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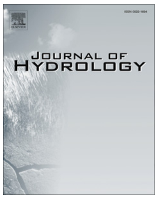

Inverse modeling of soil water content to estimate the hydraulic properties of a shallow soil and the associated weathered bedrock

O. Le Bourgeois [a,*], C. Bouvier [a], P. Brunet [a], P.-A. Ayral [b]

[a] Hydrosciences Montpellier, UMR 5569 CNRS-IRD-UM, 300, avenue du Professeur Emile Jeanbrau, 34000 Montpellier, France
[b] Ecole des Mines d'Alès, Centre de Recherche LGEI, 7, rue Jules Renard, 30319 Alès, France

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SUMMARY

Modeling soil water flow requires the knowledge of numerous parameters associated to the water content and the soil hydraulic properties. Direct estimations of those parameters in laboratory require expensive equipment and the obtained parameters are generally not representative at the field scale because of the limitation of core sample size. Indirect methods such as inverse modeling are known to get efficient estimations and are easier to set up and process for large-scale studies. In this study, we investigated the capacity of an inverse modeling procedure to estimate the soil and the bedrock hydrodynamic properties only from *in situ* soil water content measurements at multiple depths under natural conditions. Multi-objective parameter optimization was performed using the HYDRUS-1D software and an external optimization procedure based on the NSGA-II algorithm. In a midslope shallow soil, water content was monitored at 3 depths, 20, 40, and 60 cm during 12 intense rainfall events, whose amounts ranged between 50 and 250 mm and duration between 1 and 5 days. The vertical profile was considered as 2 layers of soils above a third layer representing the weathered schist rock. This deep layer acted as a deep boundary condition, which features the bedrock permeability and water storage. Each layer was described trough the 6 parameters of the Mualem–van Genuchten formulation. The calibrated parameters appeared to have very low uncertainty while allowing a good modelisation of the observed water content variations. The calibrated saturated water content was close to the laboratory porosity measurements while the saturated hydraulic conductivity showed that the soil was highly permeable, as measured in the field. The inverse modeling approach allowed an estimation of the hydraulic properties of the bedrock layer where no measurement was available. The bedrock layer was found to have a low saturated hydraulic conductivity ($<5\ \text{mm h}^{-1}$), which means that the schist bedrock is poorly weathered and that saturated area can be generated above this depth, as it was observed. The simulated water contents were generally close to the measured water contents, but the model failed sometimes to reproduce the saturation of the soil in the deeper layers, probably because of sub-surface flux at the soil/bedrock interface. In these cases, further investigation will have to be made by using a 2D-model.

0. Introduction

Soil water content and flow are crucial to understand small-scale processes involved in many hydrological applications, e.g. flash-flood genesis occurring on small watersheds (Braud et al., 2010). Hydrological models used to simulate soil water flows are generally based on Richards' equation (Richards, 1931) involving hydraulic conductivity, water pressure head and soil water content, as well as boundary conditions. The main difficulty in using such model lies in the access to the soil hydraulic properties, i.e. the parameters that governs both the soil water retention and the soil water conductivity curves. Moreover, recent studies showed the importance of investigating the bedrock conductivity function since the water flow at the interface between soil and bedrock is one of the key processes involved in flood genesis (Hopp and McDonnell, 2009; James et al., 2010).

Soil hydraulic parameters can be estimated by many direct or indirect methods. Direct methods are based on small soil sample laboratory experiments or small scale field experiments. Laboratory methods allow a total control of boundary conditions and precise data acquisition (Durner and Lipsius, 2005) but according to Dirksen (1999), the presence of large unstable structural elements such as discontinuous granitic slabs or abundance of stones are overriding reasons to perform *in situ* experiments. Likewise, direct

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* Corresponding author. Tel.: +33 (0) 4 67 14 90 44.
E-mail address: olivier.le-bourgeois@hotmail.fr (O. Le Bourgeois).

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field experiment methods involve high cost, significant time demand and are very sensitive to small scale heterogeneity (Tseng and Jury, 1993; Basile et al., 2003).

On the other hand, automatic-calibration (inverse modeling) aims to find the hydraulic parameters by minimizing the difference between simulated and observed data such as water content, head pressure or geophysical prospection (for a review of inverse methods, see Vrugt et al., 2008). It is one of nowadays most used methods thanks to its ability to give good estimates of hydraulics properties from relatively simple data (Ritter et al., 2003; Loew and Mauser, 2008; Wollschläger et al., 2009; Scharnagl et al., 2011; Schelle et al., 2013; Werisch et al., 2014). However, much attention must be paid in the following aspects:

(i) *Non-optimal solution:* inverse modeling is based on the minimization of an objective function, which can be performed by using several algorithms and methods. Many studies compared the search algorithms (Madsen, 2003; Wöhling et al., 2008; Efstratiadis and Koutsoyiannis, 2010) and concluded that a global optimization approach was more effective than local search optimization because it reduces the risk of being trapped in a local optimum during the optimization process. By definition, the multiple objective functions approach also allows a more complex constraint on the model which is preferred when the number of estimated parameters becomes important (Efstratiadis and Koutsoyiannis, 2010).

