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Potential and limitations of using soil mapping information to understand landscape hydrology

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Abstract

The role of soil properties and their spatial distribution in the landscape are already recognised as crucial issues greatly affecting rainfall-runoff dynamics and hence landscape hydrology. This becomes even more important when hydrological monitoring data are lacking. This applies to the critical issue of making hydrological predictions for ungauged basins. The rapid development of hydropedology along with Digital Soil Mapping (DSM) is promising to both enhance our understanding and (spatial) prediction capacity of rainfall-runoff processes and to be a powerful tool for environmental policy research. Despite these developments and broad conceptualizations, the crucial point as to how the soil data from typically available soil mapping databases can be usefully employed by the hydrologist has yet to be addressed. This question implies detailed knowledge of the quality and quantity of information embedded in and behind a soil map.

This work produced an analytical evaluation of the potential and limitations of soil data obtained through soil surveys and soil mapping. This evaluation is made from a landscape hydrology viewpoint and is also developed through the following Italian case studies: irrigation management at the district scale, assessment of groundwater vulnerability, flood peak forecasting, and land evaluation for maize production. We show that special care is required in handling soil database data if their full potential is to be achieved. Further, all the case studies agree on the appropriate degree of complexity of the soil hydrological model to be applied. We also emphasise that effective interaction between pedology and hydrology to address landscape hydrology requires (i) better awareness of the hydrologic community about the type of soil information behind a soil map or soil database, (ii) the development by the pedological community of a better quantitative framework for evaluating surveyed hydrological features, and (iii) quantitative information on soil spatial variability and, if possible, on the spatial distribution of prediction errors.

1 Introduction

There has been an increase of attention to quantitative taxonomy in hydrology (McDonnell et al., 2007; Wagener et al., 2007). Most authors and scientists select modelling strategies and components of simulation based on intuitive basis, or without any explicit explanation at all. This leads to a fundamental non-reproducibility of results since the most fundamental aspects of the modelling strategy are hidden. But independent reproducibility is a fundamental requirement of scientific validity and subjective approaches represent a critical obstacle to it. For this reason we argue the necessity of a scientifically rigorous methodology to classify and then model the processes. In such framework, in hydrologic catchments, soil plays the crucial role of partitioning water between infiltration and runoff, storage, filtering, physical and chemical support to vegetation, etc (Dunne, 1978). The importance of soils further increases when hydrological monitoring data are lacking, such as when hydrological predictions are required in ungauged basins.

In recent years many advances have been attained by soil scientists in ameliorating soil information in both the estimate of hydrological parameters (e.g. PTF; Pachesky and Rawls, 2004) and the spatial inference of soil information. In this regard, hydropedology (Bouma, 2006; Lin et al., 2006) has emerged as a new discipline devoted to the close interaction between soil science and hydrology, embracing multiscale process analysis in saturated and unsaturated soil conditions. This discipline promises to both enhance the understanding and prediction of rainfall-runoff processes (Lin et al., 2008) and to be a powerful tool for environmental policy research (Bouma, 2006).

Some evident examples of this potential are given in the literature on the relationships between soil (soil architecture) and rainfall/runoff processes. Amongst others, Lin et al. (2008) analyzed the contributions of hydropedology to the understanding and modelling of surface/subsurface runoff processes at microscopic (macropores and aggregates), mesoscopic (horizons and pedons) and macroscopic scales (hillslopes and catchments); Bouma (1981) and Ritsema et al. (2005) related preferential flow paths to soil morphology and soil hydrophobicity, respectively; Coppola et al. (2009) studied the effects of a bimodal pore-size distribution and its variability on a hillslope water balance. Along with these contributions here we report four case studies of hydropedology applications with respect to soil mapping issues (Fig. 1).

In an attempt to conceptualize the relationships between hydrology and pedology, Lin et al. (2008) have created a hierarchical framework for bridging soil type distribution (forms) and soil processes (functions) in hydropedology. They also emphasise the "soil architecture" encompassing the soil structural complexity at different scales (aggregates, horizon, profile, catena, etc.) and define the Hydrologic Functional Unit (HFU) as the mapping tool combining soil and processes. Despite these conceptualizations one basic point, yet to be addressed by hydropedologists, concerns how soil data from standard soil mapping databases (often the only soil data available) can be usefully employed by hydrologists. To answer this question we need detailed knowledge on the quality and quantity of information embedded in and behind a soil map.

The lack of scientific literature on this crucial question is rather unfortunate and surprising and it is possibly related to the evidence (by surveying the scientific literature and from the few references quoted above) that at present hydropedology has been very much driven by soil hydrologists rather than pedologists (who typically produce soil maps). In this regard, our contribution, which emphasises pedological issues, may provide a more suitable better framework for hydropedology and its contribution to solving hydrological problems at the landscape scale.

From a landscape hydrology perspective, along with such recent advances in hydropedology, in the last few years much has been achieved by the community of soil scientists in mapping soils (Table 1). More specifically, Digital Soil Mapping (DSM) has emerged as a credible alternative to traditional soil mapping. It entails the use of new tools and techniques coming from different branches of a broader scientific community (e.g. spatial statistics, GIS, remote and proximal sensing, computer programming) in order to put into a quantitative framework the spatio-temporal study of soils (McKenkie and Ryan, 1999; McBratney et al., 2003).

DSM overcomes some serious limitations of conventional soil mapping such as the description of soil variability. For instance, the conventional approach describes soilscape complexity by means of a robust mental model developed by the pedologist using an implicit predictive model which is strongly qualitative, complex and rarely communicated in a clear manner. The approach has a high degree of subjectivity and uncertainty, and the soil spatial variability is not described. Moreover DSM, unlike conventional soil mapping, emphasises the soil continuum, where soil properties at a given location depend also on their geographic position and on the soil properties at neighbouring locations, and then overcome limitations and coarseness of using large discrete polygons as a means of describing soil variability in the landscape in both the geographic and the attribute domains.

We can distinguish (Carré et al., 2007) the DSM sensu stricto (DSMss) which is involved in the creation of soil information in the space domain, from the DSM sensu lato (DSMsl) which generates derived soil attributes from the outputs of DSMss by using attribute domain inference systems (e.g. water retention capacity). Accuracy is a key aspect of DSM, partly given the nested structure of some inference systems. The global accuracy of a DSM product depends upon the accuracy of the whole set of soil data (localization, measurements, etc.), covariates and inference systems used. One of the most interesting outputs of such DSM methods may be the spatial distribution of the prediction error (soil type and soil attributes); this can be usefully employed in applying hydrological modelling at the landscape scale. Despite all the important advances by DSM, unfortunately it is rather evident (e.g. Jones et al., 2005) that in most countries, regions, municipalities and so forth, classical soil maps still constitute the only real soil data available – and usable – for landscape and watershed hydrology.

Despite the progress made on the subject, the scientific literature is rather devoid of critical and analytical evaluation concerning the use of soil map information (traditional and/or obtained by DSM) for landscape and watershed hydrological studies. This is rather unfortunate, given that policy makers and communities worldwide still have to rely strongly on such maps for decision making. In this context, going beyond the generic statement concerning the importance of hydropedology, we believe it is of the utmost importance to examine whether and to what extent soil maps (and associated soil data), produced in accordance with different aims, scales and procedures (traditional or by DSM), can play a role in hydrological applications at the landscape scale.This work aims to address the above question, focusing on the potential and limitations of soil surveys and soil mapping. Our appraisal is made from a landscape hydrology viewpoint, and will draw on some relevant some case studies from Italy. In this paper, first we describe the process of making soil maps, showing their limitations and potential, and those of associated soil databases. We then emphasise the need to reinforce and to rethink the interaction between pedology and landscape hydrology.

2 Soil mapping: a hydrological viewpoint on making soil maps

2.1 Introduction to the making of soil maps

Dokuchaev and Jenny, respectively in 1882 and 1941, first recognized and then attempted to formalize soil formation by the following equation:

$$s = f(\mathrm{cl}, o, r, p, t, \ldots)$$

(referred to here as CLORPT), where s is any soil property, cl the climate, o the organisms, r the topography, p the parent material (the state of the soil at time zero), t the absolute age of the soil, and where ... represents additional non-specified factors.

Albeit mainly useful as a conceptual framework (correct values of many parameters cannot be obtained), this equation emphasises some important points, also for hydrologists: (i) soil formation has a strong mechanistic basis, (ii) if we aim to understand soil properties, functions and their spatial distributions then we must adopt a robust multidisciplinary approach including those environmental factors (geology, geomorphology, climate, land use, etc.) that have forged soil development, (iii) it is not possible to derive soil information from solely geological data (as is often done in environmental catchment hydrology), (iv) soils can differ greatly and the spatial distribution of this diversity depends on the spatial distribution of the factors that induced soil formation.

In a landscape, the above equation is a powerful conceptual framework rather than a practical tool for producing a spatial analysis of soils. Indeed, despite some recent important conceptualization, reviews and local studies on the use of mechanistic models of soil formation at both point-based and landscape scale (Samouëlian and Cornu, 2008; Minasny et al., 2008; Salvador-Blanes et al., 2007), some of the factors of soil formation, formalized in the equation, are still very difficult or even impossible to determine and then model, such as the age of pedogenesis and/or the status of other soil-forming CLORPT factors during the (long) life of a developing soil.

Despite these well known problems, in the last century the scientific community of pedologists used the CLORPT conceptualization and standardized survey methods to analyze and report the spatial distribution of soils through the production of soil maps. These were then employed as indispensable tools for planning proper land management.

On the other hand, DSM scientists (McBratney et al., 2003) have translated Jenny's qualitative CLORPT formulation into the more quantitative and inference-based SCORPAN model. It consists of an empirical quantitative description of relationships between soil and environmental factors with a view to using these as soil spatial prediction functions for determining the spatial distribution of soil types and soil attributes. It is an adaptation of CLORPT not for a mechanistic explanation of soil formation but for an empirical representation of relationships between soil and other spatially referenced factors. In SCORPAN this is obtained by extending the five soil forming factors with the addition of geographical position. The prediction of soil properties of a given site is thus obtained from known observations neighbouring the point. Much DSM work worldwide is based on the use of already existing soil databases (as laboratory-measured data using surveyed soil samples), and conventional and analogical soil cartography itself is not necessarily required. DSM thus typically consists in creating soil information combining point-based data (from field survey and laboratory analysis) and mostly exhaustive auxiliary information with models of inference in the spatial, temporal and/or attribute domains.

A detailed discussion of both conventional and DSM methods may be found in some reference books (Dent and Young, 1981; McKenzie et al., 2008). We report here a brief description of this complex procedure for the purposes of environmental hydrologists.

2.2 The standard process of soil survey and soil mapping

The main steps typically employed in producing soil maps are illustrated in Fig. 1 and include:

1. Acquisition of all available information on the spatial distribution of soil-forming factors (e.g. geological map, geomorphology, DEM, climate data, etc.) including those obtained after remote and proximal sensing.
2. A synopsis of all such information for producing a preliminary landscape classification. This synopsis, assisted by the use of photointerpretation (either analog or digital), consists in segmenting a region into many landscape units considered (supposedly), in this preliminary step, internally homogeneous in terms of soil-forming factors (at least those available). In other words, the procedure employs the strongly deterministic basis of the soil-forming factors to segment, with a first approximation, the region of interest into areas for carrying out soil sampling and analysis.
3. In these segmented areas a preliminary soil survey is then carried out. This survey consists in opening up holes and trenches (and also in performing hand drilling) where, following standardized procedures, a vertical section of soil called the soil profile and the site (about 10 m^2) where the profile is located, are described.

