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Prediction of soil water retention using soil physical data and terrain attributes

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Abstract

Characterization of soil hydraulic behavior at large scales using traditional methods is time-consuming and very costly. Efficient and cheap means of providing hydrological models with such information are procedures based on pedotransfer functions (PTFs) that estimate soil hydraulic parameters from easily measurable or already available soil physical data. Major objectives of this study are to compare the prediction performance of some published PTFs and to improve their predictive capability by accounting for certain landscape variables, such as slope, aspect, and wetness index, for example. This additional information can be easily extracted from a digital elevation model of the area under study. While topographic attributes have shown potential for mapping soil properties over a region with higher precision and simplifying estimation of some model parameters, the challenge is also to examine whether, and to what extent, ancillary data of this kind can specifically contribute to improve the predictions of soil hydraulic characteristics. Since the most recent distributed hydrological models rely even more on an accurate representation of landscape features, improving PTFs with the inclusion of topographic variables is in line with this tendency. Statistical indices of goodness-of-fit are calculated to evaluate the effectiveness of the proposed methodology. It is shown, for example, that systematic biases in water retention predictions from an original PTF can be conveniently corrected by adding some primary or compound terrain attributes. The results confirm the role of terrain variables in assessing the spatial patterns of soil hydraulic characteristics. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Unsaturated soil; Water retention; Pedotransfer function; Digital elevation model; Terrain analysis

1. Introduction

The emerging importance of hydrological studies at the scale of hillslopes and small catchments has brought about increased interest in cost-effective but reliable characterization of unsaturated soil hydraulic behavior. The hydrologic community has recognized the crucial role exerted by soil in the hydrological cycle. This is chiefly because soil controls the partitioning of incident water in runoff and infiltration, but partly because soil water flow phenomena (e.g. infiltration into the soil, redistribution of water in soil, evaporation from land surface) evolve over time at different and varying rates allowing the soil to fulfill the valuable function of storage of water with its dissolved nutrients and thus to meet the water demand of growing plants during periods of precipitation shortage. Some hydrologic models exploit this

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buffering capacity of soil to simplify the complexity of processes taking place in the unsaturated zone of the system.

Without falling into the large debate between conceptual/physically-based and lumped/distributed models, it suffices to say that most mathematical models of hydrological processes synthesize the hydraulic behavior of soil using nonlinear relationships between the volumetric soil water content, θ, the matric pressure head, h, and the hydraulic conductivity, K (Hillel, 1998). Usually these relationships are the soil water retention, $\theta(h)$, and hydraulic conductivity, $K(\theta)$, functions that are often referred to as the soil hydraulic properties and conveniently described by closed-form parametric expressions (Leij et al., 1997).

Many laboratory and field methods have been developed to determine the soil hydraulic properties, but none of them perform well in a wide range of circumstances and for all soil types. In one category we can comprise the direct and inverse methods. Direct methods are notoriously expensive and burdensome. Inverse methods represent a natural evolution and extension of the direct methods, although their use still require some time and expertise (Hopmans et al., 2002). The major extension is that they provide, at least in principle, more degrees of freedom in selecting suitable experimental conditions and permit the simultaneous estimation of the soil water retention and hydraulic conductivity functions by processing the data gathered during a single experiment. Both these approaches provide accurate descriptions of the functions $\theta(h)$ and $K(\theta)$ and are very effective for analyses at point scale (e.g. the scale of an undisturbed soil core or a field plot). Although a few investigations have also focused on the use of these methods for spatial variability studies, for instance in conjunction with geostatistics (Ciollaro and Romano, 1995; Vereecken et al., 1997), there is the perception that even the more flexible inverse methods become inefficient when the hydraulic properties of unsaturated soil zone have to be determined at larger scales, such as hillslopes or small catchments.

Predictive methods have been proposed to identify key parameters affecting soil water flow in the unsaturated zone from more easily measured and accessible soil variables. These methods were originally proposed as approaches for inferring the hydraulic conductivity characteristic, which is difficult to determine chiefly because of its strong nonlinear dependence on water content, from knowledge of the soil water retention curve whose measurement requires rather simple instrumentation and relatively easy calculations. Some predictive methods rely upon direct observations of soil water content over a range of matric pressure heads to indirectly estimate the hydraulic conductivity function. As an alternative, recently developed procedures, such as the pedotransfer functions (PTFs), relate both the water retention and hydraulic conductivity functions to some more easily measured soil physical and chemical properties, such as texture, oven-dry bulk density, porosity, organic carbon content (Tietje and Tapkenhinrichs, 1993; Tietje and Hennings, 1996; Elsenbeer, 2001). The majority of PTFs are regression equations that are derived from data collected during site-specific field campaigns and have demonstrated their ability to predict soil hydraulic data at many positions over a region with acceptable precision compared to the costs of investigation.

The concept of a general pedotransfer rule appears promising, although most efforts have been undertaken to develop empirical relationships for particular data sets (e.g. Rawls and Brakensiek, 1989; Vereecken et al., 1989). Bastet et al. (1999) stated that PTFs should be employed with confidence only within restricted ranges of soil types and environmental conditions. In an attempt to avoid this shortcoming, new sets of PTFs are being established that benefit from information stored in comprehensive databases, such as those developed at European scale (Wösten et al., 1999) or in Australia (Minasny et al., 1999). Discrepancies between the actual and predicted soil hydraulic parameters should be viewed as a price to be paid when simplified approaches are utilized against more accurate, but much more expensive and burdensome methods. However, the subject of validating existing PTFs is fundamental but lacking, especially when the PTF-predictions are intended as input data for simulation models.

Apart from requiring detailed site characterization, reliable process-based hydrological modeling has also highlighted the need to deal with spatial variability issues, as horizontal variations in soil hydraulic properties exert a significant influence on the exchange of water fluxes between the different parts on the system (for example, evapotranspiration fluxes toward the atmosphere, or recharge fluxes toward the groundwater table). Geostatistics or, more recently, stochastic simulation techniques can be employed to analyze the spatial structure of soil hydraulic properties and to calculate values at unsampled nodes of the superimposed numerical grid. Quantitative information on spatial variability is also valuable for assessing 'equivalent' grid-scale parameters, which can be defined as areally averaged values over the selected numerical grid square or elementary portion of the landscape.

Therefore, a serious problem is whether the simplified methodology looses precious information and becomes unable to correctly represent soil behavior in particular locations of the area. As a result, the observed discrepancies between actual and predicted soil hydraulic properties may obscure any actual spatial dependence, so result in unsound maps. Ideally, the spatial fluctuations of the predicted values should mimic those exhibited by the actual values and preserve data properties such as the sample histogram or the variogram model. On the other hand, a simplified methodology should at least provide a realistic value of the average soil hydraulic behavior over the region of interest. Contributions to these questions are scarce in the literature, and little attention has been paid to practical applications of PTF predictions as well as to consequences of PTF-prediction uncertainties in hydrologic modeling issues. Romano and Santini (1997) showed that the spatial series of water retention data points generated by some published PTFs from data gathered along a transect hillslope led to shapes of their probability distributions that differ, in some cases markedly, from those relating to the measured water retention values. They also found that only a few of the PTFs tested were able to represent the average soil water retention behavior of the study area. Even though biases in the PTF-predictions were detected, the subsequent variogram analysis showed the potential of the pedotransfer approach to provide quantitative information on the structure of spatial variations.

Among the various soil-forming factors, topography exerts a significant control on hydrological, geomorphological, and biological processes active in the landscape at the hillslope scale and can explain a good amount of spatial variability at this scale. Moore et al. (1991) discussed the rationale behind the existence of relationships between hydrological and erosional processes occurring in a certain area and some relevant topographic attributes, such as elevation, slope gradient, slope aspect, plan and profile curvature. Moore et al. (1993) then employed these relations to enhance an existing soil map. Different statistical procedures, from multiple-linear regression to more advanced regression-kriging type methods, were compared to find the optimal prediction of soil properties from terrain attributes and other ancillary information (Odeh et al., 1994, 1995). More recently, a number of authors directed their research towards effectively characterizing the spatial variability of surface soil water content and understanding how, and to what extent, topography may influence this variability. Famiglietti et al. (1998) characterized the spatial variability of near surface soil water contents along a transect and found that the impact on spatial variations resulting from topography was more evident under drier than wetter soil conditions. Western et al. (1999b) laid great stress on the degree of spatial organization exhibited by the patterns of water contents in soil, arguing that reliable hydrologic responses of a catchment may depend on a suitable representation of such an organization. They also acknowledged the role of topography in predicting this spatial organization. Overall, the widespread recognition that seasonal changes in soil water content patterns, and hence water flow pathways, are controlled by catchments morphology has given impetus to the development of even more sophisticated hydrological models based on terrain analysis (Western et al., 1999a).

