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Functional evaluation of PTF prediction uncertainty: An application at hillslope scale

G.B. Chirico [a,*], H. Medina [b], N. Romano [a]

[a] Department of Agricultural Engineering, University of Naples Federico II, Naples, Italy
[b] Agrarian University of Havana, Havana, Cuba

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ABSTRACT

This study presents a methodology to assess uncertainties resulting from the use of pedotransfer functions (PTFs) when soil water budget is modelled at a hillslope scale. Two sources of uncertainty are examined: (i) errors in the assessment of the soil physical and chemical properties at unsampled locations, as related to the spatial spacing of the sample measurements across the entire study area, and (ii) errors associated to the PTF relations and parameters. This methodology is applied to an experimental hillslope in Southern Italy, where an intensive field campaign has been conducted to gather several soil physical and chemical properties and soil hydraulic properties. A sequential Gaussian simulation algorithm is used to generate multiple equally probable images of PTF input soil data, consistent with the estimated spatial structure and conditioned to the measured soil core properties. Two PTFs commonly used in Europe, Vereecken's PTF [Vereecken, H., Diels, J., van Orshoven, J., Feyen, J., Bouma, J., 1992. Functional evaluation of pedotransfer functions for the estimation of soil hydraulic properties. Soil Sci. Soc. Am. J. 56, 1371–1378] and HYPRES PTF [Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90, 169–185] are applied to predict the soil hydraulic properties, which in turn are employed into a soil–vegetation–atmosphere model to evaluate the propagated uncertainty in simulated target variables, such as evaporation, transpiration and root zone soil water content variation during a wet-to-dry transition season. The outcomes of this case study suggest that accurate estimates of transpiration and soil water storage variation at the hillslope scale are obtained even when PTF input data are collected with a relatively coarse sampling strategy. The examined PTFs show worse level of performance with respect to the simulated evaporation. The simulated evaporation is much more affected by the PTF model error than by the input data error. A major implication of these results is that if one would reduce the prediction uncertainty in simulated evaporation, the PTF model structure has to be improved prior of reducing the uncertainty into the PTF input data.

1. Introduction

Modelling soil hydrologic processes across different landscape elements is of prime importance for many studies applied to environmental and land-use planning problems. Nevertheless, the application of soil hydrological models at large spatial scales is often limited, mainly because it requires the determination of soil hydraulic parameters that are unfeasible to be assessed by direct observations over relatively large land areas. Pedotransfer functions (PTFs) are being developed as simplified methods to assess soil hydraulic parameters from soil physical and chemical properties which are much less laborious and expensive to determine and more routinely measured than the actual soil hydraulic properties (Bouma, 1989).

The application of a simpler method, such as a PTF compared to a direct measurement, generally involves a cost in terms of increased uncertainty in the predictions. Therefore, an important aspect that needs consideration when a simpler method is applied, is to assess whether the increase of uncertainty is acceptable, given the objectives of the research or the type of decisions that are to be made.

Nowadays, the uncertainty analysis is becoming fundamental in applications which are employed for assessing environmental risks and guiding decision makers in planning mitigation strategies. Uncertainty analysis is also useful for model developers, who need to evaluate the performance of different modelling strategies, assess the main sources of prediction uncertainties and identify the priorities to be followed within a research program aiming at improving the overall model performance.

Model prediction uncertainties arise from errors in evaluation data, input variables, and model structure and parameters. At the local scale, error in input variables can be originated by measurement errors. Minasny et al. (1999) analysed the uncertainty in water retention predictions at local scale, accounting for both measurement errors in

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[*] Corresponding author. Dipartimento di Ingegneria Agraria, Università degli Studi di Napoli Federico II, Via Università, 100, 80055 Portici, Napoli, Italy. Tel.: +39 081 2539415; fax: +39 081 2539412.
E-mail address: gchirico@unina.it (G.B. Chirico).

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input variables and uncertainties in PTF parameters. They showed that the predictions are much more affected by errors in input variables than by the errors in model parameters.

From a practical perspective, one is interested in evaluating the PTF prediction uncertainty at relatively larger scales, i.e. at the hillslope or catchment scales, since these are the scales at which PTFs result as prime alternatives to direct measurements. At non-local scale, the uncertainty of the input variables due to local measurement errors is enhanced by the uncertainty in their spatial variability. Since PTF input variables are observed only in a limited number of locations, the assessment of the input variables at unsampled locations can be achieved only by interpolation. However, the results of any interpolation procedure are affected by uncertainty. Chirico et al. (2007) explored the uncertainty in PTF model predictions at the hillslope scale due to the error in the estimated soil physical and chemical properties at unsampled locations and to the PTF model error, including both model structure and parameter errors. The uncertainty of the predicted soil water retention function due to the PTF model error resulted as much as or more significant than the uncertainty associated with the estimated input variables, even for a relatively coarse sampling resolution. Moreover, the study showed that the uncertainty in the predicted saturated soil hydraulic conductivity is dominated by the model error, while the contribution of the input errors is negligible.