The description typically consist in recognising different horizontal layers, called pedogenic horizons, and also in determining, for each of the identified horizons, specific features and properties that can be directly derived in the field (Soil Survey Staff, 1993; FAO, 2006). Finally, soils are sampled for chemical and physical analysis to be performed in the laboratory. An example of the kind of soil features that are described in a soil survey is given in Table 2 where we have highlighted in bold and italics those features which are of great relevance to hydrology.

Assuming a profile consisting of only three horizons, the potential output will include about 257 field data (including descriptions of the profile and the soil sampling station and in the theoretical case where that all types of soil features occur) and 36 laboratory-based data for each soil observation. Using the (qualitative, semi-quantitative, quantitative) field and laboratory data obtained, soils are then classified into categories using international systems of soil classification such as Soil Taxonomy (USDA, 2010) or World Reference Base (WRB, 2006).

1. On the basis of the results obtained after the preliminary soil survey, a preliminary soil mapping units (SMU) map is produced after a synopsis of both landscape and soil information (also named preliminary soil correlation). In this map, one or more soil types (Soil Typological Units also typically named as STU) are associated to each preliminary SMU.

2. Systematic soil survey (in accordance with standards required by the organization commissioning the survey) and soil analysis on the basis of the preliminary SMU map.

3. First draft of the final SMU map and soil legend. In this drafting process, the aim is to organize and produce a synthesis of all the soil knowledge in the study area within a coherent framework (typically named as final soil correlation). This rather complex task is typically performed by aggregating all soil information into a limited number of soil mapping units (SMU), each being represented by the dominant (and co-dominant) soil type (STU).

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4. Field control to check soil mapping units and drafting of the final soil map (SMU) with explanatory notes where for each STU is also given a representative profile including field description and lab analysis.
5. Final test of the soil map, typically performed by the organization commissioning the soil map.
6. Final review and publication and release (upon request) of .shp file and soil database.

What is evident here is the complexity of the process of surveying and mapping of soils, the large quantity of data to be processed and the importance of a good synopsis of the obtained soil knowledge. With these considerations it is hardly surprising that the entire process of surveying, making and publishing a soil map (1:50 000) for an area of about 20 000 ha may take 2–3 years.

2.3 The DSM process of soil surveying and soil mapping

The general procedure of digital soil mapping may be schematized in a few key steps. The soil modeller first needs basic knowledge about the soils: soil information is gathered in both qualitative and quantitative forms. According to the type of pre-existing information, this may lead to a new survey in order to integrate the data. Due to time and money constraints, which inevitably affect the sampling scheme, this stage is characterized by observing in the geographical domain only a limited number of points of the soilscape continuum. Soils are now coded on a points basis by different types of information, such as soil profile field descriptions, soil types, and quantitative laboratory analysis.

The second step consists in gathering low cost and spatially continuous auxiliary covariates related to the factors of the SCORPAN model. The soil-forming factors are put into a quantitative empirical relationship with specific soil properties/classes. Depending on the target soil attribute at hand, more or less SCORPAN factors are elaborated on a mathematical and/or statistical basis to yield a wide range of spatially exhaustive soil covariates. Digital terrain analysis, using a Digital Elevation Model (DEM) as input, accounts for the calculation of the so-called terrain (or land surface) parameters (Wilson and Gallant, 2000), such as those referring to the geomorphology (e.g. concavity, convexity, etc.) or to the potential solar radiation.

Thirdly, a spatial soil inference system is used to predict continuous soil attributes from soil observations and auxiliary data. The empirical function can have different forms according to the type of input data, the scale of target, the modeller's know-how, computing power, and so on.

The output can be used in a DSMsI inference system that makes predictions in the soil attribute domain (pedotransfer rules, mechanistic models) to infer soil hydrological attributes (e.g. water retention capacity).

3 Soil mapping: a hydrological view of the final result

The result of soil surveying and soil mapping is the production of a georeferenced soil database containing all the information obtained from field work and laboratory analysis, along with GIS vector data containing the geometry of the soil mapping unit polygons. Hitherto the same information was produced in analogical format. Examples of soil databases and vector data themes may be found on the internet (e.g. in the USA). Soil maps can be easily accessed through services such as web soil survey programs at national scale (e.g. in the USA http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) or also at regional level (e.g., https://applicazioni.regione.emilia-romagna.it/cartografia_sgss).

Analysis of the soil map as a product must really start from its information content, which is obviously highly dependent on the scale. For the sake of this specific paper, we only report some examples of methods and standards as given in Table 3.

The availability of soil maps varies from country to country and their quality is often related to the presence of soil survey agencies. It has been estimated (Dobos et al.,

2006) that over 500 000 detailed soil profiles have been described in EU countries in the last 20–30 years. In the EU despite this potential, unfortunately many national institutions (which typically commissioned soil maps) are unwilling to reveal soil data; they only provide processed generalized products (Rossiter, 2004). By contrast, in the USA soil datasets are easily accessible (http://www.nrcs.usda.gov). The availability of soil maps obtained through DSM procedures and with a hydrological content is still rather limited (Table 1) but it embeds high potential in future prospects.

Despite this complex scenario, already reported in Dobos et al. (2006) and Jones et al. (2005), many European regions are gradually moving to adopt standardization such as the case concerning the scale of soil maps. At present, the latter are generally produced at the inventory (1:250 000) and semidetailed (1:50 000) scales.

The 1:250 000 scale aims at an inventory of regional soil resources. Most European countries either already have such maps or are in the process of obtaining them. The 1:50 000 semidetailed scale aims to produce soil information directly usable in planning and land management (mainly in agriculture and forestry) but also possibly in landscape hydrology. Availability of these semidetailed scale soil maps varies greatly: there is a marked discrepancy in map coverage from several European regions and most of the mapped areas refer to plains. This situation, to be regretted from a hydrology viewpoint (plains are just one component of a catchment), is due to the fact that public agriculture departments, aiming at better agriculture management, are the main financiers of such maps. At this scale in many countries, hill and mountain areas are rarely included in such maps.

From this scenario it seems evident that soil mapping, being heavily financed by agricultural departments and organizations, is strongly focused on providing answers to agricultural questions. This means, for instance, that the massive databases generated by soil mapping projects have no quantitative data directly usable for soil hydrology unless specific processing is performed (e.g. estimate of PTF).

In this paper we do not aim to go further into this subject. However, soil map content (e.g. data from specific soil mapping units) can be easily browsed for specific areas by searching through the many dedicated websites (such as those given above).

4 Soil mapping and environmental hydrology: interaction yet to be formed

Since soil mapping (and related soil databases) offers a rather large number and type of soil/land information and produces a qualitative and quantitative description of the spatial distribution of soils, it is evident that environmental hydrology, applied to landscape issues, can largely benefit from this type of information. The interaction between environmental hydrology and soil mapping may thus seem rather obvious but in reality it is interaction only in theory. In order to understand this issue it is very important to perform a detailed examination of the information contained in soil databases (from a hydrological perspective) rather than the usual examination of soil map legends. In fact soil map legends and reports provide a synopsis of soil information where parameters which maybe important for hydrology are not anymore available being embedded and aggregated along with other information in the process of soil mapping. This situation also applies to soil classification. Pedologists typically classify soils, indeed using updated international soil classification schemes (e.g. Soil Taxonomy: USDA, 2010; World Reference Base: WRB, 2006) that are still very much developing in the framework of agriculture/forestry (e.g. FAO, USDA) rather than in hydrology. Then hydrological features (e.g. field estimate of infiltration and runoff, water retention at specific pressure heads, etc.), if present, in the best of the cases have been employed as one of the many parameters enabling the soil classification. Then, in some cases, the final soil classification may be far from give the indication of the soil hydrological behaviour. Then the worse outcoming result is that soils classified with the same name may have a rather different hydrological behaviour. Then, from our viewpoint, it is better to focus on actual database rather than on soil classification as given in standard soil legend/report.

In Table 2 we have already reported soil features contained in the soil mapping databases. In theory, any given soil characteristic may have a direct/indirect interest in hydrology; for instance soil pH, governing the composition of the soil solution and influencing ion exchange on clay minerals, can greatly affect aggregation and hence soil porosity and hydrological behaviour. However, soil pH, even if strongly influencing the soil system and thus potentially the hydraulic properties, has no direct quantitative relationship with them. This is because pH is only one of the many soil features (processes) occurring at different spatial scales and governing soil porosity and then in turn soil hydraulic properties such as the soil water retention and the hydraulic conductivity function.

Another soil feature worth mentioning because having a closer interaction with soil hydrology is the occurrence of coatings in soils. Those are soil material typically deflocculated, transported and deposited (flocculated) in lower horizons. Water is a crucial factor affecting the occurrence of these soil features and then we would expect that their occurrence and quantification could help us in understanding underlying soil hydrology processes. Unfortunately the issue is far more complex, in fact we must consider the following: (i) coatings can be of different type such as clay, silt, organic matter etc.; then the physics governing each of these type of materials is different and it is very indeed much affect by the particle size. For instance, the usually called clay coatings are typically fine clay coatings (<0.2 microns), this is because only fine clay is able to pass through the filtering action of soils. Then this fine clay can move in very small pores (not simply in pores where bypass flow occurs) and then the hydrological significance of coatings must be related to this complexity. The next issue (ii) is that coatings can move both vertically and horizontally; then their hydrological meaning is not unique. Moreover (iii) the field quantification of these features is not always easy and its detectability (even with magnifying lenses) it depends by the degree of colour contrasts between the coatings themselves and the soil matrix; finally, (iv) coatings can be formed under different climatic condition (e.g., paleoclimate).

In order to shed some hydrological light on this matter, we reclassified all the soil features occurring in a typical soil database in accordance with their direct, indirect and negligible hydraulic relevance.

Another crucial issue we considered is the quality of the estimate/measurement of soil characters. In soil databases almost all parameters have a quantitative formalization. In reality, the methods by which this information is obtained may be qualitative, semiquantitative or quantitative, as illustrated in Table 2. This difference is important if this information is then to be effectively used in environmental hydrology (e.g., parameterization of hydrological models).

Given the complexity of the issue and the need to go into the hydrological usability of data presented in soil databases, we summarized in Table 4 the main potential and limitations in using the 17 soil features typically found in soil databases and directly related to hydraulic properties and hydrological processes. Analysis of the table clearly shows both the enormous potential but also caution in using some of these soil parameters in environmental hydrological applications.

For example, the analysis of water balance, using bucket-based models, might induce one to assume that a soil db provides high quality data for hydrological applications. Unfortunately this is not always the case because, for example, the AWC (Available Water Capacity, the reference water storage in the rhizosphere) is calculated on the basis of particle size classes by means of a PTF and not through direct measurement.