In view of these general statements and the papers reviewed above, it is our belief that the use of topographic information as ancillary data not only can meet the important requirement to pick the average soil hydraulic behavior correctly, but also can describe more efficiently the actual spatial distributions of the hydraulic variable of interest. Since PTFs take only a limited number of explanatory static variables into account and, as a result, may capture with difficulty the inherent dynamic behavior of a soil hydraulic characteristic, there remains considerable interest in including variables that appear somewhat more involved in dynamic rather than static processes. In addition, establishing a link between landform features and soil hydraulic properties predicted by PTFs seems a consistent and operational way to account for those parameters that are still easy to measure or retrieve from existing databases.

Topographic information is generally given in the form of a digital elevation model (DEM), which is an ordered array of numbers representing the spatial distribution of the elevations above some arbitrary datum level being associated to geographical locations. A DEM can be considered as a subset of a digital terrain model (DTM) comprising ordered arrays of numbers that represent the spatial distribution of terrain attributes (Moore et al., 1991). The increasing availability and recent advances in quality of DEMs foster the development of new research activities. Digital terrain analysis can provide a systematic basis to calculate topographic attributes and relate them to soil hydraulic characteristics. To the authors' knowledge, Palladino et al. (2000) were the first who explored the feasibility of gaining better PTF-predictions of soil water retention characteristics by taking terrain attributes also into account.

The general aim of our current investigations on this subject is to integrate and expand the results of Romano and Santini (1997) and Palladino et al. (2000). The focus of the present paper is on using terrain attributes as auxiliary variables to determine soil water retention functions and show whether this approach can improve the average description of soil hydraulic behavior over a certain area. A subsequent paper will tackle spatial variability issues in more detail. Therefore, specific objectives of this paper are (i) to analyze the performance of some PTFs when applied along hillslopes with different soil-landscape units, and (ii) to further examine the feasibility of enhancing the predictive capability of PTFs using topographic information retrieved from a DEM. If the approach is successful, it can provide a systematic basis to attach the predictions offered by PTFs to a specific environment. Although the procedure developed in this work should be considered of general extent and basically serve as a framework, we will specifically show results for the water retention properties of soils. This is also partly due to the fact that to date the more reliable PTFs available in the literature refer to this soil hydraulic characteristic.

2. Methods and experimental work

2.1. Site description and data sets

The research site is the catchment of River 'Fiumarella di Corleto', which is located in Basilicata Region, Italy, and has a drainage area of approximately 32 km^2 (see Fig. 6). The environment has a dynamic geomorphology and interesting features from the soil-landscape modeling viewpoint (Santini et al., 1999). East and west sides of the Fiumarella River show different geologic features and this occurrence also influences the morphology of the related hillslopes. Mostly, the catchment area shows facies of the Gorgoglione Formation of Middle Miocene. The basement is an arenaceous flysch, consisting of massive feldspathic–quartzitic sandstones, generally graded in banks and layers that are contained in finely stratified, feldspathic–quartzitic clays. Because of the miocenic transgression, the flysch was mainly generated by debris flows caused by slumps. Deposits of such mass movement lay down on shale clays having gray-yellowish color and being part of the 'Corleto Perticara' Formation (Eocene). Land-uses in the Fiumarella catchment underwent major changes during the last decades, mainly along the east side of the catchment. Grass and horticultural crops prevailed up to 1955, the only exception being the wood areas. Later on, many lands were abandoned giving thus place to shrubs, partly because of the 'set-aside' policy adopted by the European Union. Two pedological pits were dug in each of the main soil-landscape units (see the caption of Fig. 6) and hundreds of hand augerings were sampled in the catchment. Soil profiles were described according to the Soil Survey Manual (SSDS, 1993). Soils in the 'Fiumarella di Corleto' catchment ranged from Vertisols to Mollisols, Inceptisols and Entisols. The soil-landscape units presented in the paper refer to the 'Keys to Soil Taxonomy' system (SSDS, 1998), partly because this classification system is widespread in Italy.

The data used in this paper were obtained along two linear transects established at the opposite sides of the stream channel of Fiumarella river. Looking in the downstream direction, one hillslope transect was located on the right catchment side and oriented in the NW/SE direction, whereas the other transect run along the left catchment side and had a NE/SW direction. Both transects run from about 770 m above mean sea-level near the Fiumarella river, to about 1200 m above mean sea-level. Along the right-side transect from upslope to downslope, the following main soil-landscape units were identified: rounded ridges on clay and marl rocks (CAM), hillslopes on arenaceous clay flysch (VAR), slightly unstable hillslopes on clay flysch (VAS). The following main soil-landscape units were identified from upslope to downslope along the left-side transect: sharp ridges on arenaceous flysch (CAR), strongly unstable hillslopes on clay flysch (VAI).

Undisturbed soil cores (7.2 cm in diameter and 7.0 cm in length), spaced 50 m apart, were collected along the transects at depths from 5 to 12 cm. Specifically, sampling consisted of taking $N_{\mathrm{right}} = 45$ undisturbed soil cores from the right-side transect and $N_{\mathrm{left}} = 43$ from the left-side transect, for a total of $N = 88$ undisturbed soil cores. All cores were subjected to laboratory measurements to determine the particle-size distribution, organic carbon content, and soil water retention characteristics. The cores were oven-dried at 105 °C to determine dry bulk density, ρ_b. Total porosity was calculated from the measured oven-dry bulk density assuming that particle density is 2.65 g cm^{-3}. Organic carbon in soil was determined with the dichromate method, whereas organic matter content, OM, was calculated by multiplying the organic carbon content by 1.724. Sand, silt, and clay contents were expressed as percentage by mass of the fine-earth fraction (<2 mm) and soil texture was identified according to the USDA soil classification. Drying water retention data points $\theta(h)$ were measured at several matric pressure heads using a recently designed suction table apparatus (Romano et al., 2002).

To allow comparisons between the measured and predicted $\theta(h)$ curves, in the present paper we shall further assume that the soil water retention function for each soil sample is described by van Genuchten's closed-form relationship (hereinafter referred to as the VG relation)

$$\theta(h) = \theta_r + (\theta_s - \theta_r)[1 + |\alpha h|^n]^{-m} \quad (1)$$

where θ_s and θ_r are the saturated water content and residual water content, respectively, whereas the VG parameters α, n, and m control the shape of the soil water retention curve. By imposing the condition $m = 1 - 1/n$, Eq. (1) is defined by the unknown parameters θ_s, θ_r, α, n, which were estimated using the RETC software package (van Genuchten et al., 1991). For all of the collected soil cores the VG relation (Eq. (1)) fitted the observed retention data points very closely, and therefore the fitted water retention curves represent a consistent and relatively unbiased information for comparison purposes.

2.2. Pedotransfer functions and terrain attributes

PTFs employed in this study are those that predict soil hydraulic characteristics by means of empirical regression equations with combinations of soil physical and chemical properties: primarily, texture, bulk density, and organic matter (Wösten et al., 2001). While predictions of the water retention functions of soils using the pedotransfer concept is a relatively well established procedure, the assessment of unsaturated hydraulic conductivity is still uncertain (Tietje and Hennings, 1996; Sobieraj et al., 2001).

Tietje and Tapkenhinrichs (1993) suggested splitting the existing PTFs into two major groups: point regression methods and functional parameter regression methods. The point regression methods comprise those PTFs that predict selected points of the soil water retention function. These methods usually provide relatively larger errors than the functional parameter regression methods and can also generate unreliable water retention data points, namely for certain PTFs of this group it was found that some water content values increase when matric pressure heads decrease. In contrast, the functional parameter regression method inherently assumes that the soil water retention characteristic $\theta(h)$ is described by a closed-form parametric relationship. Therefore, PTFs that belong to this method appear as a set of empirical regression equations relating the unknown parameters of the selected $\theta(h)$ function to soil physical and chemical properties.

In the present study, we shall evaluate the proposed procedure by using three published PTFs for $\theta(h)$ that are functional parameter regression methods: (1) the PTF-HYPRES developed from European soil data (Wösten et al., 1999), (2) the PTF of Rawls and Brakensiek (1989), referred to hereinafter as PTF-RB, and (3) the PTF of Vereecken et al. (1989), referred to hereinafter as PTF-VER. Parametric equations defining these PTFs are not reported here for the sake brevity, but readers are directed to the cited publications for details. To make comparisons with the VG relation easier, the Smith modification to the analytical structure of PTF-RB was adopted (Tietje and Tapkenhinrichs, 1993). Palladino (2000) also analyzed the results obtained from some PTFs pertaining to the point regression approach.

