A methodology to map the surface soil hydraulic conductivity at saturation in mesoscale Alpine basins

STEFANO BARONTINI, ALBERTO CLERICI, ROBERTO RANZI & BALDASSARE BACCHI

DICATA Department of Civil Engineering, Architecture, Land and Environment, University of Brescia, Via Branze, 43. I-25123 Brescia, Italy

barontin@ing.unibs.it

Abstract An experimental field- and laboratory-based methodology is presented to get quantitative maps of the upper soil vertical hydraulic conductivity at saturation. The hypothesis that the soil response to a rainfall event is largely influenced by its lithology, and land cover is introduced, obtaining a preliminary qualitative infiltration map. A protocol of soil investigation, based on the use of the single-ring infiltrometer and of the laboratory falling-head permeameter, is then defined. *In situ* and laboratory measurements of the upper soil conductivity are performed for each infiltration class and a mean value is derived. Two different methods to treat the field data are recalled, and their reliability is discussed after the analysis of the data collected in our campaigns. As an application of the methodology, the conductivity maps of three mesoscale Alpine basins were drawn. The use of field infiltration tests interpreted within a 2-D theoretical framework was addressed as a reference standard procedure.

Keywords hydraulic conductivity at saturation; conductivity map; mesoscale Alpine basin; single ring infiltrometer; falling head permeameter; infiltration; Jenny's equation; Darcy's law; Reynolds & Elrick's law

INTRODUCTION

The vertical hydraulic conductivity at saturation in the upper soil layers, K_s, is a key property affecting a number of hydrological processes. Particularly in mountain basins and during heavy rainfall events, it plays an important role in the separation between quick overland flow and low flow components such as interflow and baseflow. In hydrological applications, quantitative K_s maps can therefore be of great importance for implementing physically-based rainfall–runoff models. The upper layers of mountain soils, due to weathering and to intense erosion, transport and sedimentation processes, are highly non homogeneous, even at small scales. Often soils are rich in organic matter content, root cavities and animals holes, and where the clayey fraction is not negligible desiccation cracks are observed after drying. Therefore the usual relationships based only on physical properties of the porous medium, such as characteristic grain size and porosity, prove not to be fully reliable to predict acceptable estimates for K_s. On the other hand, due to a variability frequently spanning several orders of magnitude, to a scale of variability often finer than the scale of sampling (Schloeder *et al.*, 2001), and to the cost of the experimental activities, it is really difficult to guess an "objective" and "experimentally based" quantitative map of surface conductivity over a whole mesoscale basin (from few hundreds to few thousands square kilometres). Here, after a long experimental activity over the past eight years, when 373 experimental sites were investigated, we propose and discuss some aspects of a mapping methodology originally formulated by Clerici & Cantoni (2000). This methodology is based on a preliminary delineation of a potential infiltration map, following a CN like method (cf. USDA, 1986), and on the use of the single ring infiltrometer and of the falling head laboratory permeameter measurements to derive K_s values. The single ring infiltrometer in fact, because of its simplicity and low cost, is still widely used in field campaigns (Lassabatère *et al.*, 2006) especially in mountain areas (Orlandini *et al.*, 1999). The falling head permeameter, on the other hand, is a standard laboratory instrument. The methodology was applied to derive the K_s map of three Alpine mountain basins, respectively characterised by mainly metamorphic rocks (Toce River basin at Candoglia, 1532 km^2, 146 experimental sites, Barontini *et al.*, 2005), by significant intrusive formations (Oglio River basin at Costa Volpino, 1433 km^2, 100 sites) and by mainly sedimentary rocks (Mella River basin at Stocchetta, 311 km^2, 127 sites, Barontini *et al.*, 2005).