Another case worth mentioning concerns mottles. Their occurrence (frequency, size, location) is a very important index for assessing water saturation patterns. This is certainly true, but some caution must be taken if these mottles refer to iron or manganese: these two elements have rather different solubility at different pH and redox potentials. For instance, if two soils show very different pH values, then the same mottles may indicate rather different hydrological conditions. In addition, mottles can occur as the result of ancient water saturation processes, such as those occurring for instance in many Italian palaeosols in the Po Valley.

In this scenario it is also very important to emphasize that standard soil mapping does not provide true quantitative information as to ensure detailed soil spatial variability and related spatial uncertainty. In the scientific literature there are a few cases where this information has been produced ex post but in most localities this spatial information cannot be retrieved mainly (i) due to loss of data and (ii) because customers (e.g. administrative regions) who commissioned the soil survey (in many cases long ago) only rarely allow access to the original soil information in their possession (if they still have it).

The publication of soil maps and soil reports (both in analogical and/or digital format) does not include all the produced soil information but rather an extensive summary of the main soil types (reference profiles) and the related landscape features. Although this summary is a fairly standardized process where much care is taken to ensure internal consistency, it does not provide a tool to investigate the spatial variability of soils between and especially within the soil mapping units.

5 Some examples of interaction

Landscape hydrology typically requires an understanding of soil hydrology as one component of a larger environmental system. This can be generally performed through the use of soil water balance models. However, tackling landscape hydrology issues poses some classic but crucial questions concerning the type of soil water balance models to be employed. It is known that there is no generally acceptable choice between empirical (e.g. land evaluation) versus mechanistic simulation models.

Indeed, despite several positive judgments the Land Evaluation (LE) procedure has also been widely criticized by the scientific community for its qualitative and empirical basis which makes it difficult to successfully address many new soil-(agro-)environmental challenges which require the dynamic characterization of the interrelated physical and chemical processes taking place in the soil landscape. On the other hand, many theoretically problems in the hydrological application of physically-based model (e.g., physics of heterogeneity, equations and parameters scale integration, etc.) are still unsolved, despite they where posed several years ago (Beven, 1989). Moving between these two extreme approaches, it is generally accepted that an increase in model complexity provides a more accurate description of the phenomenon but also requires an increase in the number and quality of parameters and hence higher costs. Indeed, there exists the need to find the optimal model complexity in accordance with the need to obtain "the right results for the right reasons" (Grayson and Blöschl, 2000).

The latter concept was fully explored in the first of four case studies centered on the interaction between pedology and hydrology. Although the case study is devoted to a land evaluation exercise for maize production in a typical agroecosystem, it is an excellent methodological example to show the overall potential of applying hydropedology even in hydrology. The other three case studies mainly focus on soil functionality in hydrological problems. Specifically, they deal with irrigation planning and management at the district scale, aquifer vulnerability assessment, and flood forecasting in an ungauged basin. The latter and (partially) the aquifer vulnerability case study were developed by applying novel data.

5.1 Case study 1 – comparative land evaluation approaches: from the FAO framework to simulation modelling

In real life situations, where funding and data quality are the basic constraints, the logical conceptual frameworks of hydropedology may be of little help to landscape hydrologists who need to know the cost/benefit ratio of the different modelling approaches, and then whether complex models (e.g. mechanistic simulation models) are really sustainable and appropriate for a specific landscape hydrological task. In the current example an evaluation of this issue is attempted by combining pedological information and the soil hydrological characterization using models at increasing level of complexity (Manna et al., 2009).

In general, Land Evaluation (LE) has been the most commonly used procedure worldwide to address local/regional/national land use planning. Here a LE for forage maize biomass production was conducted in an area of about 2000 ha in northern Italy in the Lodi plain (Po valley) using nine alternative methods (Fig. 2). They ranged from a simpler standard LE approach to a more extensive use of physically based simulation modelling (SWAP; van Dam et al., 1997 and CropSyst; Stockle et al., 2003), using as data input a pre-existing 1:50 000 soil map with relative database, a further 100 sites located after a stochastic spatial simulation annealing procedure (Aarts and Korst, 1989) using the particle size distribution and the main chemical parameters (e.g. pH, EC, OC, etc.), and measurements of bulk density, water retention curve ($\theta(h)$) and saturated hydraulic conductivity (k_s on 50 of the 100 supplementary sites. In the remaining supplementary sites the water retention curves were derived using the PedoTransfer Function (PTF) by Vereecken et al. (1989) and the saturated hydraulic conductivity were computed using HYPRES PTF (Wösten et al., 1998). For modelling purposes, data on groundwater level (lower boundary conditions) were obtained from a monitoring site (Bonfante et al., 2010) and from the soil report. Daily climatic data were obtained from the meteorological monitoring network of Regione Lombardia (ARPA Lombardia – http://www.arpalombardia.it). The comparison between the different methods is based on both the predictive ability and cost. Locally tested remote-sensing measurements provided an independent estimate of forage maize biomass for comparison purposes; the predictive ability was calculated using several statistical indexes, including the Pearson correlation coefficient (r) and the relative variance (1-RV), while the ANOVA test was carried out to evaluate the maize biomass difference.

The outcome of this analysis (Fig. 3) demonstrates that there are four groups of models behaving similarly. Classical and hybrid land evaluation methods (methods 1, 2 and 3 in Fig. 3) provide poor results over all the LE performance indexes. These results confirm that the FAO-like approaches perform best at regional scale rather than the detailed scale of our case study. The first leap forward in results occurred when simulation modelling was used on real benchmark soils (Method 4), and to a greater extent if their hydraulic properties were measured (Method 6). These results emphasize the importance of working on real soils and on real measured data rather than processing or averaging observations of several soils.

The best prediction results were obtained by abandoning the support of the soil-mapping units, dramatically increasing the number of samplings and analyses and performing geostatistical analysis (Method 9) as a mean of digital soil mapping processing (Fig. 1). Needless to say, this approach was 47 times more costly than standard LE approaches and poses major questions on its sustainability, while method 6, which is based on a new field campaign and hydrological analysis on reference profiles, is indeed the one with all good performance indexes at the lowest cost (but still 19-fold higher than method 1). Thus, strictly speaking, this method is the cheapest to be chosen, producing consistent results.

Summing up, comparison between the FAO framework and mechanistic simulation modelling disproved the assumption that an increase in model mechanics and complexity always means an increase in its predictive ability. Indeed, in this case study, the predictive ability evolves discontinuously with respect to model complexity. Data quality is indeed the leading parameter affecting the performance of land evaluation and also plays a major role in determining final costs.

Our findings, being largely based on detailed characterization of soil hydropedological behaviour, show great potential also in other applications where such characterisation is the main land evaluation engine. This is the case for instance of addressing environmentally related topics (e.g. groundwater vulnerability, nitrate pollution, rainfall-runoff processes, etc.) where soil functions such as storing, filtering, transformation and interface for runoff generation are important. Moreover, even if this case study is not exclusively related to a landscape hydrology issue, it is in our opinion a suitable methodological example as to how the statement “the right results for the right reasons” (Grayson and Blöschl, 2000) may be concretely translated.

5.2 Case study 2 – mapping of irrigated areas

One typical issue in landscape hydrology applied to agriculture is both the planning and management of irrigation at the district scale (typically lower than 10^4 ha). This is traditionally achieved by using soil information to derive in a simplistic way the land suitability classes for irrigation (USBR, 1981). The purpose of this approach is to assess whether a soil has an inherent capacity to pay off both the overall investment plan of the hydraulic system for irrigation and to provide appropriate added value to farmers.

A case study in Sardinia (Arangino et al., 1986) can help appreciate the procedure in question: an irrigation capability class was assigned to each soil unit using the soil map information, both qualitative (i.e., drainage class, risk of soil erosion, etc.) and quantitative (i.e., clay content, EC, SAR, water table depth, profile depth, etc). These parameters were combined into an empirical multiparameter scheme (USBR, 1981) in order to produce a soil suitability map for irrigation. It is used as a template to review all the areas included in the project and also to identify new areas suitable for irrigation.

This approach is a kind of land evaluation largely employed in the world to address local/regional/national land use planning. Despite its widespread use the scientific community has largely criticized the procedure for its qualitative and empirical basis. From the optimal irrigation management standpoint, a further step should take into account the inherent soil spatial variability within each soil unit, especially of those soil properties mainly influencing the soil water balance, such as water retention and hydraulic conductivity.

The current example highlights the importance of the pedological information along with the spatial variability of soil hydraulic properties in lending a major contribution to optimal irrigation management. In this respect physically based numerical models are known to be a valuable tool to simulate soil water flow, yielding the soil-vegetation-atmosphere water balance. In particular these algorithms, once calibrated and validated to the specific conditions of a study site, can be used to improve the efficiency

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of irrigation, thus contributing to the rational use of water resources (Bonfante et al., 2010).

Unfortunately, the application of these models at the landscape scale is strongly limited by the availability of spatially variable information for correct description of the soil hydraulic behaviour. By coupling pedological information, as already available in a soil map, and a small number of hydrological analyses, D'Urso and Basile (1997) proposed a method to classify soils according to their hydrological behaviour in an earlier application of the Hydropedological Functional Unit (HFU) concept, later defined as a soil-landscape unit with similar pedologic and hydrologic functions (Lin et al., 2008).

The main points of the procedure were as follows:

1. Identification of the representative soil profile within each soil mapping unit.
2. Characterization of the hydraulic properties (namely, $\theta(h)$ and $k(\theta)$ functions) and particle-size distribution for each soil horizon of the representative soil profiles.
3. Calibration of a specific soil unit quasi physically-based PTF (Arya and Paris, 1981; Basile and D'Urso, 1997), through coupling the measured hydraulic properties and the particle size distributions.
4. Application of the calibrated PTFs to several points in the whole area.
5. Definition of specific "functional properties" (output of the simulation model) and application of the model in all the soils.
6. Classification of soils on the basis of the "functional properties" and demarcation of hydrologically homogeneous new units (HFUs).

The method was developed on a 11 km^2 river plain serviced by the Sinistra Sele Irrigation Consortium (southern Italy), an irrigated area where a soil map was already available at a scale of 1:10 000 (Fig. 4a). The drainage process following irrigation was simulated and the chosen output was the “functional property” d_{800}, defined as the number of days required to reach an average pressure head of −800 cm in the soil layer between 10 cm and 30 cm depth. The value of −800 cm is the soil pressure head at which stress starts in the chosen crop (alfalfa) and therefore the calculated “functional property” represents the optimal interval between two irrigations in the event of irrigation supply on demand. The functional property d_{800} ranges from a minimum of 4 to a maximum of 8 days. The soil classification map shown in Fig. 4a was modified to take account of the hydrological similarities highlighted by evaluating d_{800}. The new classification allows production of the HFU map shown in Fig. 4b.

5.3 Case study 3 – the role of soil in assessing groundwater vulnerability

In natural ecosystems soil filters water that falls as rain and goes into rivers. In anthropogenic ecosystems this becomes a very important function because of the soil’s ability to filter pollutants out of water. Therefore the need is increasing to assess the likelihood for groundwater to be impacted by contaminants at concentrations that would pose a health concern (the new Groundwater Directive, 2006/118/EC). Groundwater vulnerability assessment is generally performed by using one model from the following three groups (Tesoriero et al., 1998): (i) the simple and widespread overlay and index methods, (ii) process-based methods and (iii) statistical methods.