(ii) *Non-uniqueness solution:* dependency between hydraulic parameters leads to the existence of multiple set of parameters, which give equally satisfying simulations. This problem is known as equifinality (Beven, 1993). It is one of the major difficulties for the interpretation of parameters values, their comparison in time or in space, as well as the extrapolation of the model beyond the observed conditions. Multi-objective methods were proved to be satisfactory to reduce the non-uniqueness problem (Madsen, 2003; Bekele and Nicklow, 2007; Vrugt and Robinson, 2007) because they provide the trade-off of all the objective function used leading to Pareto-optimal set of solutions (Horn et al., 1994; Wöhling et al., 2008; Efstratiadis and Koutsoyiannis, 2010). The compromise solution representing the best fit to multiple aspects of the problem leads to the most behavioral hydraulic properties.

In Mediterranean mountainous catchments, thin but pervious soils and high rainfall intensities cause the water storage at the hillslope scale to be largely influenced by the bedrock permeability. Thus, different responses can be induced by the geological features of the bedrock, for example shale or granites (Vannier et al., 2013).

In addition, temporal variations of water content are the result of combined complex processes such as infiltration and evapotranspiration, among others. An event-based inverse modeling approach can reduce the processes to be taken into account in the temporal variation of the water content, by, for example, neglecting the evapotranspiration processes during the short rain events. Such method was proved to be efficient for rainfall–runoff modeling (Berthet et al., 2009; Tramblay et al., 2010).

This study aims to understand the influence of the weathered bedrock on the vertical water flow during high intensity rainfall events which lead to flash floods in the Cevennes region (Southeast of France). To do so, we need to determine the hydraulic properties of a mountainous sandy-loam soil and the schist substratum under it. Beyond the study case presented here, it is expected to get a method in order to explore furthermore a wide area still poorly documented, with respect to the hydrodynamic properties of the soils and their spatial variability. Inverse modeling is based on a multi-event based approach using the NSGA-II (Deb et al., 2002) multi-objective algorithm in order to avoid accounting for the evapotranspiration processes and to reduce the equifinality problem. In addition, special attention is paid to the estimation of the bedrock hydraulic properties and its influence on soil saturation and runoff.

1. Material and methods

1.1. Study area

The study area is a small plot about 420 m^2 located in Sumène (Fig. 1), 50 km north of Montpellier in the Cévennes mountains (43°58′55″N, 3°42′58″E). The plot presents a medium slope of 15% west oriented.

1.1.1. Soil properties

The soil is a thin Brunisol over schist bedrock. As represented in Fig. 2 (left), the five first centimeters consist in a C-org rich layer, followed by a thirty centimeters thick first mineral layer which contains lots of coarse fragments and roots. Finally, the lowest mineral layer is in contact with the bedrock. Soil thickness ranges from 60 to 90 cm down to the top of the schist bedrock across the plot. To estimate granulometry, 9 soil samples have been taken from 3 locations over the experimental plot. In every location, 3 samples have been taken at increasing depths: 5, 30, and 50 cm. The mean percentage of sand, silt, clay, and coarse fragments is shown in Fig. 2 (center). The soil is characterized by 30–37% of coarse fragments, and for the matrix component, 60–73% of sand, 20–27% of silt, and only 7–13% of clay.

Using 100 cm^3 steel cylinders, 7 soil samples have been taken from surface to 85 cm every 10 cm deep. The density ranges from 1.1 (in the first structural layer) to 1.5 g cm^{-3} due to the increase of coarse fragments, while porosity decreases from 0.50 to 0.40 cm^3 cm^{-3} (Fig. 2, right).

In order to get a direct estimation of the soil conductivity, we made 3 set of measurements using a tension disc infiltrometer (*SDEC SW080B* model). Two out of the 3 set of measurements were done at the soil surface, and the last one at 20 cm depth. The three near-saturated hydraulic conductivity estimations were 204, 208, and 219 mm h^{-1} with respectively last measured potentials -5, -3, and -1 mm.

1.1.2. Soil water content data

Soil water content was monitored by 3 Theta-probe ML2-X sensors installed at 3 depths: 20, 40, and 60 cm. In the neighboring of the probes, the soil depth is around 70 cm. Probes were spaced approximately 50 cm apart sideways to limit the vertical water flow disruption. Volumetric soil moisture (θ) values was derived from the soil dielectric capacity using the following equation given by the constructor (Delta-T devices Ltd, 1999):

$$\theta = \frac{[1.1 + 4.44V] - a_0}{a_1} \quad (1)$$

with θ the volumetric water content (cm^3 cm^{-3}), V the output voltage of the probe (V), a_0 and a_1 two calibrated constant (–).

The probes are calibrated by the constructor and generally need to be adjusted. But, thanks to the large majority of mineral particles in the studied soil, the calibrated parameters obtained oncore samples were very close to the original calibration so we choose to directly use the constructor calibration for mineral soil.

Water contents were monitored at a 15 min time step during three years from 2008 to 2010. The example of year 2008 exhibits a strong contrast between very dry soil during hot summer and