Terrain attributes can be divided into primary and secondary (or, compound attributes). Primary attributes include variables such as elevation, slope and aspect, plan (across-slope) and profile (down-slope) curvature, flow path lengths, and specific catchment area. Slope, measured in degrees, represents the slope in the direction of the steepest ascent or descent from a fixed location and it is thus the first-order derivative of the topographic surface. A second-order derivative is, for instance, the profile curvature at a certain location, which represents the rate of change of slope in the direction of the steepest ascent or descent from that location and indicates a locally concave surface when it assumes a positive value. Secondary attributes involve combinations of the primary attributes and can be used to characterize the spatial patterns of specific processes occurring in the landscape (Moore et al., 1991). Therefore, a secondary attribute acts as a sort of topographic index that provides a knowledge-based approach to specific soil management and can be conveniently embedded within the data analysis module of a geographical information system (GIS). As many GISs are based on a raster structure, grid-based methods of terrain analysis can easily provide primary geographic data for GIS applications. Typical secondary terrain attributes are: wetness index, stream power and sediment transport capacity indices, and potential solar radiation index (Beven and Kirkby, 1979; Moore et al., 1993).

In this study, terrain attributes were calculated by digital terrain analysis using the GRASS-GIS environment. Various GRASS routines were used to obtain the terrain attributes and indices (Mitášová and Hofierka, 1993). Elevation data for the study area were provided in a digital format by Military Geographic Institute of Italy (IGM). Although we tested the proposed procedure using two different grid resolutions (25 and 50 m), the results of this study refer only to the 25-m grid-based DEM. The primary terrain variables employed in this study are: elevation (cm, above mean sea level), slope angle (degrees; 0–90°), aspect angle (degrees, counter-clockwise from East; 90° to the North, 180° to the West, 270° to the South, and 360° to the East), plan curvature, profile curvature, tangential curvature, distance from the middle stream (cm), downward or upward flow-path lengths (cm), specific contributing area ($\mathrm{m}^2\,\mathrm{m}^{-1}$). Curvatures are positive for convex and negative for concave areas; original curvature values are multiplied by a factor of 10^5. We used the following compound topographic indices: wetness index, $\mathrm{wi} = \ln(a/\tan\beta)$, where a is the cumulative upslope area draining through a point (per unit contour length) and β is the surface slope at the point (Beven and Kirkby, 1979), and amount of direct solar energy for a given day of the year, kw, which is computed by integrating the illumination angles between sunrise and sunset times for given day (Moore et al., 1993). For calculating the kw-index, the time step is 1 h and as reference day we selected an average day within the period in which the soil sampling campaign was carried out. Only correlations and relationships between topographic attributes and soil variables measured at topsoil were explored.

2.3. Method description

Let $\theta(h)_{\mathrm{VG}}$ be the soil water retention function described by Eq. (1) and fitted to the measured soil water retention data points using the RETC computer program. Let us also assume this function represents the observed soil water retention property at one generic position of the study transects. The soil water retention function $\theta(h)_{\mathrm{VG}}$ can be interpreted as a probabilistic process

$$\theta(h)_{\mathrm{VG}} = \theta(h)_{\tau} + \varepsilon(h) \tag{2}$$

which has a deterministic component $\theta(h)_{\tau}$, defined by a pedotransfer rule (for example, the PTF-VER proposed by Vereecken et al., 1989) together with terrain information, and a stochastic component $\varepsilon(h)$ accounting of both random and systematic errors since both measurement errors and model errors contribute to produce noises in the data. The residual $\varepsilon(h)$ can be spatially uncorrelated (white noise) or may exhibit explicitly some degrees of spatial correlation.

The method employed in this paper to incorporate landscape features into pedotransfer predictions supposes that the residual between $\theta(h)_\tau$ and the original PTF-predicted soil water retention function, $\theta(h)_{\mathrm{PTF}}$, is modeled by the following polynomial expression:

$$\theta(h)_\tau - \theta(h)_{\mathrm{PTF}} = \sum_{j=1}^{t} a_j \tau_j \tag{3}$$

where τ_j denotes independent variable representing the generic terrain attribute (for example, slope or plain curvature) and a_j is the coefficient of variable τ_j. Specifically, as the soil water retention function (Eq. (1)) is described by the set of four parameters θ_s, θ_r, α, and n, we pose:

$$\begin{cases} \theta_{s,\tau} = \theta_{s,\mathrm{PTF}} + \sum_{j=1}^{t} a1_j \tau_j \\ \theta_{r,\tau} = \theta_{r,\mathrm{PTF}} + \sum_{j=1}^{t} a2_j \tau_j \\ \alpha_\tau = \alpha_{\mathrm{PTF}} + \sum_{j=1}^{t} a3_j \tau_j \\ n_\tau = n_{\mathrm{PTF}} + \sum_{j=1}^{t} a4_j \tau_j \end{cases} \tag{4}$$

where the subscript PTF means that the specific retention parameter is calculated using the pedotransfer algorithm as originally proposed by their authors. The unknown coefficient values appearing in Eq. (4) are determined by minimizing a performance-based objective function of the form:

$$\mathrm{OF}(\mathbf{a}) = \sum_{i=1}^{N} \left\{ \frac{1}{(\xi_u - \xi_l)} \int_{\xi_l}^{\xi_u} [\theta(\xi)_{\mathrm{VG}} - \theta(\xi;\mathbf{a})_\tau]^2 \, \mathrm{d}\xi \right\}_i \tag{5}$$

that accounts for the discrepancies between the observed, $\theta(\xi)_{\mathrm{VG}}$, and the predicted, $\theta(\xi;\mathbf{a})_\tau$, soil water retention function, with $\xi = \log(|h|)$ and $\mathbf{a}$ being the vector of unknown polynomial coefficients $a1_j$, $a2_j$, $a3_j$, and $a4_j$. The summation term is extended to the whole dataset of available retention functions, with index i representing the ith soil sample collected along the transects. The function in the right-hand side of Eq. (5) is integrated between the lower limit $\xi_l = \log(|-1\ \mathrm{cm}|) = 0.00$ and the upper limit $\xi_u = \log(|-16{,}000\ \mathrm{cm}|) = 4.20$. Solving the nonlinear problem of minimizing the objective function OF($\mathbf{a}$) is accomplished using the trust region method of Moré (1983), which is a version of the well-known Levenberg–Marquardt's iterative algorithm. Although computationally more expensive than, for instance, the Gauss–Newton method, the trust region approach uses an approximation of the Hessian matrix and a search algorithm that provides global convergence capabilities, in the sense that the code converges to a stationary point of the objective function for every starting vector $\mathbf{a}_0$. Once the minimum $\mathbf{a}_{\mathrm{opt}}$ is found, an approximation of the posterior covariance matrix for the polynomial coefficients a_j is found according to the Cramér–Rao theorem (Bard, 1974). This matrix enables the reliability and correlation among the estimated coefficients to be assessed. The optimizations were run with constraints on the soil hydraulic parameters according to the type of PTF being examined. For instance, in the case of PTF-HYPRES whose parameters have the same meanings as those of the VG relation, we imposed $\theta_r \geq 0$ (fixing this parameter at zero if $\theta_r < 0.0001$), $0.01 \leq \alpha \leq 100\ \mathrm{cm}^{-1}$, and $1.05 \leq n \leq 5.0$.

3. Results and analyses

Table 1 summarizes the statistics for soil physical variables measured in the study area and used as input for the PTFs. Statistics are presented first for the two transects separately, and then for the whole measured data set. Mean values of the particle-size fractions are virtually the same for both right-side and left-side transects. The two transects appear slightly different with respect to mean bulk density, ρ_b, and particularly for percent organic matter content. The mean OM-value of the right-side transect is about double that of the left-side transect and this mainly reflects the different land-uses over the two hillsides. More naturally vegetated areas are located along the right-side transect than the left-side transect, which instead shows a predominance of cultivated zones subject to tillage practices ranging from no tillage to deep plowing. The fact that the variance of OM for the right-side transect is nearly two times greater than that for the left-side transect also confirms the above

Table 1
Summary statistics for soil physico-chemical variables measured along the study transects

Statistical index	ρ_b (g cm^3)	US clay (%)	US silt (%)	US sand (%)	OM (%)
	Right-side transect				
Min	1.003	15.05	33.84	8.776	3.610
Max	1.466	47.44	52.20	48.42	14.36
μ	1.193	32.04	43.48	24.48	6.016
σ	0.1075	8.670	4.123	8.979	2.071
CV%	9.01	27.06	9.48	36.69	34.43
	Left-side transect				
Min	1.012	18.24	36.08	8.300	1.430
Max	1.577	50.15	57.05	37.55	6.090
μ	1.338	32.87	45.24	21.89	3.038
σ	0.1151	7.221	5.509	7.050	1.100
CV%	8.60	21.97	12.18	32.21	36.21
	All data				
μ	1.264	32.45	44.34	23.21	4.561
σ	0.1325	7.960	4.902	8.153	2.235
CV%	10.48	24.53	11.05	35.13	49.01

Min = minimum; Max = maximum; μ = mean; σ = standard deviation; CV% = coefficient of variation (in %).

comment and indirectly shows a homogenizing effect exerted by long-term plowing on the physical properties of the uppermost soil horizons. Note that the influence of different plowing practices on water retention characteristics for a soil widespread in the area was investigated by Santini et al. (1995).