An example of the first group of models is DRASTIC (Aller et al., 1987), which is based simply on ratings and weights. Of the seven required inputs, the soil media (S), the impact of the vadose zone (I) and sometimes also the hydraulic conductivity (C) factors are calculated using the soil texture.

Here we report an example, applying a process-based method to emphasize the role of different soils in determining groundwater vulnerability in the Sarno river plain (southern Italy), one of the most polluted rivers in Europe. This plain is characterized by sandy to sandy loam soils which have a practically negligible effect in differentiating the role of the soil on applying DRASTIC-like models.

A combined standpoint, both pedological (1:50 000 soil map; Terribile et al., 2003) and hydrological, was established to select 18 soil types on the basis of the hydropedological configuration of the soil mapping units. For each soil mapping unit a reference profile was opened and in each horizon undisturbed soil samples were collected for laboratory determination of both the hydraulic properties (i.e., water retention and hydraulic conductivity) and the solute transport parameters (i.e. dispersivity). For example, Fig. 5 shows *Ap* retention curves of horizons with the same sandy loam texture. Although they show the same DRASTIC score, the hydraulic differences are considerable, reflecting both the soil structural complexity and the influence of other factors than texture on the arrangement of elementary particles in producing the actual soil pore system.

Recognition of the variability in space domain of any individual property like water retention, although significant in discriminating soils, does not itself provide reliable information on the real risk of groundwater pollution. The relation between hydropedological information and groundwater vulnerability is highly complex due to the non-linearity of the hydraulic properties and the combined effects of the soil and subsoil stratifications.

Considering the proposed limitations concerning the use of an overlay and index method (DRASTIC) and then the potential of embedding the available hydraulic information in a more mechanistic model, a process-based modelling approach was carried out. The parameters of $\theta(h)$ and $k(\theta)$ functions (van Genuchten, 1980) and dispersivity were incorporated into a 1D model (SWAP; van Dam et al., 1997), simulating the flow of water and transport of solute applying respectively the Richards differential equations and the convection-dispersion module. Functional properties representing the water flow and solute transport through a 80 cm depth section were calculated. As expected, despite the similar soil texture, reference soil pedons show very different water and solute discharge (Basile et al., 1999).

However, application of this type of process-based method is not suitable in ungauged basins where very little information, especially on hydraulic properties, is available. On the other hand, the understanding of the process, both pedological and hydrological, enabled other soil parameters already available in the soil database to be identified and selected, which were important in explaining the solute transport. The occurrence of low order clay minerals (allophone-like) in the soil matrix lends these soils distinctive physical and chemical characteristics which are very important for the water and solute fluxes (i.e. high permeability associated with high values of water retention and high CEC). From this (mechanistic) knowledge, a modified empirical scheme of land evaluation was applied. The chosen factors were: saturated hydraulic conductivity, depth of groundwater, texture, saturated soil water content, andicity (Alox +1/2 Feox). The map of groundwater vulnerability based on an LE approach was produced (Fig. 6a). It was compared with the map (Fig. 6b) produced first by applying a physically based model (SWAP) and then calculating the soil protection efficiency index (a measure of soil protection capacity): $I_e = [1 - (Df/In)] \times 100$ where Df/In is the ratio between the leaving flux at the bottom and the incoming flux at the top of a soil profile.

The pattern of spatial variability is quite similar considering the maps of groundwater susceptibility (Fig. 6) produced by the two methods (using the process-based method as benchmark). The worst soil protection capacity refers to the Pie3 unit (but also Pie1 and Pie2 units), characterized by poorly evolved mountain foothill and colluvial soils, and by poorly expressed andic properties. The soil mapping unit with the highest protection capacity is Vas1, an intra-mountain valley where soils are very deep with well expressed andic properties, and formed by re-deposition of already pedogenizated andic materials.

5.4 Case study 4 – flood forecasting in the Sangone basin

This case study evaluates the contribution of soil data to flood forecasting in an ungauged basin. In the Sangone basin the only data available refer to the meteorological and discharge time series at the closure section. This basin of about 150 km^2 shows considerable pedological and hydrological complexity. It is formed by three main geomorphologic units: the crests, the slopes at different gradients and aspects, and the valleys. The main question is to what extent a parsimonious identification of soils (*forms*) can help in interpreting the hydrological complexity hidden in flood forecasting (*functions*).

The study was performed through a comparison of the results obtained by using TOPKAPI, a physically based distributed model of infiltration-runoff processes with parsimonious parameterization. The parameter values of the TOPKAPI model can be obtained from a digital elevation model, soil maps, vegetation and land use maps. The TOPKAPI model was developed in two different forms: the distributed and the lumped (Todini and Ciarapica, 2001; Ciarapica and Todini, 2002; Liu et al., 2005; Martina et al., 2011). Several applications of the distributed model (Bartholmes and Todini, 2005; Martina et al., 2006; Diomede et al., 2008a,b; Liu et al., 2008; Vischel et al., 2008a) have shown its ability to correctly reproduce not only the discharge but also other internal variables such as soil moisture (Vischel et al., 2008b). The lumped TOPKAPI model has also been applied on several catchments with good hydrological capabilities (Liu and Todini, 2002; Martina et al., 2011).

Results obtained applying a blind (i.e. without any calibration) simulation relative to two different levels of soil knowledge were compared, namely: (i) soil characteristics retrieved after a global soil map resource, (ii) soil characteristics derived after a detailed soil survey campaign. The soils were accordingly parameterized relative to the different approaches.

In the first approach a global data set of soil types was used: the FAO/UNESCO Soil Map of the World. This data set was developed under the SOTER Programme and the FAO legend was replaced by the World Reference Base for Soil Resources (WRB, 2006). The global dataset includes 106 soil units of which four are in the study area, based on Zobler's assessment of the FAO/UNESCO Soil Map of the World. Soil properties such as soil depth and saturated hydraulic conductivity are derived for each soil type from the FAO-UNESCO soil classification. The soil-water properties, i.e., water-retention relationship and unsaturated hydraulic conductivity, are represented by van Genuchten's formula (van Genuchten, 1980). Mean saturated hydraulic conductivity is estimated using the soil texture. This dataset clearly has the limitation of a coarse resolution and of qualitative information on the soil characteristics. However, it is representative of the minimum level of knowledge available for the implementation of a hydrological model. Moreover, the dataset was also used in several applications (Doll et al., 2003; Liu et al., 2008) where other (local) sources of data were not available.

The second approach consists of the following main steps:

1. A preliminary study of pre-existing available information (soil use map, 1:250 000 soil map, 1:50 000 soil map available for the only lower plain area, 1:50 000 geological map, 10 m DEM).
2. A synopsis and definition of preliminary soil mapping units (P-SMU) obtained, along with standard thematic layers (e.g. geology, land use, etc.), using some environmental covariates data which resulted, from a pedological viewpoint, very useful for describing the specific soil distribution of the study area. Between them, a fuzzy c-means clustering to classify the DEM (de Bruin and Stein, 1998), and a study of vegetation by analysing the NDVI (Normalized Difference Vegetation Index) using Landsat and Modis images (Rouse et al., 1973; Tucker et al., 1986; Wang et al., 2004).
3. A soil survey mainly limited to describe and to sample supposedly representative profiles inside each identified P-SMU (about 50 soil profiles and 50 minipits). The choice of representative soils is indeed crucial (and questionable) in this procedure; but at the present day we do not think that there are better "sustainable" options to the use of a traditional pedological understanding (clorpt).
4. Soil chemical analysis on about 220 soil samples (pH in H_2O, pH in KCl, pH in NaF, EC, OC, CEC, EB, and then Fe, Al and Si extracted in oxalate at pH = 3).
5. A synopsis of all acquired data and definition of a schematic soil map having 19 SMU. These units were combined into the three main landscape systems namely mountain, piedmont and plain. It must be emphasise that this soil map

is named "schematic" because has much less soil observations (and then lower costs) than those required by standard soil maps (Table 3).

6. A reaggregation of those SMU expected to have, potentially, a similar hydrological behaviour, using the hydropedological reasoning given in Table 4. Then the original 19 SMU were then aggregated to form eight mapping units named here as "soil-landscape" units, because strongly based on the landscape features.

7. Determination of soil hydraulic properties at the eight soil-landscape units. In some stony soils and thin horizons, water retention and hydraulic conductivity curves were determined through an inverse method following a process of infiltration at predefined pressure heads (Šimunek et al., 1998). Undisturbed soil samples were analyzed in the laboratory by applying the fallow head method (Reynolds et al., 2002) for the saturated hydraulic conductivity, Wind's method (Arya, 2002) for the unsaturated hydraulic conductivity and the wet branch of the soil water retention curve, and the WP4-T method (Bittelli and Flury, 2009) for the dry branch of the soil water retention curve. Data were parameterized according to the constitutive functional relationships of the TOPKAPI model.

Points (1) to (6) refer to the specific contribution of pedology to discriminate the *forms* of the area and point (7) refers to the *functions* study.

In the Fig. 7a and b the results of the simulations in the two approaches are shown. As can be easily seen, simulation from the first approach using the FAO soil map reproduces none of the important features of the hydrograph such as peak flow, the rising and recession limb. Simulation from the second approach instead, which exploits the soil data collected in the field and the classification, is able to reproduce such features. The importance of the soil properties which most affect the simulation performance can be recognized.

The peak of the discharge is meaningful of the runoff mechanism. In the first parameter set, the soil is shallow and with low permeability. The runoff volume is then overestimated because the soil capacity is exceeded in much of the catchment and the volume infiltrated into the soil is very low. In the second parameter set, the soil distribution is more accurate, enabling a distinction to be made between the hillslope, with a shallow soil, and the valley, with deep, permeable soils. The peak flow is correctly estimated, which means that also the runoff mechanism is captured.

The recession limb of the hydrograph is strongly connected with the baseflow. In the first approach the baseflow is underestimated since the transmissivity of the soils, especially those beside the river, is not correctly parameterized. In the second approach the slope of the hydrograph is very similar to that observed. An important role here is played by the soils in the deposit (downstream) which, according to the parameterization, have a high transmissivity (relative soil thickness and permeability) such that the low flow is also captured.

In Table 5 are given the computed Nash-Sutcliffe (NS) and the Root Mean Square Error (RMSE) coefficients aiming to assess the overall simulation performance. Both the NS and the RMSE show a clear improvement of the model performance when the soil-landscape map is applied. Particularly the NS coefficient, which is more hydrologically based, show a large increase since both peaks and baseflow are better captured by the soil-landscape unit map rather than the FAO UNESCO soil map.

6 Conclusions

The importance of knowing the soil distribution (*forms*) and processes (*functions*), which determines a sort of physical signature of the catchment, becomes even more important in the absence of hydrological monitoring data. This applies, for example, to the crucial issue of making hydrological predictions in ungauged basins. In the general sense of making the interaction between hydrology and soil effective and also in the specific sense of producing a catchment classification system, this paper aimed to contribute to exploring potential and limitations of soil survey and soil mapping. It was shown that special care is required in handling data obtained after soil survey database if their hydrological full potential has to be achieved; one of the main reasons for this situation is the traditional goal of soil maps that are very much focused on agricultural concerns.