Determining soil hydraulic properties is not in itself the aim of hydrological applications, rather it is essential for simulating water flow and transport processes in the unsaturated soil zone. Thus the uncertainty analysis should be extended toward evaluating the propagation of PTF prediction uncertainties in the results of specific applications. This type of analysis is equivalent to a “functional evaluation” of PTFs, as firstly proposed by Wösten et al. (1986) and then applied by quite a few studies focused on local-scale analysis. Vereecken et al. (1992) assessed the effect of the PTF prediction error in a model of soil water dynamics. Cresswell and Paydar (2000) evaluated the performance of different methods for estimating soil hydraulic properties in Australia, by comparing the cumulative evapotranspiration and drainage simulated with a soil water budget model over a 5 year period for 66 different soil horizons. Christiaens and Feyen (2001) used a Latin Hypercube sampling strategy to evaluate how the uncertainties in the predicted soil hydraulic properties propagate into the output of a distributed model applied to a 1 km^2 catchment, assuming homogenous soil properties within land units. Minasny and McBratney (2002b) evaluated how measurement errors of the PTF input variables affect the uncertainty in the simulated soil water budget. They concluded that the soil water budget is more sensitive to input uncertainties during dry periods rather during wet periods.

This study extends the analysis of Chirico et al. (2007) in a functional way, to assess how the simulated soil water budget is affected by uncertainty when PTFs are used to estimate the soil hydraulic parameters at the hillslope scale. The paper is structured as follows. The overall method is described in the next section. The experimental hillslope and sample data are discussed in the third section, whereas the soil water budget model is presented in the fourth section. The fifth section describes the procedure followed for representing the uncertainty of the soil hydraulic parameters predicted with PTFs across the experimental hillslope. The sixth section analyses the propagated uncertainty in the simulated soil water budget components. The last section is devoted to the conclusions.

2. Method

The overall methodology is structured in two stages (see Fig. 1). The first stage is focused on the stochastic generation of patterns of soil hydraulic functions across the hillslope. The second stage is focused on the soil water budget modelling and on the analysis of the propagated PTF prediction uncertainty into the simulated soil water budget components.

The first stage has been developed by Chirico et al. (2007). Data collected along an experimental hillslope transect, together with terrain attributes taken as ancillary information, are employed to identify the spatial structure of the PTF input variables. Hereinafter, the PTF input variables are named “basic soil properties”, while an ensemble of patterns representing the basic soil properties across the hillslope is named “set of basic soil properties”. A multivariate geostatistical analysis is carried out to identify the structure of the spatial variability of the basic soil properties at the support scale of the soil samples, while choosing the hillslope as spatial extent. The deterministic component of the spatial variability is first identified, accounting for the correlation of the soil properties with the terrain attributes through linear regressions. The residual stochastic component is then derived accounting for the auto- and cross-correlation of the basic soil properties.

Then a multivariate stochastic simulation is performed for generating a high-resolution set of basic soil properties, hereafter referred to as the “full dataset”. The simulation is performed on a spatial domain corresponding to the hillslope surrounding the experimental transect. The stochastic component identified along the experimental transect is assumed stationary across the entire study hillslope. The deterministic component is computed according to the hillslope terrain through the regression rules identified along the transect.

The “full dataset” is generated as conditioned to the values observed across the hillslope transect. The conditional simulation is performed by employing the Gstat software package on S (R/S Plus) (Pebesma, 2004). The generation of independent realizations in the Gstat package is carried out from a sequential simulation algorithm (Gómez-Hernández and Journel, 1993).

The full dataset is taken as the true representation of the hillslope soil variability and is considered as reference “measured” set of basic soil properties for the subsequent uncertainty analysis. Since the major aim of this study is to quantify the propagation of the PTF prediction uncertainty due to both PTF model error and input estimation error from sparse samples, the full dataset is sampled and multivariate stochastic simulations are then performed to generate sets of basic soil properties conditioned to these sparse samples. These stochastic simulations are employed to describe the PTF input uncertainty associated to the assessment of the unknown input variables at unsampled locations by interpolation of sparsely measured values. The realisations of the PTF input variables are then employed to perform Monte Carlo simulations of the soil hydraulic properties to be used as parameters for the subsequent runs of the soil water budget model. The support scale of the input realisations corresponds to the support scale at which the soil water budget model is applied.

Each generated set of basic soil properties is named as “image” of the “full dataset”. The full dataset and its images are translated into patterns of soil hydraulic functions by applying PTFs.

At the end of the first stage, three types of soil hydraulic functions are available for the subsequent simulations: 1) soil hydraulic functions derived from observations along the experimental transect, referred to as “observed soil hydraulic functions”; 2) soil hydraulic functions derived by applying PTFs to the full dataset, considered as “measured” basic soil properties across the entire hillslope, referred to as “indirect soil hydraulic functions”; 3) soil hydraulic functions derived by applying PTFs to the images of the full dataset, referred to as “image soil hydraulic functions”.

The study conducted in the second stage is the main advance with respect to what has already been presented in Chirico et al. (2007). A soil water budget model is executed across the entire hillslope in order to evaluate the propagation of the PTF input errors and model error into the simulated soil water budget. The above patterns of hydraulic functions are employed for parameterising the soil water budget model, while the initial and boundary conditions as well as the vegetation cover and