Basic statistics of the observed soil water retention data and those predicted by the original PTFs are reported in Table 2 for water content θ at selected pressure heads of -0.1, -1, and -10 m, referred hereinafter to as $\theta_{-0.1}$, θ_{-1}, and θ_{-10}, respectively. This table also offers a comparison between statistical indices calculated for both the single transects and the whole data set. In terms of CV%, the water retention spatial series observed along the right- and left-side transects behaves similarly and, as often reported, the coefficient of variation increases when pressure head decreases, namely moving from wetter to drier soil conditions. Overall, CV%-values of the observed $\theta(h)$ data range approximately between 8 and 16% and can be considered as typical for this hydraulic property. Table 2 shows results of the statistical *t*-test conducted at 10% level of significance (5% in each tail) to check whether or not the two sets of soil water retention data have different means. The *t*-test was performed after having verified the condition of homoscedasticity or heteroscedasticity of the data sets, and footnote ‘a’ refers to PTF-predicted data whose means should not be considered as statistically different from those observed. PTF-HYPRES performs satisfactorily with respect to the considered water retention data sets: the single set of $\theta(h)$ data observed and predicted along the right-side transect seem to belong to the same population, whereas only variables θ_{-1} and θ_{-10} relating to the whole data sets show equality of the mean values. PTF-RB and PTF-VER do not show a sufficient level of performance and in most cases these PTF-predictions are on average different from the observations. Moreover, PTF-HYPRES and PTF-VER both tend to smooth somewhat the variability of the data around their mean values. Romano and Santini (1997) also observed this behavior of PTF-VER.

Fig. 1 shows spatial patterns along the study transects of soil water retention variable θ_{-1} as predicted by the original PTF-VER. For comparison purposes, this plot also shows all 88 observed values and offers a visual representation of the biases between observations and PTF-predictions. Soil water retention data for the sampled area show variations with distance along the two hillslope transects. In some locations the original PTF-VER fails to identify the water retention characteristics of the sampled soils and produces some smoothing. Note

Table 2
Summary statistics for selected soil water retention data in the study transects as observed or predicted by the original PTFs

Variable	Data set	Min	Max	μ	σ	CV%
	Observed data					
$\theta_{-0.1}$	Right-side transect	0.391	0.560	0.481	0.04003	8.32
θ_{-1}	Right-side transect	0.307	0.538	0.417	0.05132	12.3
θ_{-10}	Right-side transect	0.217	0.423	0.322	0.04616	14.3
$\theta_{-0.1}$	Left-side transect	0.348	0.477	0.419	0.03662	8.74
θ_{-1}	Left-side transect	0.286	0.446	0.367	0.04599	12.5
θ_{-10}	Left-side transect	0.173	0.389	0.296	0.04855	16.4
$\theta_{-0.1}$	All data	0.348	0.560	0.451	0.04907	10.9
θ_{-1}	All data	0.286	0.538	0.392	0.05474	14.0
θ_{-10}	All data	0.173	0.423	0.310	0.04888	15.8
	Original PTF-HYPRES					
$\theta_{-0.1}$	Right-side transect	0.406	0.532	0.483[a]	0.03152	6.53
θ_{-1}	Right-side transect	0.328	0.467	0.418[a]	0.02907	6.95
θ_{-10}	Right-side transect	0.220	0.369	0.324[a]	0.03086	9.52
$\theta_{-0.1}$	Left-side transect	0.381	0.540	0.447	0.03357	7.51
θ_{-1}	Left-side transect	0.310	0.466	0.384	0.03056	7.96
θ_{-10}	Left-side transect	0.205	0.361	0.290[a]	0.03345	11.5
$\theta_{-0.1}$	All data	0.381	0.540	0.465	0.03710	7.98
θ_{-1}	All data	0.310	0.467	0.401[a]	0.03416	8.52
θ_{-10}	All data	0.205	0.369	0.308[a]	0.03629	11.8
	Original PTF-RB					
$\theta_{-0.1}$	Right-side transect	0.447	0.617	0.549	0.04019	7.32
θ_{-1}	Right-side transect	0.286	0.484	0.421[a]	0.04824	11.5
θ_{-10}	Right-side transect	0.167	0.357	0.275	0.04547	16.5
$\theta_{-0.1}$	Left-side transect	0.405	0.617	0.495	0.04338	8.76
θ_{-1}	Left-side transect	0.318	0.492	0.418[a]	0.03580	8.56
θ_{-10}	Left-side transect	0.189	0.371	0.280	0.03855	13.8
$\theta_{-0.1}$	All data	0.405	0.617	0.523	0.04965	9.49
θ_{-1}	All data	0.286	0.492	0.419	0.04241	10.1
θ_{-10}	All data	0.167	0.371	0.278	0.04206	15.1
	Original PTF-VER					
$\theta_{-0.1}$	Right-side transect	0.419	0.535	0.489[a]	0.02765	5.65
θ_{-1}	Right-side transect	0.367	0.497	0.449	0.02849	6.34
θ_{-10}	Right-side transect	0.242	0.412	0.363	0.04137	11.4
$\theta_{-0.1}$	Left-side transect	0.381	0.535	0.448	0.03003	6.70
θ_{-1}	Left-side transect	0.334	0.484	0.408	0.03079	7.55
θ_{-10}	Left-side transect	0.228	0.408	0.327	0.04241	13.0
$\theta_{-0.1}$	All data	0.381	0.535	0.469	0.03538	7.54
θ_{-1}	All data	0.334	0.497	0.429	0.03599	8.39
θ_{-10}	All data	0.228	0.412	0.345	0.04546	13.2

Min = minimum; Max = maximum; μ = mean; σ = standard deviation; CV% = coefficient of variation (in %).

[a] The null statistical hypothesis of the *t*-test cannot be rejected at 10% level of significance.

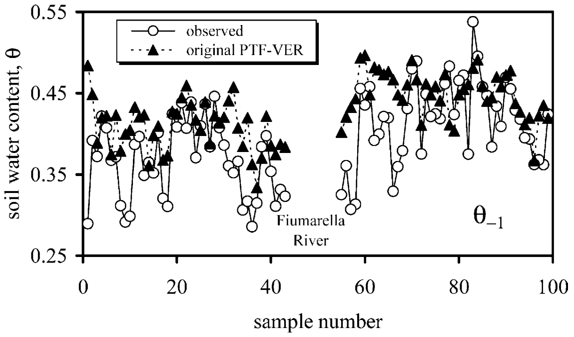

Fig. 1. Soil water retention variable θ_{-1} at each sampling location along both right- and left-transect as observed or predicted by the original PTF-VER.

that PTF-VER generates larger discrepancies for the soils located near the sides of the river. In these parts of the hillslopes the slope angles are rather steep. Therefore, this graph shows that the observed discrepancies are not random, but they are linked to specific landscape features. Although the question of bias and dispersion shall be discussed quantitatively later in this paper, a typical overprediction is depicted. It is also apparent that a relatively small spread occurs for variable θ_{-1} (see Table 2), the standard deviation of θ_{-1} for PTF-VER data ($\sigma_{\text{PTF-VER}} = 0.0360$) being smaller than that of the observed data ($\sigma_{\text{obs}} = 0.0547$).

From a hydrologic modeling perspective, one could also accept a relatively large spread around the mean value generated by a simplified methodology; it should be desirable, instead, that the PTF provides a reasonable picture of the average soil hydraulic behavior within the study area.