In this respect, the rapid development of hydropedology, a new discipline merging pedology, hydrology and geomorphology, can contribute to extending the use of soil map information. We evaluated its potential and limitations from a landscape hydrology viewpoint, using several case studies from Italy (Fig. 1). Regardless of the specific goal of these case studies (i.e., irrigation management at district scale, groundwater vulnerability assessment, peak flood forecasting, land evaluation for maize production) a common aspect concerned the complexity of the model to be applied. It is well known that, albeit not linearly, increasing model complexity and hence the accuracy of the described phenomenon requires an increase in basic data parameters and thus generates higher costs. This is even more important in ungauged basins where the lack of data is a crucial factor towards the proper modeling choice, according to "the right results for the right reasons" statement (Grayson and Blöschl, 2000). In this respect, a generalization of the methodological pathway from simple to complex modelling application in a land evaluation procedure for maize production (case study 1) can be extended to landscape hydrology issues. Despite remarks on the applicability of physically-based model at landscape scale (Beven, 1989), it was proven that, at least for this case study, the Richards' equation can be effectively applied also at landscape scale. This good result may be explained by the specific environmental setting of case study 1: (i) rather homogeneous geomorphologic situation consisting in an alluvial plain (but still having two very distinct terracing systems); this setting may have made the 1D water flow assumption feasible; (ii) no distinct pedological evidences of preferential flows (e.g. cracks, silt coatings); (iii) no distinct pedological evidences of soil layers (horizons) limiting water flow (e.g., iron pan, fragipan, etc.).

On the other hand it must be emphasised that both the identification of soil mapping units (SMU) and the selection of "representative soils" (for each soil typological units included in each SMU) is more complicate in an alluvial plain settings rather than in typical upper catchment landscape where both topography and soil outcrops better assist these critical choices made by the pedologist.

From this case study we obviously confirmed that simple approaches are less expensive and produce results commensurate with their investment but, most importantly, that a major leap in the quality of results can indeed be obtained by adding to an existing soil map (i) a representative soil profile hydrological characterization and, hopefully, (ii) a spatial analysis taking into account intra-unit spatial variability of hydraulic properties.

Then here we showed four case studies based on the "representative soil profile hydrological characterization" applied in the contest of physically-based modelling. The approach shown to be effective in reproducing inter-unit variability (case study 1) and lumped discharge data without any calibration (case study 4). It is of great interest to emphasise that case study 4, characterised by a limited dataset of hydrological measurements, demonstrated the effectiveness of a hydrology devoted and relatively inexpensive soil survey (with respect to standard soil survey approaches) only aiming to identify the main SMU and to select few representative soil profiles where to produce a soil hydraulic characterization.

Along with addressing the issue of "representative soils" indeed it is required to address the complex problem of soil heterogeneities, typically performed through a spatial analysis taking into account intra-unit spatial variability of hydraulic properties. To this respect, a simple widely used approach is the application of PTFs to spatialize soil hydraulic characteristics (parameters). This lead to assumes that the spatial variability of texture and soil pore architecture (e.g., pore size distribution, pore connectivity, water retention, hydraulic conductivity) is similar. This assumption can be rather weak considering the different underlying physics governing soil particles and soil pores; this can produce misleading results when directly using texture data for deriving hydraulic conductivity properties. To this respect, in case study 1 we showed that the heterogeneity was better described, in terms of statistics and spatial pattern, by real measurements of hydraulic properties than those estimated by PTFs.

The issue has been further explored in the case study 2 where a quasi physically-based PTF was calibrated for each soil mapping unit; in this specific case the inter-unit uncertainty was taken on board by the representative soil profile hydraulic properties measurement and the intra-unit heterogeneity estimated by the coupling of PTF and the unit-specific calibration function.

In all given case studies, soil map database have been integrated with some extra soil hydrological data. The consequent high increase in investment for such an analysis can be fully justified only in a more inclusive hydropedological framework where the same information – in terms of *forms* and *functions* – can produce integrated results in different applications with a very similar data requirement. An example of these complementarities may be the contribution of soil mapping to the production of a soil protection capability map (case study 3), which might be crucial, given its ability to overcome several limitations in current vector-based approaches.

To sum up, it is important to emphasise that effective interaction between pedology and hydrology to address landscape hydrology requires the following:

- Greater awareness on the part of hydrologists about how much and what information, both directly and indirectly related to landscape hydrology issues, lies behind a soil map in the attached soil database.

- Awareness on the part of pedologist of the need to move actual assessment of some hydrological features/properties (i.e., runoff, cracking, permeability, flood, structure, mottles, etc.) from qualitative to quantitative or at least semi-quantitative schemes to better incorporate hydrological parameters in soil classification.

- The inclusion of quantitative information on soil spatial variability (e.g., variance, semivariogram) and spatial distribution of prediction errors within a new conception of soil maps. In this framework digital soil mapping can give a major contribution to hydropedology.

- In a context of a wider environmental management planning, the use of a common base of mainly physical soil information, as a fundamental tool able to unify different soil hydrological processes.

References

Agyare, W. A., Park, S. J., and Vlek, P. L. G.: Artificial neural network estimation of saturated hydraulic conductivity, Vadose Zone J., 6, 423–431, 2007.

Aller, L. T., Bennet, T., Lehr, J. H., and Petty, R. J.: DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic setting, US EPA Robert S. Kerr Environmental Research Laboratory, EPA/600/287/035, Ada, OK, 1987.

Arangino, F., Aru, A., Baldacchini, P., and Vacca, S.: I suoli delle aree irrigabili della Sardegna, R.A.S.-E.A.F., Cagliari, 1986.

Arya, L. M.: Wind and hot-air methods. In: Methods of soil analysis, Part 4, Physical methods, SSSA Book Ser. 5., Madison, WI, 916–926, 2002.

Arya, L. M. and Paris, J. F.: A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data, Soil Sci. Soc. Am. J., 45, 1023–1030, 1981.

Basile, A. and D'Urso, G.: Experimental corrections of simplified methods for predicting water retention curves in clay-loamy soils from particle-size determination, Soil Technol., 10, 261–272, 1997.

Basile, A., De Mascellis, R., and Terribile, F.: Il suolo e la protezione degli acquiferi: studio pedologico e idrologico dei suoli della piana del F. Sarno (Campania), Quaderni di Geologia Applicata, 1, 251–261, 1999.

Basile, A., Acutis, M., Buttafuoco, G., De Lorenzi, F., De Mascellis, R., D'Urso, G., Mele, G., and Terribile, F.: L'uso di modelli idrologici di simulazione numerica nella soluzione di problemi agro-ambientali a differenti scale spaziali, Convegno inaugurale ISAFOM, Ercolano, 2002.

Basile, A., Mele, G., and Terribile, F.: Soil hydraulic behaviour of a selected benchmark soil involved in the landslide of Sarno 1998, Geoderma, 117, 331–346, 2003.

Bittelli, M. and Flury, M.: Errors in water retention curves determined with pressure plates, Soil Sci. Soc. Am. J., 73, 1453–1460, 2009.

Bonfante, A., Basile, A., Acutis, M., De Mascellis, R., Manna, P., Perego, A., and Terribile, F.: SWAP, CropSyst and MACRO comparison in two contrasting soils cropped with maize in Northern Italy, Agr. Water Manage., 97, 1051–1062, 2010.

Bouma, J.: Soil morphology and preferential flow along macropores, Agr. Water Manage., 3(4), 235–250, 1981.

Bouma, J.: Hydropedology as a powerful tool for environmental policy research, Geoderma, 131, 275–286, 2006.

Campling, P., Gobin, A., and Feyen, J.: Logistic modeling to spatially predict the probability of soil drainage classes, Soil Sci. Soc. Am. J., 66, 1390–1401, 2002.

Carré, F., McBratney, A. B., Mayr, T., and Montanarella, L.: Digital soil assessments: Beyond DSM, Geoderma, 142, 69–79, 2007.

Chaplot, V., Walter, C., and Curmi, P.: Improving soil hydromorphy prediction according to DEM resolution and available pedological data, Geoderma, 97, 405–422, 2000.

Cialella, A. T., Dubayah, R., Lawrence, W., and Levine, E.: Predicting soil drainage class using remotely sensed and digital elevation data, Photogramm. Eng. Rem. S., 63, 171–178, 1997.

Coppola, A., Basile, A., Comegna, A., and Lamaddalena, N.: Monte Carlo analysis of field water flow comparing uni- and bimodal effective hydraulic parameters for structured soil, J. Contam. Hydrol., 104, 153–165, 2009.

Costantini, E. A. C.: Rilevamento e cartografia dei suoli, Il Suolo – Pedologia nelle scienze della terra e nella valutazione del territorio, La Nuova Italia Scientifica, Roma, 259–275, 1991.

D'Urso, G. and Basile, A.: Physico-empirical approach for mapping soil hydraulic behaviour, Hydrol. Earth Syst. Sci., 1, 915–923, doi:10.5194/hess-1-915-1997, 1997.

Dent, D. and Young, A.: Soil survey and Land evaluation, Allen Unwin., London, 1981.

Di Gennaro, A., D'Antonio, A., Ingenito, M. R., Lulli, L., Marseglia, G., Terribile, F., and Toderico, L.: I suoli della provincia di Napoli, CUEN, Napoli, 1995.

Di Gennaro, A., Aronne, G., Buonanno, M., and Terribile F.: Carta dei suoli della provincia di Napoli in scala di semi-dettaglio 1:50.000, SISS, Ischia, 1998.

Dobos, E., Carré, F., Hengl, T., Reuter, H. I., and Tóth, G.: Digital Soil Mapping as a support to production of functional maps, EUR 22123 EN, 2006.

Dunne, T.: Field studies of hillslope flow processes, in: Hillslope Hydrology, edited by: Kirkby, M. J., Wiley, New York, 227–293, 1978.

FAO: Guidelines for soil profile description, Organization United Nations, Rome, 2006.

FAO: World Reference Base for soil resources. World Soil Resources, Reports n. 103, Rome, 2006.

Grayson, R. and Blöschl, G.: Spatial modelling of catchment dynamics, in: Spatial Patterns in Catchment Hydrology: Observations and Modelling, edited by: Grayson, R. and Blöschl, G., Cambridge University Press, 51–81, 2000.

Joel, A., Wesstrom, I., and Messing, I.: Mapping suitability of controlled drainage using spatial information of topography, land use and soil type, and validation using detailed mapping, questionnaire and field survey, Hydrol. Res., 40, 406–419, 2009.

Jones, A., Montanarella, L., and Jones, R.: Soil atlas of Europe, European Soil Bureau Network, European Commission, Luxembourg, 2005.

Jost, G., Heuvelink, G. B. M., and Papritz, A.: Analysing the space-time distribution of soil water storage of a forest ecosystem using spatio-temporal kriging, Geoderma, 128, 258–273, 2005.

Kravchenko, A. N., Bollero, G. A., Omonode, R. A., and Bullock, D. G.: Quantitative mapping of soil drainage classes using topographical data and soil electrical conductivity, Soil Sci. Soc. Am. J., 66, 235–243, 2002.

Lagacherie, P. and Voltz, M.: Predicting soil properties over a region using sample information from a mapped reference area and digital elevation data: a conditional probability approach, Geoderma, 97, 187–208, 2000.

