/\psi_1\right)^n\right]^{-m}, \tag{4}$$

$$K(s)=K_s s^{0.5}\left[1-\left(1-s^{1/m}\right)^m\right]^2, \tag{5}$$

where ψ_1 [L], m [-] and n [-] are fitting parameters of the soil water retention relationship, and K_s [L/T] is the hydraulic conductivity at soil saturation. In order to obtain the constitutive law *(5)* also the condition:

$$m=1-\frac{1}{n} \tag{6}$$

applies. The soil—water retention curve as described by *(4)* has an inflection point at ψ_f given by:

$$\frac{\psi_f}{\psi_1}=\sqrt[n]{\frac{n-1}{nm+1}}\,. \tag{7}$$

By means of the condition *(6)*, the inflection point is then calculated as:

$$\frac{\psi_f}{\psi_1}=\sqrt[n]{\frac{n-1}{n}}\,. \tag{8}$$

As $n > 1$, one gets $\psi_1 < \psi_f < 0$, and ψ_f tends to ψ_1 as n increases. The soil hydraulic properties are therefore fully defined if it is known the vector (θ_r, ϕ_e, ψ_1, m, n, K_s), in which only five parameters are independent.

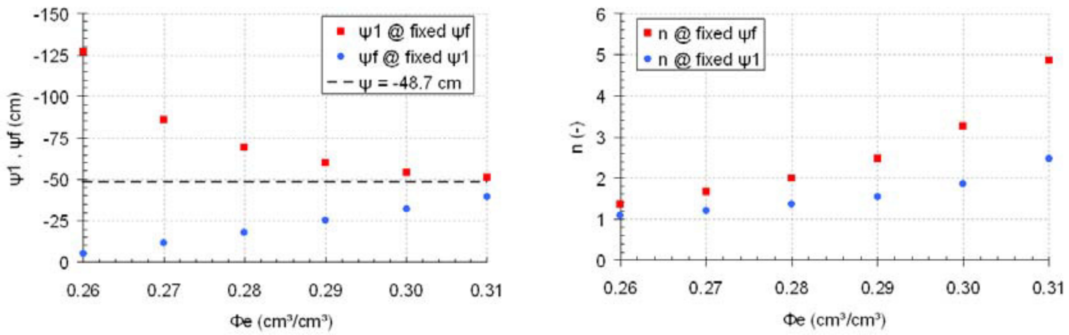
3.2. Hypotheses on the retention curve and on the effective porosity

The first and the third sets of experiments are richer in quantitative details, with respect to the second and to the fourth one. Comparing them, it is possible to recognize that in the first series Perrault characterizes the hydrostatic conditions of the soil within the column only by means of the height, from the bottom, above which the soil is less wetted. In the third set, instead, also an approximated quantitative value of the retained water in hydrostatic conditions is given (3.5 *fioles*). Measuring small volumes with reference to a small, medium or big ball of the *jeau de paulme* (ancient name of the *jeu de paume*) is quite common in the French literature of that age, but it seems that there is not a fixed equivalence even with the coeval metric system. A quantitative estimate is anyway given by the note that a water volume V_w = 3.5 *fioles* corresponds to the third part (258.2 cm³) of the wetted volume of soil (774.5 cm³), i.e. 1 *fiole* can be assumed to correspond to 74.0 cm³ and the diameter of the vial, supposed spherical, is 52 mm. This value is in agreement with the modern diameter of the ball of the *jeau de paume* (53 mm), but bigger than traditional balls (from 32 to 48 mm) [12].