3.1. Performance evaluations

As a preliminary analysis, classic multivariate techniques were used to identify those terrain attributes that are significant in reducing the discrepancies detected along the transects between observed water retention and water retention as predicted by the original or modified PTFs. The topographic variables selected in this study have been reported in Section 2.2, also including some of their transformations, such as natural logarithm, square root and trigonometric operators. The aspect of the slope is directional information; therefore a trigonometric transformation is more appropriate to calculate its mean and variance. In this study we transformed aspect by the cosines of the angles (Davis, 1986). From this preliminary analysis we found that the best terrain attributes for explaining observed discrepancies in soil water contents are slope, aspect, profile curvature, wetness index, and direct solar energy index. Soil surveyors utilize slope angle and aspect angle to delineate soil-landscape mapping units and identify soil transitions. Profile curvature, profc, may be related to greater or lesser runoff depending on convex or concave surface areas, respectively, which in turn can affect the development of thinner or thicker soils. The wetness index, wi, accounts for the mutual tendency of water to accumulate at a point of the catchment and to move downslope as a result of the gravitational force. The amount of direct solar energy for given day and latitude influences evapotranspiration processes and can be related to organic matter content as well as to cation exchange capacity. With reference to the sampled transects, Table 3 reports minimum and maximum values of primary and compound terrain attributes retrieved from the DEM and used in the subsequent analysis. The variables have different magnitudes and range of variations. These variables were normalized relative to their minimum and maximum values leading to figures scaled from 0 to 1 before being applied to minimization of Eq. (5).

The prediction quality of the proposed procedure is evaluated by comparing the observed and the corresponding PTF-predicted soil water retention functions. The measure of prediction performance is computed in terms of integral mean deviation (IMD) and integral root-mean-square deviation (IRMSD), as follows:

$$\mathrm{IMD} = \frac{1}{(\xi_u - \xi_l)} \int_{\xi_l}^{\xi_u} [\theta(\xi)_{\mathrm{VG}} - \theta(\xi)_{\mathrm{PTF}/\tau}] \mathrm{d}\xi \tag{6}$$

$$\mathrm{IRMSD} = \left[\frac{1}{(\xi_u - \xi_l)} \int_{\xi_l}^{\xi_u} [\theta(\xi)_{\mathrm{VG}} - \theta(\xi)_{\mathrm{PTF}/\tau}]^2 \, \mathrm{d}\xi \right]^{\frac{1}{2}} \tag{7}$$

where $\xi = \log(|h|)$, $\theta(\xi)_{\mathrm{VG}}$ is the observed soil water retention function, and $\theta(\xi)_{\mathrm{PTF}/\tau}$ is the corresponding PTF-prediction including or not terrain attributes. Again, we integrated the soil water retention functions

Table 3
Range of variation (min = minimum; max = maximum) of some primary and compound topographic variables of the study transects retrieved from the DEM

Topographic variable	Unit	Min	Max
Right-side transect			
Elevation	m	783.13	1180.61
Slope	Degrees	2.00	31.0
cos(Aspect)	–	−0.39	1.00
Tangential curvature, tangc	–	−542.0	2062.0
Profile curvature, profc	–	−480.0	1131.0
Direct solar energy, kw	kW m^{-2}	7532.0	9789.0
Wetness index, wi	–	4.42	8.36
Left-side transect			
Elevation	m	773.90	1158.70
Slope	Degrees	1.00	27.0
cos(Aspect)	–	−0.99	1.00
Tangential curvature, tangc	–	−986.0	948.0
Profile curvature, profc	–	−893.0	1090.0
Direct solar energy, kw	kW m^{-2}	8222.0	10,547.0
Wetness index, wi	–	4.67	9.83

between the lower limit $\xi_l = 0.00$ and the upper limit $\xi_u = 4.20$. The IMD index reveals the presence of biases in prediction (systematic underprediction, IMD > 0, or systematic overprediction, IMD < 0), whereas IRMSD provides a measure of the overall precision, namely the degree of dispersion offered by a prediction method. These indices were calculated for each of the prediction methods, it being an original PTF or the proposed procedure that takes topography also into account along with the PTF. If small systematic errors occur (i.e. small IMD), the prediction method is accurate; if IRMSD is small, the prediction method has good precision.

Table 4 presents the arithmetic means of percent IMD and IRMSD for the whole data set ($N = 88$) and for the tested PTFs, whether or not including topographic variables into the original pedotransfer rule. On average, the original PTFs have different prediction performance. The negative values of IMD% indicate that systematic overpredictions, albeit of different magnitude, are detected with respect to the observed water retention functions. Values of IMD close to zero means that on average there is little difference between observed and PTF-predicted soil water retention functions. Overall, PTF-HYPRES (Table 4) reproduces reasonably well the observed water retention functions, whereas some larger uncertainty and worse overall prediction performance are detected for PTF-RB (Table 4) and PTF-VER (Table 4). These results might be viewed as obvious since they are due in part to the fact that PTF-HYPRES is based on information retrieved from (i) a recent and relatively large soil database that (ii) were developed using data from laboratory analysis on soil cores and from field experiments, and (iii) were established at European scale. However, on closer examination of the regression equations of this pedotransfer rule, one should also note that PTF-HYPRES accounts somehow for some landscape characteristics. In fact, PTF-HYPRES makes the distinction between topsoil and subsoil, with topsoil hydraulic properties being more affected by differences in land-use than subsoil properties. This latter feature could also be the reason why PTF-HYPRES shows inertia in providing better predictions of water retention curves by adding only primary topographic variables. Inclusion in this PTF of compound topographic indices, such as the wetness index, gives better average predictions. When the original realizations of PTF-HYPRES predictions are modified by adding one topographic variable, only profile curvature, profc, does improve the predictability of soil water retention functions significantly. This topographic variable represents the rate of change of slope in the across slope direction per 100 m of length. The smallest calculated mean IMD is equal to 0.036% and relates to the case of adding information about the amount of direct solar energy, kw, and wetness index, wi. A common feature of the IRMSD performance indices of original and modified PTF-HYPRES predictions is their small changes in the different cases examined. For the original PTF-HYPRES we have IRMSD% equal to 3.47%, whereas minimum values for this index are detected when adding profc and kw (IRMSD% = 3.36%) or for the case with information about slope, kw and wi (IRMSD% = 3.30%).

Table 4 presents results for the pedotransfer PTF-RB and shows that the original method proposed by Rawls and Brakensiek generates on average a larger systematic overprediction (IMD% = −1.70%) than PTF-HYPRES. The mean value of IRMSD% is relatively large (IRMSD% = 6.00%) showing a low

Table 4
Means for PTF-HYPRES, PTF-RB and PTF-VER of IMD% and IRMSD% calculated from the whole set of soil water retention functions

Type of prediction method	PTF-HYPRES		PTF-RB		PTF-VER	
	IMD%	IRMSD%	IMD%	IRMSD%	IMD%	IRMSD%
(a) Original PTF	−0.532	3.47	−1.70	6.00	−2.77	4.02
(b) PTF + 1 terrain attribute						
PTF + slope	0.361	3.45	0.136	4.08	−0.0239	3.21
PTF + aspect	0.694	3.71	−0.527	4.22	−0.624	3.36
PTF + profc	−0.041	3.50	−0.145	4.11	−0.128	3.34
PTF + kw	0.180	3.41	0.0011	3.98	−0.0685	3.31
PTF + wi	−0.272	3.48	−0.413	4.37	−0.411	3.41
(c) PTF + 2 terrain attributes						
PTF + (slope,aspect)	0.143	3.39	0.0638	3.85	0.00550	3.18
PTF + (slope,profc)	0.205	3.42	0.203	3.78	0.0741	3.17
PTF + (slope,kw)	0.274	3.35	0.215	3.65	0.206	3.13
PTF + (slope,wi)	0.0729	3.39	0.226	3.79	0.0885	3.20
PTF + (aspect,profc)	−0.0728	3.51	−0.126	3.94	−0.114	3.31
PTF + (aspect,kw)	0.0211	3.38	0.0698	3.72	0.0057	3.18
PTF + (aspect,wi)	−0.274	3.45	−0.248	3.98	−0.281	3.30
PTF + (profc,kw)	0.0651	3.36	0.144	3.80	0.0643	3.20
PTF + (kw,wi)	0.0363	3.43	−0.0057	3.91	−0.0553	3.24
(d) PTF + 3 terrain attributes						
PTF + (slope,kw,wi)	0.114	3.30	0.221	3.59	0.138	3.07

level of precision of the original PTF-RB. This can be partly due to organic matter being excluded from the pedotransfer rule. However, for PTF-RB the impact of adding topographic variables on predicting the water retention functions becomes more apparent. Specifically, adding aspect, or kw, produces a significant benefit as the mean value of IMD% when aspect is taken into account is −0.527%, or 0.0011% for kw. This is an important and significant result attributable, as we shall discuss later, to the information contents that terrain variables such as aspect and kw appear to bring in. Coupling slope and aspect as ancillary information generates a relatively low IMD value (IMD% = 0.0638%), whereas adding slope and kw, or combining information about slope, kw and wi, produce the largest reductions in IRMSD values with respect to the original PTF-RB. There is a reduction of 39.1% for the case PTF-RB + slope,kw and of 40.2% for the case PTF-RB + slope,kw,wi. For the case of PTF-RB plus just one terrain attribute, the best estimator in terms of precision occurs when adding the compound variable kw, having an IRMSD% value equal to 3.98%. Note that only when adding variables that are somewhat linked to information on soil organic matter, the precision of PTF-RB becomes comparable with that of PTF-HYPRES.