Lin, H., Bouma, J., Pachepsky, Y., Western, A., Thompson, J., van Genuchten, R., Vogel, H. J., and Lilly, A.: Hydropedology: Synergistic integration of pedology and hydrology, Water Resour. Res., 42, 1-13, 2006.

Lin, H. S., Brooks, E., McDaniel, P., and Boll, J.: Hydropedology and Surface/Subsurface Runoff Processes. In Anderson, M. G., Encyclopedia of Hydrologic Sciences, John Wiley & Sons, 2008.

Manna, P., Basile, A., Bonfante, A., De Mascellis, R., and Terribile, F.: Comparative Land Evaluation approaches: An itinerary from FAO framework to simulation modelling, Geoderma, 150, 367–378, 2009.

McBratney, A. B., Odeh, I. O. A., Bishop, T. F. A., Dunbar, M. S., and Shatar, T. M.: An overview of pedometric techniques for use in soil survey, Geoderma, 97, 293–327, 2000.

McBratney, A. B., Mendoça Santos, M. L., and Minasny, B.: On digital soil mapping, Geoderma, 117, 3–52, 2003.

McDonnell, J. J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M. L., Selker, J., and Weiler, M.: Moving beyond heterogeneity and process complexity: a new vision for watershed hydrology, Water Resour. Res., 43, W07301, doi:10.1029/2006WR005467, 2007.

McKenzie, N. J. and Austin, M. P.: A quantitative Australian approach to medium and small scale surveys based on soil stratigraphy and environmental correlation, Geoderma, 57, 329–355, 1993.

McKenzie, N. J. and Ryan, P. J.: Spatial prediction of soil properties using environmental correlation, Geoderma, 89, 67–94, 1999.

McKenzie, N. J., Grundy, M. J., Webster, R., and Ringroase-Voase, A. J.: Guidelines for surveying soil and land resources, CISIRO PUBLICHING, Collingwood, Australia, 2008.

Minasny, B., McBratney, A., and Salvador-Blanes, S.: Quantitative models for pedogenesis – A review, Geoderma, 144, 140–157, 2008.

Oberthur, T., Goovaerts, P., and Dobermann, A.: Mapping soil texture classes using field texturing, particle size distribution and local knowledge by both conventional and geostatistical methods, Eur. J. Soil Sci., 50, 457–479, 1999.

Pachepsky, Y. A. and Rawls, W. R.: Development of Pedotransfer Functions in Soil Hydrology, Elsevier, New York, 2004.

Rasio, R. and Vianello, G.: Classificazione e cartografia del suolo, CLUEB Bologna, 1995.

Reynolds, W., Elrick, D., Youngs, E. G., Amoozegar, A., Bootlink, H. W. G., and Bouma, J.: Laboratory methods, in: Methods of Soil Analysis, Part 4 – Physical Methods, edited by: Dane, J. H. and Topp, G. C., Soil Sci. Soc. Am. Book Ser., vol. 5, Soil. Sci. Soc. Am., Madison, Wis., 802–816, 2002.

Ritsema, C. J., van Dam, J. C., Dekker, L. W., and Oostindie, K.: A new modelling approach to simulate preferential flow and transport in water repellent porous media: model structure and validation, Aust. J. Soil Res., 43, 361–369, 2005.

Rossiter, D. G.: Digital soil resource inventories: status and prospects, Soil Use & Management, 20, 296–301, 2004.

Salvador-Blanes, S., Minasny, B., and McBratney, A. B.: Modelling long-term in situ soil profile evolution: application to the genesis of soil profiles containing stone layers, Eur. J. Soil Sci., 58, 1535–1548, 2007.

Samouëlian, A. and Cornu, S.: Modelling the formation and evolution of soils, towards an initial synthesis, Geoderma, 145, 401–409, 2008.

Shrestha, M. S., Artan, G. A., Bajracharya, S. R., and Sharma, R. R.: Using satellite-based rainfall estimates for streamflow modelling: Bagmati Basin, J. Flood Risk Manage., 1, 89–99, 2008.

Soil Survey Staff: Soil Survey Manual, USDA handbook N. 1, 1993.

Šimunek, J., van Genuchten, M. Th., Gribb, M. M., and Hopmans, J. W.: Parameter estimation of unsaturated soil hydraulic properties from transient flow processes, Soil Till. Res., 47, 27–36, 1998.

Terribile, F., Aronne, G., Buonanno, M., Di Gennaro, A., and Leone, A. P.: Inventory of volcanic soils in the surroundings of Napoli (Italy), Proceedings of COST Action Meeting 622 on Soil Resources of European Volcanic Systems, Iceland, 1998a.

Terribile, F., Aronne, G., Buonanno, M., Di Gennaro, A., and Leone, A. P.: Un modello pedogeografico in scala di riconoscimento 1:250.000 della fascia costiera napoletana, Atti Convegno SISS “Suoli tra vulcanismo ed antropizzazione”, Ischia, 1998b.

Terribile, F., Basile, A., De Mascellis, R., Di Gennaro, A., Mele, G., and Vingiani, S.: I suoli delle aree di crisi di Quindici e Sarno: proprietà e comportamenti in relazione ai fenomeni franosi del 1998, Quaderni di Geologia Applicata, 7, 59–79, 2000a.

Terribile, F., Di Gennaro, A., Aronne, G., Basile, A., Buonanno, M., Mele, G., and Vingiani, S.: I suoli delle aree di crisi di Quindici e Sarno: aspetti pedogeografici in relazione ai fenomeni franosi del 1998, Quaderni di Geologia Applicata, 7, 81–95, 2000b.

Terribile, F., De Mascellis, R., di Gennaro, A., Ferruzzi, T., Laruccia, N., Magliulo, P., and Vingiani, S.: Carta dei suoli dell’Agro Noverino Sarnese in scala 1:50.000, Relazione finale convenzione CNR ISAFOM-Regione Campania SeSIRCA, 2003.

Tesoriero, A. J., Inkpen, E. L., and Voss, F. D.: Assessing ground-water vulnerability using logistic regression, Proceedings for the source water assessment and protection 98 conference, Dallas, Tx, USA, 1998.

USBR-Bureau of Reclamation: Irrigated Land Use, Land Classification, V, Bureau of Reclamation, Dept. of Interior, Denver Federal Center, Denver, 1981.

USDA: Keys to Soil Taxonomy, 11th edition, NRSC, 2010.

van Dam, J. C., Huygen, J., Wesseling, J. G., Feddes, R. A., Kabat, P., van Walsum, P., Groenendijk, P., and van Diepen, C. A.: Theory of SWAP version 2.0, Report 71, Dpt. of Water Resources, WAU, Wageningen, The Netherlands, 1997.

Van Genuchten, M. Th.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, 892–898, 1980.

Voltz, M., Lagacherie, P., and Louchart, X.: Predicting soil properties over a region using sample information from a mapped reference area, Eur. J. Soil Sci., 48, 19–30, 1997.

Wagener, T., Sivapalan, M., Troch, P., and Woods, R.: Catchment classification and hydrologic similarity, Geography Compass, 1, 901–931, 2007.

Wilson, J. P. and Gallant, J. C.: Terrain analysis, Principles and applications, John Wiley & Sons, New York, 2000.

Zheng, D., Hunt, E. R., and Running, S. W.: Comparison of available soil water capacity estimated from topography and soil series information, Landscape Ecol., 11, 3–14, 1996.

Table 1. Selection of works involved in the (digital) soil mapping and hydrologically relevant parameters.

Author (year)	Attributes	No observations	Cartographic scale (1:x)	Study Area (km^2)
McKenzie and Austin (1993)	clay content, CEC, EC, ph, bulk density and COLE	224	100 000	500
Zheng et al. (1996)	soil available water capacity	–	–	–
Cialella et al. (1997)	soil drainage classes	–	12 000	24
Voltz et al. (1997)	wiliting point	426	100 000	17, 36
Obertur et al. (1999)	soil texture classes	384, 208	100 000	192, 39
Chaplot et al. (2000)	redoximorphic features, hydromorphy index	182	–	0.2
Legacherie and Voltz (2000)	wilting point	374	100 000	20
Campling et al. (2002)	soil drainage classes	295 + 72	50 000	589
Kravchenko et al. (2002)	EC, soil drainge	107	–	0.2
Jost et al. (2005)	soil water storage	195		0.005
Agyare et al. (2007)	soil texture, ph, OC, CEC, bulk density, saturated hydraulic conductivity	600, 400	–	6, 0.64
Shrestha et al. (2008)	soil water-holding capacity, saturated soil hydraulic conductivity, hydrologically active soil layer depth, soil texture, rainfall	165	–	3550
Joel et al. (2009)	soil texture, groundwater level, occurence of poorly permeable layers	–	50 000 to 100 000	7260

Table 2. Example of soil features to be described in a typical pedological description. Numbers indicate the sub-characters to be described for each feature. Normal: characters with low hydrological interest. [1]Characters with an indirect hydrological interest. [2]Characters with a direct interest in hydrology. [3]quantitative evaluation. Not underlined: qualitative and semiquantitative evaluation.

Field analysis at the soil survey station (32 features)	Field analysis of the soil profile (73 features per horizon)	Laboratory analysis of the soil profile (12 features per horizon)	Process for determining water and temperature regime- soil taxonomy (monthly data from weather stations nearby)
Location	Type of horizon	pH (H_2O)[3]	Rainfall[2,3]
Type of observation	Matrix colour 4	pH (Kcl)[3]	Temperature[2,3]
Soil surveyors	Concentrations 6	CEC[3]	ET_p[2,3]
Lithology[3]	Coatings[1] 8	Exchageable bases[3]	
Land use[1]	Slickensides 2	Carbonates[3]	
Vegetation[1]	Biological activity 2	Total N[3]	
Morphology[1]	Carbonates 2	Electrical conductivity[3]	
Curvature[1]	Roots[1] 6	Organic carbon[2,3]	
Erosion 2[1]	Mottles[2]	Granulomety[2,3]	
Deposition[1]	Coarse fragments (>2 mm)[2] 10		
Rooting depth[1]			
Depth of rock[1]	Texture[2] 4		
Parent material 3[1]	Consistency 5[2]		
Elevation[3]	Structure[2] 6		
Slope[3]	Pores[2] 4		
Exposure[3]	Cracks[2] 2		
Vegetation cover[3]	Boundaries[2,3]		
Rockiness[3]			
Stoniness 2[3]			
Runoff[2]			
Cracks 3[2]			
Groundwater[2]			
Flood[2]			
Internal drainage[2]			
Permeability[2]			
Estimated AWC[2]			

Table 3. Example of soil survey and soil mapping standards.

Typical user	Type of scale	Mapping scale	*N*. obs (in 100 ha)	Remotely sensed images	Minimum polygon (ha)	Cost euro/ha
Country	Schematic	1:1 000 000		1:100 000	4000	n.d.
Country Inter-region Region	Inventory	1:250 000	0.16	1:100 000	250	0.2–0.7
Province District Watershed authorities Mountain communities	Semi-detailed	1:50 000	1–3	1:20 000 1:33 000	15	7–10
Municipal district	Detailed	1:25 000	10/50	1:8000	2	n.d.
Municipal district Farms	Very detailed	1:5000	100		0.1	400–500

Table 4a. Types of data of direct hydrological interest contained in the databases of soil maps. Abbrev: QT: quantitative; QL: qualitative; SQT: semiquantitative.