In order to use the information about the observed change of water content in quantitative sense, it can be hypothesized that the height h_w is between the inflexion point of the retention curve and the height $|\psi_1|$, i.e. $|\psi_f| < h_w < |\psi_1|$. Particularly it can be guessed that h_w is about $|\psi_1|$ in the limit case in which, for very high values of n, ψ_1 corresponds to an air entry value and the water retention curve tends to a stepwise function with a matric potential threshold ψ_1 = -48.7 cm, above which the soil is saturated and below which the soil is dry. Assuming that the residual water content θ_r is comparable with the water stored in the soil after drying, it will not affect the information about the water flow or the water storage. Therefore, the upper limiting value of the effective porosity $\phi_{e,\max}$ is 0.33 as the volume of the poured water is one third of the wetted soil. For each value of the effective porosity $\phi_e < \phi_{e,\max}$ it is possible to identify two limiting retention curves, one in the case $|\psi_1|$ is fixed and equal to h_w, and one in the case $|\psi_f|$ is fixed and equal to h_w. In both the cases the following condition holds:

$$V_w = A \int_0^{65\mathrm{cm}} \phi_e s(\psi) \mathrm{d}x \equiv 3.5 \cdot 74.0\mathrm{cm}^3 , \quad (9)$$

where A is the cross sectional area of the cylinder and the integration is performed over the whole length of the column. In hydrostatic conditions the total hydraulic head $\Phi(x) = \psi(x) + x$ is uniform with x and equal to a boundary condition. In this case the boundary condition can be set at the bottom of the pipe x_b = 0 m, posing that $\psi(x_b) = 0$ for continuity of the total potential across the soil boundary. It therefore follows that $\Phi(x) = \Phi(x_b) = 0$ m and $\psi(x) = - x$. This relation allows to calculate the integral *(9)*. In Figure 1 and in Table 2 and 3 the obtained parameters of the soil—water retention relationships are presented. As ϕ_e varies, also the effective void volume of the soil V_v varies. The stored volume in hydrostatic conditions is always 3.5 *fioles*, and therefore the remaining void volume $V_v - V_w$ varies, ranging from 0.14 to 0.84 *fiole* (from 10.6 to 62.3 cm³) if ϕ_e ranges from 0.26 to 0.31.



(*a*) (*b*)

Fig. 1. Parameters of the soil—water retention curves as a function of the effective porosity ϕ_e : (*a*) scaling parameter ψ_1 and inflection point ψ_f ; (*b*) shape parameter *n*

Table 2. Soil hydraulic parameters determined for ψ_f = -48.7 cm

Φ_e	(-)	0.26	0.27	0.28	0.29	0.30	0.31
ψ_1	(cm)	-127.0	-85.8	-69.2	-60.1	-54.5	-51.1
ψ_f	(cm)	-48.7	-48.7	-48.7	-48.7	-48.7	-48.7
m	(-)	0.27	0.39	0.50	0.60	0.69	0.79
n	(-)	1.37	1.65	1.99	2.47	3.26	4.86
$K_{s,\min}$	(m/s)	$\sim 10^{-5}$	$10^{-5} \div 3 \cdot 10^{-5}$	$10^{-5} \div 3 \cdot 10^{-5}$	$\sim 3 \cdot 10^{-5}$	$\sim 3 \cdot 10^{-5}$	$3 \cdot 10^{-5} \div 10^{-4}$

Table 3. Soil hydraulic parameters determined for ψ_1 = -48.7 cm

Φ_e	(-)	0.26	0.27	0.28	0.29	0.30	0.31
ψ_1	(cm)	-48.7	-48.7	-48.7	-48.7	-48.7	-48.7
ψf	(cm)	-5.1	-11.3	-17.9	-24.9	-32.1	-39.5
m	(-)	0.09	0.17	0.26	0.35	0.46	0.60
n	(-)	1.09	1.21	1.35	1.55	1.86	2.47
$K_{s,\min}$	(m/s)	$\sim 10^{-4}$	$3 \cdot 10^{-5} \div 10^{-4}$	$3 \cdot 10^{-5} \div 10^{-4}$	$3 \cdot 10^{-5} \div 10^{-4}$	$3 \cdot 10^{-5} \div 10^{-4}$	$3 \cdot 10^{-5} \div 10^{-4}$