THEORETICAL ASPECTS

Preliminary map-delineation

A key aspect of an experimental methodology to map a soil property over wide areas is to obtain realistic areal values with an acceptable number of field and laboratory tests. To do so, a goal is to successfully merge the "hard" (Bogaert & D'Or, 2002) and quantitative, but localised, information coming from field and laboratory tests with the "soft" one of soil and land use maps. In this case the problem can be stated as how to subdivide the whole area into homogeneous areas with comparable hydraulic behaviour. Recalling the traditional Dokuchaev approach formalised in Jenny's equation (Jenny, 1941) a soil state or a soil property *S*, can be seen as a function of five factors:

$$S = \mathrm{f}(c, o, r, p, t,) \qquad (1)$$

in which the symbols stand for climate (*c*), organisms (*o*), relief (*r*), parent material (*p*) and time (*t*). Here the dependency of the soil physical properties on the parent material and the organic agents will be stressed. Following, in fact, the traditional practice of the CN method (USDA, 1986), two main soil characteristics are hypothesised to significantly affect the soil response to a rainfall event: an intrinsic soil feature directly related to the porous matrix characteristics affecting the water content dynamics, and a second one related to the effects induced by the soil use on the porous matrix. The hypothesis to assume the soil lithology as an intrinsic feature and the land cover as an index of the soil use is then introduced. The soil lithology, in fact, provides information about the soil forming rock and its evolution processes, which are strongly related to the mineralogy, the grain size distribution, the soil maturation, and eventually its hydraulic behaviour. According e.g. to Zonn (1986) the soil forming rocks can be preliminarily classified, regarding their compactness and the source of porosity, into massive rock, porous rock and loose rock. Further sub-classification can account for the mineral composition (siliceous rocks, carbonates or argillites) or the genesis of the sediment (debris, moraines, alluvia). Particularly for the loose rock it is important to apply more detailed classifications in which the age and the elevation are kept in evidence. As an example in mountain and hill basins in the southern region of the Italian Alps, more recent tills are expected to have a higher hydraulic conductivity than ancient frontal moraines, whose soils are more significantly mobilised and altered. At the same time, slope debris and alluvia belonging to different height and slope classes in the basin will be distinguished because different vegetation type and differential sedimentation affect the soil maturation, its grain size distribution and its hydraulic properties. The land-cover map can be classified according to the development of the root apparatus. Typically four main kinds of coverage are evidenced: forest or woodland with deep and well developed root apparatus, grass fields, bare soil and cultivated areas. Urban areas can have an effect on the infiltration capacity of the basin and, if not of minor importance, can be accounted for as a separate class. By a cross-tabulation of these two maps (lithology and land cover) a qualitative infiltration map is delineated. This map classifies the surface soil of the basin in areas expected to be characterised by a homogenous hydraulic behaviour.

Soil conductivity after field data

A mean value of conductivity needs to be assigned to each class. To determine K_s from single ring infiltrometer measurements, several different methods, both mono-dimensional and bi-dimensional with axial symmetry, have been presented and compared in the literature (see e.g. Smettem & Smith, 2002). They can be roughly classified into methods focused only on the soil volume inside the infiltrometer, and methods considering the water dynamics into a semi-infinite (eventually homogenous and isotropic) porous medium. A method belonging to the first class is derived as a straight application of Darcy's law to a quasi-steady, uniform, mono-dimensional flow in a saturated porous medium, which is the volume of soil inside the infiltrometer (it will be further referred to as DA method). The flow rate through the control volume, known as the drawdown of the water level, inside the infiltrometer is measured. A reliable hypothesis about the falling hydraulic head infiltrometer is that after a long imbibition all the soil inside the infiltrometer is saturated and, neglecting a residual suction, the pressure head at its bottom is set at the atmospheric value. K_s can be therefore determined as a fitting parameter of Darcy's law. Among the bi-dimensional methods, the seminal solution for steady infiltration from a shallow circular pond of negligible depth, with axial symmetry, was originally proposed by Wooding (1968) who integrated the Richards equation linearised with Gardner's constitutive laws. Wooding's solution can be used in its original form, or adapted to different field and test conditions. In order to account for the effects of the ponding depth, soil capillarity and scale effects due to the ratio between the ring diameter and the depth of ring insertion into the soil, Reynolds & Elrick (1991) proposed an empirical modification (further referred to as RE method) which expresses the steady infiltration rate as a linear function of K_s.