Type of soil feature (*N*. of sub-features)	Description of the feature	Method	Methodological description	Main potential	Main limitations
Cracks (3)	Occurence of cracks at the soil surface	SQT	Estimate (using comparative tables and metric measurements) of frequency, width and depth of cracks	It is evidence of processes of preferential water and pollutant flows (bypass flow)	It is a strongly anisotropic parameter, non-linear function of the water content in soil
Groundwater	Occurence of groundwater in the investigated soil profile	QL	Assessment made both on the basis of direct observations in the soil profile along with indirect information (interviews with farmers, land reclamation consertia, etc.)	Basic environmental data	Strongly quality-based measurement
Floods	Flood risk	QL	Estimate of morphometric, morphodynamic and hydraulic factors governing flood risk	Basic environmental data	Rather subjective evaluation
Runoff	Runoff estimate	QL	The class of runoff (from very low to very high) is established using a table. Slope angle and K_{sat} (or its estimate) must be known.	Basic environmental data	It is a subjective assessment because K_{sat} is rarely known. Hence assessment is made by "expert best estimate"
Internal drainage	Estimate of eater removal rate in the soil profile	QL	Assessment on the basis of slope, texture, skeleton, presence of horizons with low permeability and also hydromorphic horizons	It is a feature governing infiltration and runoff process	Stronly quality-based assessment on a parameter which is very difficult to estimate
Estimated AWC	Estimate of Available Water Capacity for vegetation	QL	Assessment based on texture, organic matter, bulk density, rock fragments, salinity, roots and soil horizon depth. Assessment is made by using tabular data and empirical formulas.	It is a feature governing infiltration and runoff process	Many of the parameters required for this evaluation are highly subjective and qualitative
Boundaries (2)	Lower limit of horizons. It is the thickness of each horizon	QT	Metric measurements (cm)	Essential basic information	This parameter can have marked spatial variability
Mottles (10)	Patches of different colours (usually related to Fe and/or Mn), on the surface of the aggregates produced by waterlogging	SQT	It describes the colour (Munsell Tables) frequency (visual estimate using comparative tables), size (metric measurement), contrast limits and location of the mottles.	It is information that enables the assessment of the (relative) degree of water stagnation (even if water is absent at the time of soil description)	The size of the mottles depends on the soil chemical and physical conditions (e.g. pH) and on the behaviour of the different ionic forms of iron and manganese. The mottles may have been produced in a climate different from the present day (e.g. palaeoclimate)

Table 4b. Types of data of direct hydrological interest contained in soil map databases. Abbrev: QT: quantitative; QL: qualitative; SQT: semiquantitative.

Type of soil feature (*N*. of sub-features) to be described	Description of the feature	Method	Methodological description	Main potential	Main limitations
Coarse fragments (10)	Estimate of soil particles larger than 2 mm (in the field)	SQT	Describes size (metric measurement), shape (using reference diagrams), lithology and frequency (visual estimate using comparative tables) of particles >2 mm	It is essential information for calculating water balance in soil.	Visual estimate by comparative tables.
Texture (4)	Estimate of soil particles smaller than 2 mm (in the field)	SQT	Assessment, using stadardized tactile tests schemes (e.g. USDA), of textural class and/or % estimate of sand, silt and clay	Essential parameter to estimate many hydrological parameters	Evaluation of % data requires much experience and also calibration on the specific soils under investigation
Structure (96)	Analysis of soil aggregates.	QL	Description of type (comparison with diagrams), size (matrical analysis) and degrees of destinctness of the aggregates in soils	It is a feature strongly governing the dynamics of water and pollutants in soil	It is a feature of a strongly qualitative assessment
Pores (4)	Estimate of soil macroporosity (pores >0.1 mm)	SQT	Description of size, frequency and shape (comparative tables) of macropores, using a magnifying glass (10 X)	It is a feature, connected to structure, which strongly affects water and pollutant dynamics	It is a rather difficult feature to determine. It is appraised by a strongly quality-based assessment
Cracks (2)	Occurence of cracks within a soil horizon	SQT	Frequency estimate (comparative tables), width and depth of cracks (metric measurements) in soil horizons.	Sign of potential bypass flow processes	Parameter strongly anisotropic with non-linear function of the soil water content
Consistence (5)	Soil features related to cohesion and adhesion	QL	Description of consistence and plasticity of soil aggregates by means of their resistance to hand breakage, type of breakage, degree of cementation, adhesiveness and plasticity.	It is another feature that, by influencing soil structure, can also soil hydrologic behaviour	It is a feature determined by a strongly quality-based assessment

Table 4c. Data included in the standard soil database (from soil mapping) with a direct hydrological interest. Abbrev: QT: quantitative; QL: quality; SQT: semiquantitative

Type of soil feature (*N*. of sub-features) to be described	Description of the feature	Method	Methodological description	Main potential	Main limitations
Granulometry	Laboratory analysis of the particle size classes (at least sand, silt, clay)	QT	Analysis of frequency of coarse fragments, coarse sand, find sand, silt and clay (e.g. Pipette method of hydrometer method). Since sil particles can be aggregated by organic or inorganic cementing agents, real granulometric analysis (after dissolving all cements) or apparent granulometric analysis (no pretreatments) can be performed.	Basic information for many hydrological evaluations. It is a very robust parameter governing many physical processes	Soils with similar granulometry can still have very different hydrological behaviour. This is especially th case for permeability, depending on meso and macropores, but also for water retention properties, which can change according to clay mineralogy (kaolinite versus smectite ratio)
Organic carbon	Laboratory analysis of organic C content	QT	% of organic C (e.g. typically performed after dichromate oxidation method)	It is a soil feature that strongly affects soil structure, porosity and hence many physical processes	Soils with the same organic carbon content may have very different physical properties
Water regime	Simplified water balance	QT	This analysis is generally performed to classify soils according to the Soil Taxonomy (USDA) classification scheme. Examples include Xeric Ustic, udic, aquic moisture regime. This analysis consists in a simplified water balance on the basis of monthly rainfall and evapotranspiration data and of sil AWC. Evaluation is made using bucket-based models (e.g. Billeaus, Newhall) for a specific soil depth (control section)	It is a rather synthetic but very useful assessment. It is strongly associated to the physical reality of soils	The assessment of the “water regime” is very much affected by the required rather coarse quality of inputs. This is the case for AWC, rainfall and evapotranspiration. It is a description of the rather “static” water balance.

Table 5. Statistical indexes of the simulated discharge applying FAO and soil-landscape map.

Parameter	FAO soil map	Soil-landscape unit map
Nash-Sutcliffe coefficient	0.21	0.89
RMSE ($m^3 s^{-1}$)	14.68	6.58

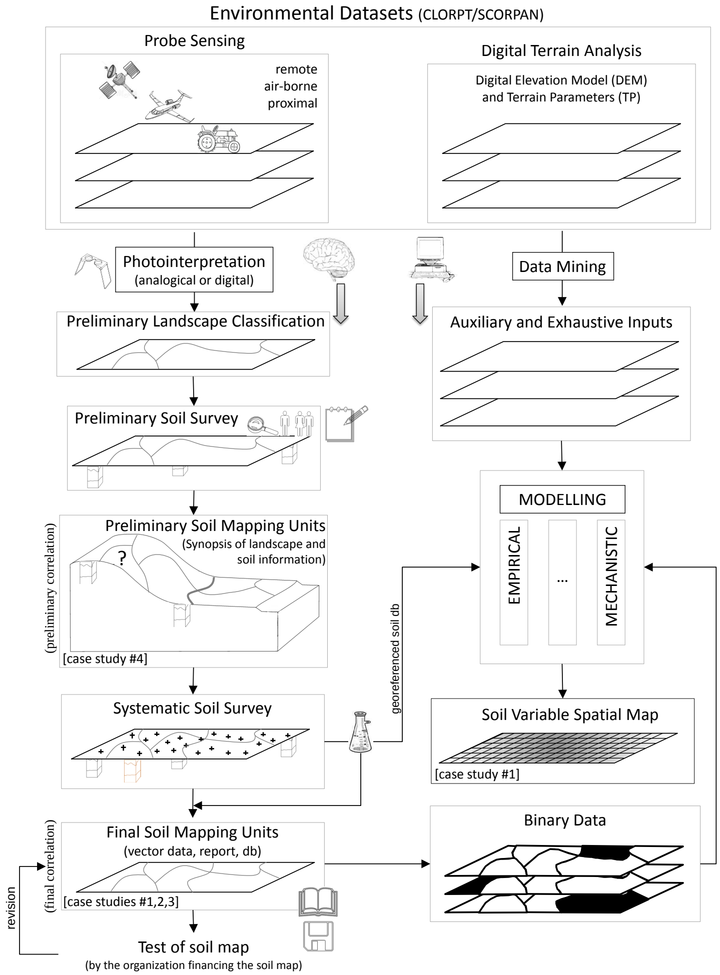

Fig. 1. Data flow of the main steps involved in both conventional and digital soil mapping.

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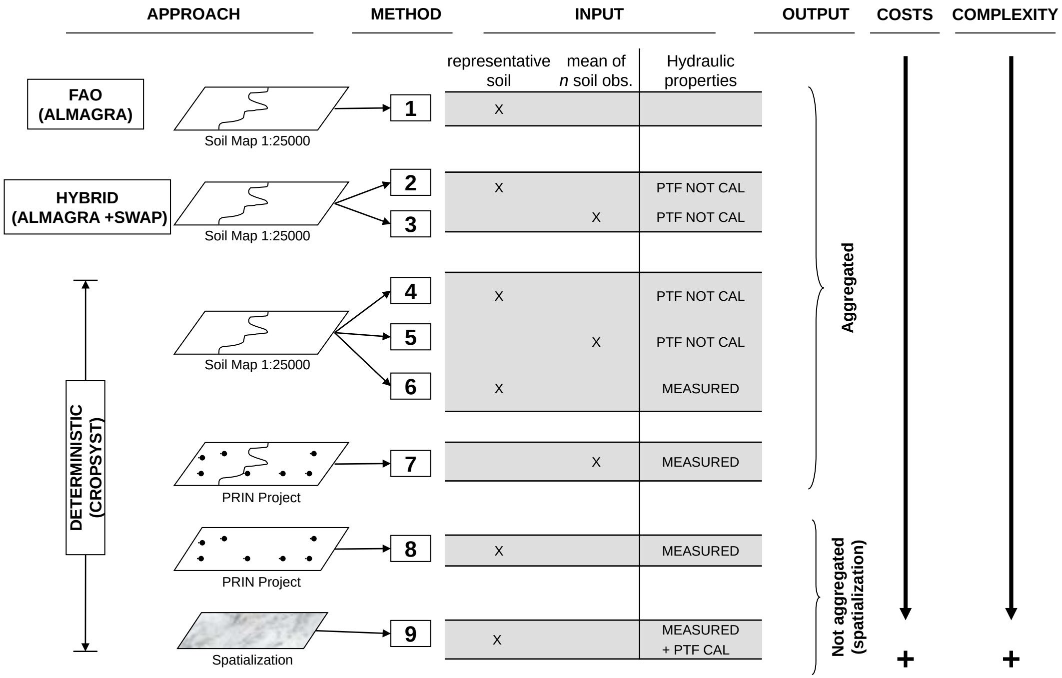

Fig. 2. Case study 1: schematic view of the different approaches applied and their main characteristics.