3.3. Hypotheses on the conductivity at saturation

The last soil parameter to be investigated is the hydraulic conductivity at soil saturation K_s. Perrault does not provide any explicit time information which can be useful at directly characterizing the soil—water dynamics but in all the cases it seems that steady conditions are reached in a somehow limited time. As an example, describing the third set of experiments, Perrault notes that, once recovered the fifth and the sixth vial of water, no more water dropped for the next 18 hours, nor it dropped for the next three days. As the timing of the soil—water dynamics directly scales with K_s, it can be guessed that Perrault's soil conductivity at saturation was such that the time scales of the water dynamics were of the order of magnitude of hours more than of days, almost during the third set of experiments. Two sets of simulations were then performed by means of the numerical code Hydrus1D [13], in order to estimate for each retention curve, obtained with condition *(9)*, the lowest compatible K_s value with this assumption. As no timing information are available on the water pouring, but as the remaining void volume, once that 3.5 *fioles* of water were stored, is small and less than 1 *fiole*, it was assumed that all the soil column was saturated at the beginning of the simulations. Five values of conductivity were adopted for each retention curve (K_s = 3E-06 m/s, 1E-05 m/s, 3E-05 m/s, 1E-04 m/s, 3E-04 m/s) and the lowest conductivity value for which the cumulated percolation reached an almost steady value within three hours was considered an estimate of the lowest conductivity value of the soil. The obtained results are reported in Table 2 and 3. Values of K_s range from 1E-05 m/s to 1E-04 m/s, increasing at increasing ϕ_e for retention curves obtained with the assumption $h_w = |\psi_f|$, and from K_s = 3E-05 m/s to 1E-04 m/s, decreasing at increasing ϕ_e for retention curves obtained with the assumption $h_w = |\psi_1|$.

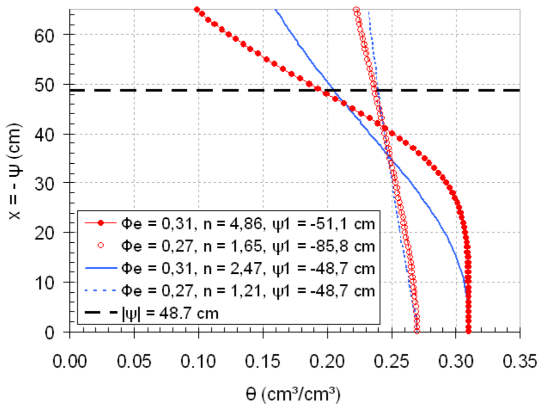


Fig. 2. Examples of the obtained soil—water retention relationships at different values of ϕ_e. Red lines with circles are determined at fixed values of ψ_f = - 48.7 cm, blue lines are determined at fixed values of ψ_1 = - 48.7 cm. The dashed line represents the 48.7 cm height

4. Results and discussion

Four different soil—water retention curves are represented in Figure 2 for two different values of the effective porosity ϕ_e. The red ones with circles are determined at fixed values of ψ_f = - 48.7 cm, the blue ones are determined at fixed values of ψ_1 = - 48.7 cm. Due to the condition *(9)*, which fixes the total amount of water stored in the soil, the shape of the curves is very sensitive to the value of ϕ_e. Defining the soil water capacity $C(\psi)$ as the derivative:

$$C(\psi) = \frac{\mathrm{d}\theta}{\mathrm{d}\psi}, \tag{10}$$

we observe that at little values of ϕ_e the curves implies little values of n and they are therefore smooth, with always little values of $C(\psi)$. At bigger values of ϕ_e they are instead sharper, with bigger values of n and of $C(\psi)$ around the inflection point. The limit case of a retention curve described by a stepwise function would have been characterized by a Dirac—δ shaped capacity function. As the function are smoother, also the difference ψ_f - ψ_1 (> 0) increases, and it decreases as the curves are sharper. Perrault stressed the importance of the soil wetting in order to onset the percolation and he identified the wet soil on a perceptive basis, as the sodden soil ("*comme du mortier ben moüillé*", p.158). As a conclusion we can therefore guess that the curves obtained with bigger values of ϕ_e, in any case lower than $\phi_{e,\max} = 0.33$, are more representative of those characterized the soils investigated by Perrault.