While Tietje and Tapkenhinrichs (1993) and Romano and Santini (1997) reported an overall satisfactorily behavior of the pedotransfer published by Vereecken et al. (1989), for the data collected in the present study the original PTF-VER gives the worst result in terms of mean IMD% value, with an average overprediction of 2.77% (Table 4). In terms of IRMSD% the original PTF-VER shows overall a fair goodness-of-fit (mean IRMSD% is 4.02%), behaving slightly worse than PTF-HYPRES but better than PTF-RB. The PTF-VER shows sensitivity to inclusion of primary and secondary terrain attributes. Adding terrain attributes always yields improvement with respect to both bias and dispersion characteristics. For PTF-VER, using both slope gradient and slope aspect substantially improves the average prediction of soil water retention. Slope gradient and slope aspect used together as ancillary information yield a virtually zero mean IMD% value (IMD% = 0.0055%) and this is an indication of highly unbiased mean water retention predictions. The benefit of considering various terrain attributes as ancillary variables does not appear significant in terms of the IRMSD% indices. For the case of PTF-VER + slope,kw,wi, we obtain the maximum change in the mean IRMSD% value of −23.6% with respect to the original PTF-VER (i.e. from 4.02 to 3.07%).

To provide a visual perception of the improvement in water retention prediction that can be gained when an original PTF is modified by adding terrain attributes as ancillary information, for each prediction method we have computed the mean relative error (MRE%), and prediction efficiency (PEf%) (also known as the Nash–Sutcliffe index), as follows:

$$\mathrm{MRE\%}(h) = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{\theta(h)_{\mathrm{PTF}/\tau,i}}{\theta(h)_{\mathrm{VG},i}}\right) \times 100 \tag{8}$$

$$\mathrm{PEf\%}(h) = \left\{1 - \frac{\sum_{i=1}^{N}[\theta(h)_{\mathrm{VG},i} - \theta(h)_{\mathrm{PTF}/\tau,i}]^2}{\sum_{i=1}^{N}[\theta(h)_{\mathrm{VG},i} - \underline{\theta(h)_{\mathrm{VG}}}]^2}\right\} \times 100 \tag{9}$$

where N is the size of the total available data and $\underline{\theta(h)_{\mathrm{VG}}}$ denotes the arithmetic mean of the individual observations of $\theta(h)_{\mathrm{VG}}$. These discrete statistical indices were selected partly because they facilitate comparisons and evaluation judgments among the various prediction methods. High values of PEf% (near 100%) indicate a very good agreement between observation and PTF-predictions, whereas negative values would suggest that only the mean of the observations yields an acceptable picture of the average patterns of the variable. Lower limit for PEf% is $-\infty$.

Considering the case in which both slope and aspect are included in a pedotransfer prediction method (solid lines), Figs. 2 and 3 show MRE% and PEf% versus h, respectively, for the three PTFs tested in this paper. To facilitate comparisons, the graphs are plotted on the same scales. The dashed lines refer to results pertaining to the PTFs as originally proposed by their own authors. All plots of these figures clearly show the substantial benefit obtained when additional terrain information are introduced into a pedotransfer rule. Both Figs. 2 and 3 enable the prediction performance to be readily assessed at different levels of soil saturation, ranging h from wetter (i.e. $|h|$ near 10^0 cm) to drier (i.e. $|h|$ near 10^4 cm) soil conditions. Therefore, these representations permit further comments to be made and specific results to be shown.

In terms of MRE%, the dashed line of Fig. 2(top) confirms the higher performance offered by the original PTF-HYPRES than the original PTF-RB (Fig. 2(middle)) and original PTF-VER (Fig. 2(bottom)). The original PTF-HYPRES yields a mild overprediction over the whole range of pressure heads and this bias reduces significantly when approaching drier soil conditions. The PTF-RB as originally proposed by Rawls and Brakensiek (Fig. 2(middle)) behaves differently when moving from wetter to drier soil conditions: severe overpredictions occur when soil is relatively wet, whereas underpredictions become evident under drier conditions. The PTF-VER (Fig. 2(bottom)) also yields systematic overpredictions with respect to the observed retention data, but the bias is well evident (for example, compared to the results of PTF-HYPRES) and, moreover, it increases as matric pressure head h decreases. It is also interesting to point out that, whereas mean IMD% of original PTF-RB was smaller than that of original PTF-VER (see Table 4), from Fig. 2(middle) it is apparent that, however, for $|h|$ ranging between 10^1 and 10^2 PTF-RB generates the largest overpredictions among the tested PTFs, with MRE% reaching values close to −20%.

Even if a correct identification of the relative importance and effectiveness of the terrain attributes may be difficult to achieve because of mutual influence and interdependency of these variables, different degrees of improvement have been obtained within the range of $|h|$ plotted in these figures. Closer inspection of Fig. 2 highlights that terrain attributes exert a somewhat greater influence at or close to full saturation conditions in soil for PTF-HYPRES. Largest benefit occurring at both low and high $|h|$ values are observed for PTF-RB. As soil dries out, including terrain attributes improves significantly the assessment of soil water retention functions, especially those retention characteristics predicted by PTF-RB and PTF-VER. At first glance, this seems consistent with the findings of Famiglietti et al. (1998), although the different results reported by Western et al. (1999b) call for further investigations being conducted in other environments. However, one

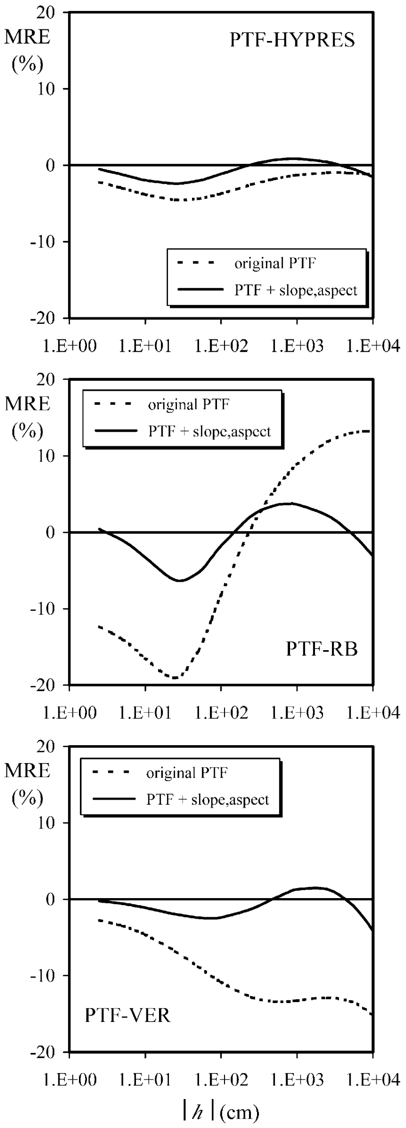

Fig. 2. Mean relative error, MRE%, as function of matric pressure head, *h*: PTF-HYPRES (top); PTF-RB (middle); PTF-VER (bottom).

should be aware of the different aims of the investigations carried out by both Famiglietti et al. (1998) and Western et al. (1999b) with respect to the objectives of the present study. Although the intimate causes of bias are not identified in this study, we argue that including terrain attributes into the regression equations that define a pedotransfer rule appears a suitable correction factor for gaining more reliable PTF-predictions of the water retention functions. The interesting result that we have obtained and would like to emphasize here refers to the fact that, whatever the PTF, the inclusion of slope and aspect attributes as additional input information has led to a significant lowering of the bias in predictions. This outcome was already evident from inspection of Table 4, but it is

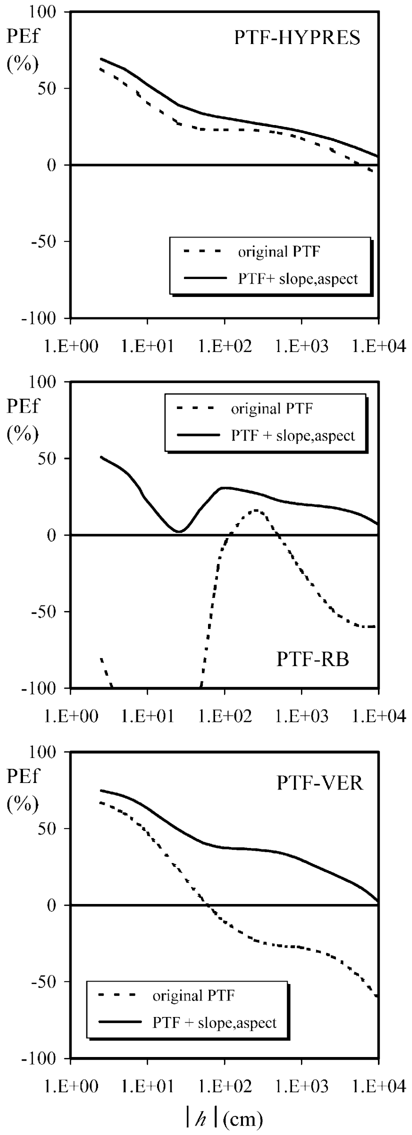

Fig. 3. Prediction efficiency (or, Nash–Sutcliffe index), PEf%, as function of matric pressure head, *h*: PTF-HYPRES (top); PTF-RB (middle); PTF-VER (bottom).

now perceivable visually from the plots depicted in Fig. 2. Similar results, of course with a different level of prediction performance, were obtained when adding some the other topographic variables considered in this study.