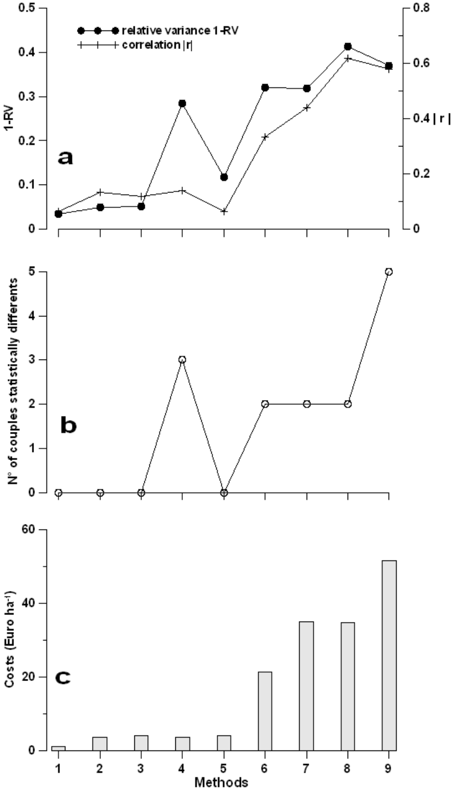

Fig. 3. Case study 1: performance indexes of the different tested LE methods in relation to the level of complexity.

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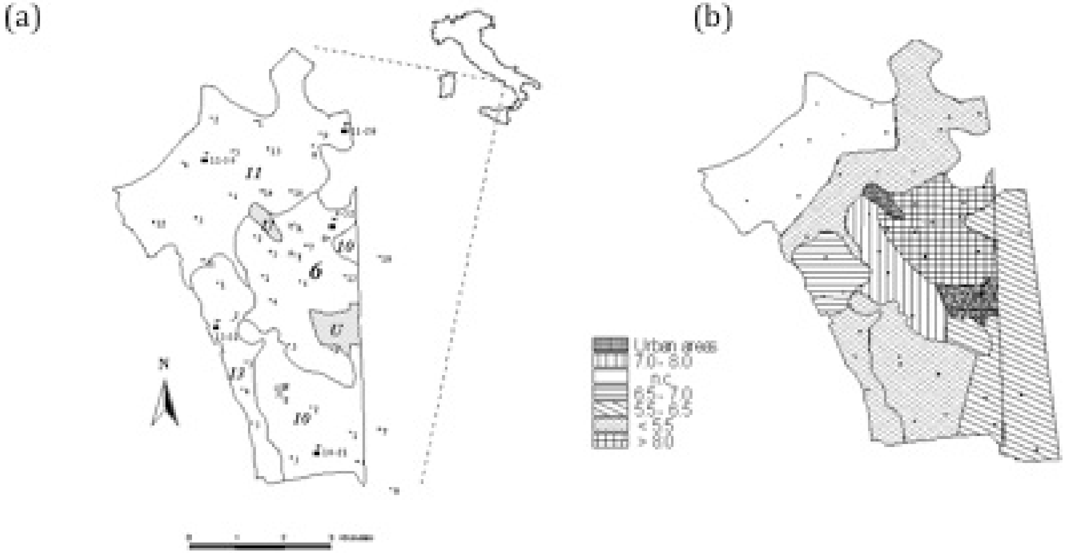

Fig. 4. Case study 2: **(a)** Soil map and **(b)** Hydrological Functional Units classified on the basis of the “functional property” d_{800}.

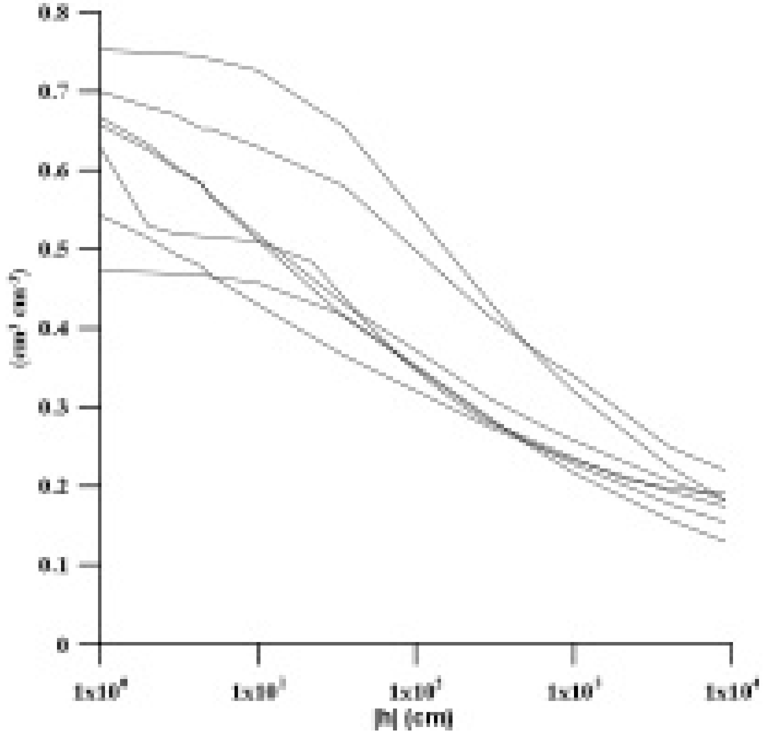

Fig. 5. Case study 3: soil retention curves of surface horizons with the same risk score in the DRASTIC-like models.

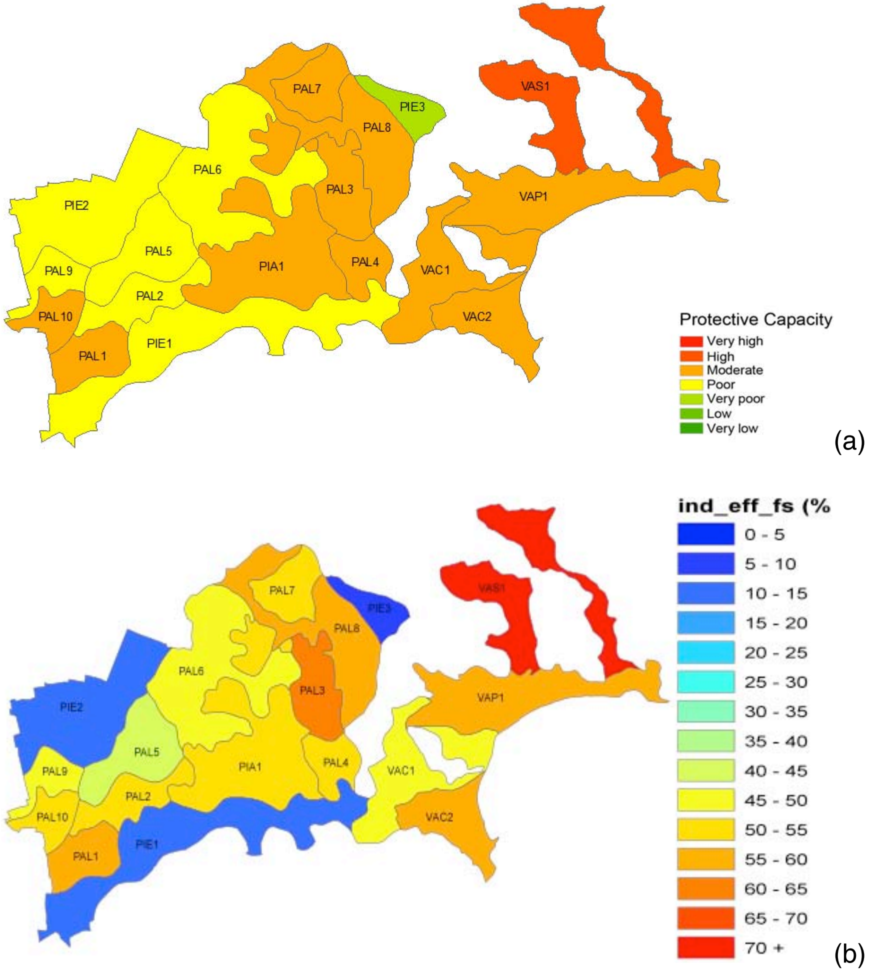

Fig. 6. Groundwater vulnerability zoning considering soil protection capacity with **(a)** a simple LE scheme and **(b)** a process-based model.

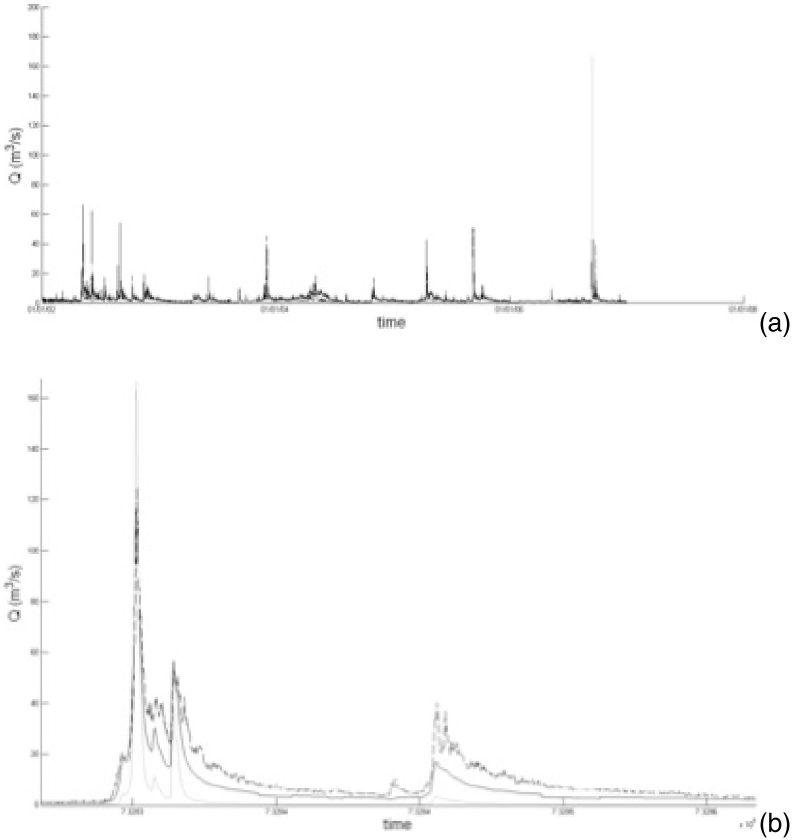

Fig. 7. **(a)** Hydrograph of the Sangone catchment from January 2002 to September 2006. Dashed line is the observed discharge, grey line is the simulation using the FAO dataset, and black line is the simulation using the soil-landscape data set. **(b)** Hydrograph of the Sangone catchment at the main flood event in September 2006. Dashed line is the observed discharge, grey line is the simulation using the FAO dataset, and black line is the simulation using the soil-landscape data set.

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