In both the cases in which either ψ_f or ψ_1 is fixed, there is a threshold for ϕ_e below which n is lower than 2. This means that, below that threshold, also the slope of the conductivity $K(\psi)$ nearby the soil saturation is infinite, i.e.:

$$\lim_{\psi \to 0^-} \left.\frac{\mathrm{d}K}{\mathrm{d}\psi}\right|_{n<2} = +\infty \,. \tag{11}$$

In order to check how it could affect the water dynamics at a global scale, the cumulated dimensionless percolation V' is represented as a function of the dimensionless time T' for different sets of soil parameters, with fixed ψ_1 = -48.7 cm, in Figure 3. For all the soils of the Figure K_s is 1E-04 m/s. The dimensionless values were obtained by means of the following relationships:

$$V' = \frac{V(t)}{V_v - V_w} \quad \text{and} \quad T' = \frac{t}{K_s}\left(V_v - V_w\right), \tag{12}$$

where $V(t)$ is the cumulated percolation from the soil column at the time t. It is remarked that the proposed dimensionless approach implicitly accounts for the different effective porosity ϕ_e by means of the residual void volume V_v - V_w. It can be observed that the soil—water dynamics are sensitive to the value of the shape factor n, and particularly they are faster as n increases. At increasing n, in fact, the slope of $K(\psi)$ nearby the soil saturation decreases and the greater is n, the greater are the values of conductivity at the same value of matric potential, thus accelerating the soil—water dynamics.

The percolation curves tend anyway to coalesce as n increases. As greater n values follow by greater ϕ_e values, which seemed to be more realistic for Perrault's soil, we can conclude that the value of n is not a major source of uncertainty at describing the soil—water dynamics of Perrault's soil. Therefore the major source of uncertainty still remains the value of the hydraulic conductivity at soil saturation.

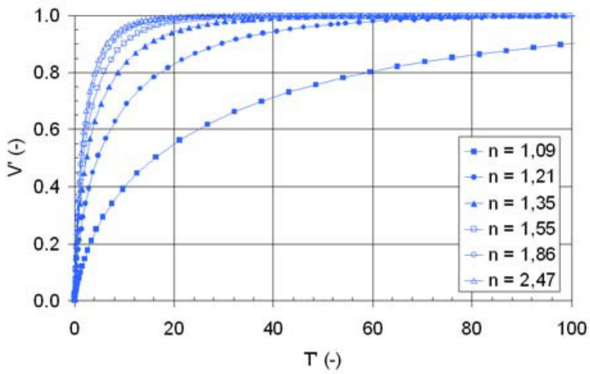


Fig. 3. Dimensionless percolation volumes V' for soils with ψ_1 = - 48.7 cm and K_s = 1E-04 m/s

5. Conclusions

Aiming at contributing to understand the circulation of the water in the subsoil and the origin of springs, Perrault presented in 1674 four sets of experiments which are recognized as one of the seminal contribution to the experimental hydrology. We re—analyzed the experiments by means of a physically based theoretical framework to infer the hydraulic properties of Perrault's soils. Focusing on the third set of experiments, which is the richest in quantitative data, we proposed some sets of the soil hydraulic properties, viz the effective porosity, the parameters of the soil—water retention curve and the hydraulic conductivity at soil saturation, which are compatible with the descriptions reported by the Author. Particularly the information directly or indirectly related with the hydrostatic behavior of the soil allowed to infer a range of reasonable values of the effective porosity and of the parameters of the retention curve. On the other hand, the lack of information about the soil—water dynamics only allowed to guess an inferior limiting value for the hydraulic conductivity at saturation. The obtained numerical values are reported in Tables 2 and 3.

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