Fig. 3 shows the PEf% index for the original (dashed lines), or modified by adding slope and aspect variables (solid lines), PTF-HYPRES (Fig. 3(top)), PTF-RB (Fig. 3(middle)), and PTF-VER (Fig. 3(bottom)). Fig. 3(top) shows that PEf% of the original PTF-HYPRES becomes negative for h lower than about -5000 cm, whereas the modified PTF-HYPRES yields positive PEf% values over the entire investigated range of matric pressure head. As the original PTF-HYPRES per se always gives good performance, the inclusion of terrain attributes can be marginal in terms of PEf%. Instead, adding slope and aspect attributes in the original PTF-RB (Fig. 3(middle)) and original PTF-VER (Fig. 3(bottom)) induces substantial benefit. In both cases, the lines referring to the PEf% index are above the 'zero' level, which can be assumed as a sort of threshold to discriminate between relatively good or poor predictions. From inspection of all three plots of Fig. 3, it is also interesting to note that the efficiency in prediction offered by the modified PTFs behaves very similar when approaching the drier part of the water retention characteristic, with the worst performance at the largest absolute matric pressure heads, i.e. approximately for $|h| > 10^3$ cm. The prediction capabilities offered by a PTF close to saturation seem to rely more upon the specific type and analytic structure of the pedotransfer rule. PTF-HYPRES and PTF-VER, which both use organic matter content as input soil property, lead to similar patterns of the PEf% index over the investigated $|h|$-range when they are adjusted by adding slope and aspect attributes with the proposed procedure.

As illustrative examples, Fig. 4(a) and (b) examine the effects that refining a pedotransfer rule with the proposed method have on predictions of $\theta(h)$ functions. Specifically, with reference to the sampling point No. 24 located along the right-side transect, Fig. 4(a) shows the soil water retention characteristics as predicted by the original PTF-RB (dashed thin line and close circles) or by adding the slope and aspect topographic attributes to this PTF (solid thin line and open circles). For the same location, Fig. 4(b) shows a comparison of the $\theta(h)$ functions as predicted by the original PTF-VER (dashed thin line and close triangles) or by PTF-VER with slope and aspect attributes (solid thin line and open triangles). The solid lines in both graphs depict the observed $\theta(h)$ functions. From Fig. 4(a) we note that the original PTF $\theta(h)_{\text{PTF-RB}}$ has difficulty predicting the observed retention function $\theta(h)_{\text{VG}}$. A crossover occurs at midrange of matric heads, yielding overpredictions at higher h and relatively large underpredictions at lower h. When slope and aspect variables are included into this pedotransfer rule the resulting adjusted retention function, $\theta(h)_{\tau}$, is in a very good agreement with the observed water retention function and capable of capturing fairly well the overall water retention behavior of soil at this location. The adjusted retention function shows some slight discrepancy at the intermediate saturation range. From Fig. 4(b) we note two points. First, the original $\theta(h)_{\text{PTF-VER}}$ curve overpredicts over the entire considered range of matric pressure heads. Second, as we progress from the highest to the lowest matric pressure head h, it is highlighted the observed tendency of PTF-VER to be more sensitive to inclusion of terrain attributes when approaching the dry end of the water retention curve (see also Figs. 2(bottom) and 3(bottom)). In general, the improvement in the description of soil water retention characteristic is evident.

The t-test at 10% level of significance is again performed using the modified PTFs to check the null hypothesis that two datasets have the same mean. Results are not shown here for brevity, but it is worth mentioning that now the t-test is verified for all water retention points (i.e. $\theta_{-0.1}$, θ_{-1}, and θ_{-10}) and for PTF-HYPRES and PTF-VER. The performances of PTF-RB remain still not acceptable. Accounting for the results already reported in Table 2, for PTF-RB and all data the t-test is now verified only for variable θ_{-1}.

A synthesis of the beneficial influence of the proposed calibration procedure is presented in Fig. 5 that, similarly to Fig. 1, compares observations and PTF-VER predictions of the spatial variable θ_{-1} when PTF-VER is now adjusted by adding slope and aspect attributes. Again, values of θ_{-1} observed along the transects are used as a benchmark. In the light of the previous results depicted in Fig. 1, it can be seen here that the proposed procedure captures fairly well the

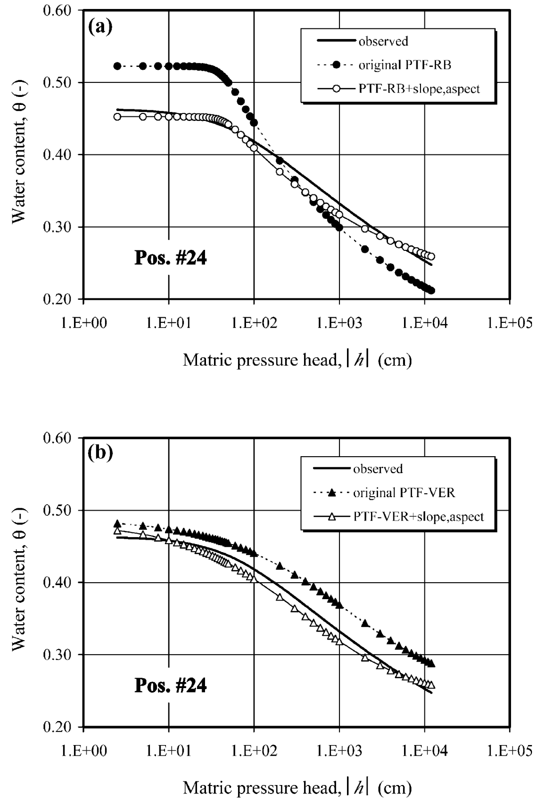

Fig. 4. Observed soil water retention function, $\theta(h)$, for one location along the study transects and comparison with the original, $\theta(h)_{\mathrm{PTF}}$, or adjusted, $\theta(h)_T$, PTFs: (a) PTF-RB, (b) PTF-VER.

general patterns of soil water retention functions along the study transects. Although deviations still appear in a few locations, an overall inspection of the graph gives the clear perception of the improvement in describing the spatial variations exhibited by the soil water retention characteristics along the hillslopes.

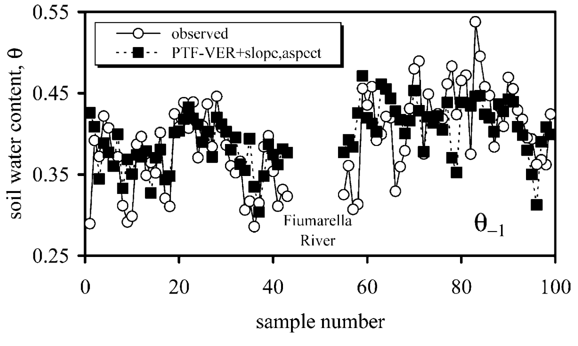

Fig. 5. Soil water retention variable θ_{-1} at each sampling location along both right- and left-transect as observed or predicted by PTF-VER adjusted with slope and aspect terrain attributes.

4. Concluding remarks

The research detailed in this paper has provided an approach for including terrain attributes into a pedotransfer rule to enable a better, but still relatively easy to achieve, description of the hydraulic behavior of soils in a region of interest.

It is important to point out that we did not design a new PTF. Rather, we focused on how published PTFs can be suitably and inexpensively calibrated to account for site-specific situations. We have proposed to refine an existing PTF by superposition to the original PTF of a linear combination of various terrain attributes that can be readily retrieved from a DEM. This refinement is expected to be more effective when addressing modeling problems at hillslope and small catchments scales. The procedure requires measurements of soil water retention characteristics in a number of sites pertaining to some representative zones (for instance, certain soil-landscape mapping units), to allow estimation of the coefficients of the topographic variables. Obviously, at the present moment this type of analysis rests on the fundamental assumption that the computed coefficients are the same in the entire area of interest, it being a hillslope or catchment.

There is a difference in sensitivity among the various PTFs to inclusion of primary and compound topographic variables. For certain PTFs, while including terrain attributes seems to exert a relatively low influence on PTF-predictions in very wet soils, it can be significant when modeling soil hydrologic processes for water contents in the mid-range of the water retention curve (i.e. between the very wet and the very dry soil water conditions). The original PTF-HYPRES is already accurate (small systematic errors) and precise (small random errors) so that relatively little improvements are gained with the proposed procedure; the others two PTFs tested, namely PTF-RB and PTF-VER, appear more sensitive to the various combinations of terrain attributes. It is worth noting, however, that modifications of these latter PTFs could also lead under certain situations to even lower mean IMD values than the corresponding modified PTF-HYPRES. Estimates of the IMD and RMSD deviations have given valuable guidance as to where one could further improve the proposed procedure. This study has demonstrated the potential usefulness in improving PTF-predictions by accounting for landscape information. It is also apparent that terrain attributes work efficiently to produce unbiased predictions. Both these features have valuable implications in distributed hydrologic modeling. Scaling up relies on some weighing techniques and thus the use of an unbiased prediction method is of crucial importance to compute reliable equivalent soil hydraulic parameters at the numerical grid scale. Although the proposed procedure has sound physical and morphological basis, it should be also viewed with the eyes of a practitioner that basically requires mapping soil hydraulic behavior in an agricultural landscape with acceptable accuracy and reasonable cost.

An original PTF for predicting the soil water retention characteristic usually employs primary physical variables, such as textural fractions and oven-dry bulk density, and progress was made by including other types of variables (e.g. organic carbon content, or the distinction between topsoil and subsoil). However, some authors have also demonstrated that including more complete soil physical information, such as the whole particle-size distribution curve, did not significantly improve the prediction of the water retention function (Tietje and Tapkenhinrichs, 1993), giving us to understand that input variables of this kind have almost exhausted their explanatory power in accounting for the deviation between observed and predicted water contents.

As a step forward, the present study was designed with the process-based rationale that variables somewhat more related to the dynamics of pedogenesis should represent valuable ancillary information being added into a pedotransfer rule to better capture the inherent hydraulic behavior of a soil and also to account for local environmental conditions. Within this conceptual framework, terrain attributes pertain to the pedotransfer philosophy and can synthesize a number of physical and pedogenic processes that appear to be not well represented in the classic input variables already used into an original PTF, but that can contribute to explaining the observed hydraulic response of a soil. The following processes or a combination thereof can justify the proposed procedure of adding local topographic information into an original PTF to improve the prediction of soil hydraulic characteristics under certain circumstances and in a specific area of interest. During precipitation events, infiltrated water persists more in locations of the landscape that are relatively flat, while areas possessing higher slopes foster rapid lateral redistribution of soil moisture. Therefore, whereas texture and bulk density can hardly help in understanding the internal architecture of a soil, slope gradient can add some useful information, albeit soft information, about the evolution of physical weathering nearby the location considered or about the fact that a certain soil horizon, especially if positioned near the land surface, could have been the product of transportation effects from one position in the landscape to another. A combination of ancillary variables, such as slope and aspect topographic variables, can give useful direction on the extent of soil profile development since, for example, north-facing, milder slopes will tend to have wetter soil moisture conditions and show better developed soil profiles than south-facing, steeper slopes. We would thus emphasize that it gathers strength the perception that some terrain attributes, such as in particular slope or aspect, can provide information on the ‘quality’ of the certain substances, such as clay particle or organic matter. The type of clay minerals in certain locations can be different from that in other locations because of erosional processes, and the subsequent aggregation process yields a particular soil structure at that location as a consequence of the different formation process of intra-aggregate pores and inter-aggregate pores. The overall soil porosity as determined by the oven-dry bulk density does not distinguish between these two categories of soil pores. Aspect influences solar irradiation and evapotranspiration, thereby providing with further information about complex interactions between the clay fraction of soils and organic substances, which in turn may

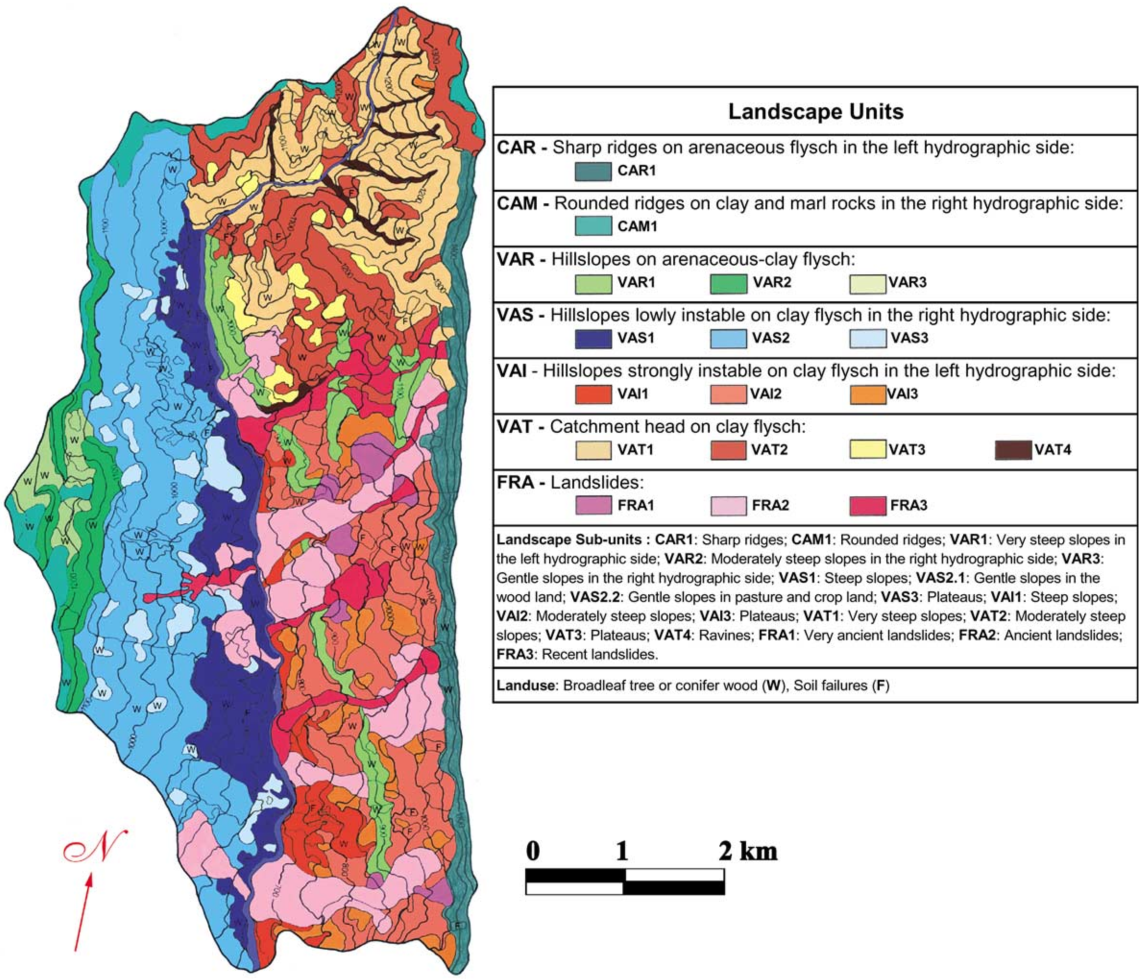

Fig. 6. The 'Fiumarella di Corleto' catchment (Basilicata Region, Italy) showing distribution of soil-landscape mapping units at scale 1:10,000 (a legend showing only the landscape units is provided). Topographic contours are shown and elevations (m) are labeled.

strongly affect the water retention capacity of soils.

Future efforts will also focus on the pedotransfer prediction of hydraulic conductivity of soil. Even though Childs (1969) already put users and specialists on their guard against statistically correlating soil hydraulic conductivity to texture only, there exists a pressing need to develop an efficient PTF for deriving parameters featuring in the soil hydraulic conductivity relationship. Up to now, almost all applications of process-based hydrologic models take soil water retention parameters from measurements, but treat soil hydraulic conductivity parameters as calibrating parameters. The availability of reliable PTFs for predicting a priori the $K(\theta)$ function will attach a more physical meaning to the hydraulic conductivity parameters, thus making model validation more effective.

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