OPERATIVE PROTOCOL

The proposed methodology is characterised by eight main steps: (a) mapping the lithology, (b) the soil-use and (c) the qualitative infiltration classes, (d) selecting the experimental sites, (e) executing *in situ* and (f) laboratory measurements, (g) data processing, (h) assignment of a legend to the "experimental" map of conductivity. In the following, these points will be briefly discussed.

Mapping the lithology, the soil-use and the qualitative infiltration classes

The lithologic map can be derived from information in the literature, as long as it is at a coherent scale with the scale of interest, and will describe the genetic characteristics of the upper soil layers. A preliminary classification into 6–10 lithologic classes can be suitable for further analysis. The soil use can be mapped on the basis of inventories of the land cover characterisation. For Europe the map of the CORINE Land Cover project is a standard reference and can be reclassified into a few classes (three or four) accounting for the different root apparatus and the anthropogenic effects. The qualitative infiltration classes map is finally drawn by cross-tabulation of the two preliminary maps and will be the reference of all the foregoing experimental work. The resulting number of classes can be high (up to 20–40), but some classes will be frequently representative of only a small fraction of the investigated area (say, <5%). The total number can be therefore reduced and these areas are assigned to the most similar ones. A number of 10–15 classes for the resulting map can be a realistic compromise. In Fig. 1(a)–(c) the preliminary maps of the Mella River basin are presented. The potential total number of 32 classes (cultivated areas and discontinuous urban areas were separately accounted) was reduced to 17 classes.

Location of the experimental sites

The criterion for the location of the experimental sites is multi-faceted and should be approached at a global and also at a local scale. For the global scale sampling the sites can be selected either on a regularly spaced grid, or randomly within some representative areas pertaining to each infiltration class. The grid element will be chosen according to the dimension of the basin and in order to get a reasonably high number of experimental points. The density of the sampling sites depends on a cost–benefit analysis. A range from 80 to 120 points is suggested for a basin up to 10^3 km^2 in extent. At the local scale the points identified by the regular or random sampling can be slightly changed or integrated on the basis of the logistics and the accessibility to the sites. In our campaigns a number of about 120 sites was chosen on average for each investigated basin. It is recommended to reach a fair balance between the percentage of area covered by each class and the percentage of experimental sites belonging to the same class.

Performance of the experimental in situ and laboratory activities

The method of the single ring infiltrometer, with a falling head measurement of the infiltration rate, is suggested during the field campaign. According to the ASTM standard, during our campaigns iron cylinders (with a height of 0.4 m and a diameter of 0.3 m and 0.36 m, respectively) were driven into the soil for a length of about 0.1 m and filled up to a standard head of 0.26 m. Then the drawdown was measured. Flat or sub-horizontal areas were chosen to perform the infiltration tests so that the axial symmetry of the infiltration process was a realistic hypothesis. The preliminary procedures last about 15 minutes, while the duration of the test depends on the soil characteristics, and ranges between some minutes and some hours. Four field infiltration tests were conducted at each experimental site. The first test was generally performed on the soil surface under natural moisture conditions; then the soil was (almost) saturated with about 0.1 m^3 of water slowly poured out over a circular area of about 1 m^2 around the infiltrometer. Then the surface test under modified ("saturated") soil moisture was performed. The degree of saturation was afterwards verified in the laboratory over a core sampled after the modified-moisture infiltration test. Finally, two other infiltration tests were performed at the same sites, after scouring a soil depth of 0.1 and 0.2 m. In order to better understand the retrieved data, useful observation can be collected during *in situ* activities. These are, e.g. the genesis and the morphology of the local sediment, a volumetric estimate of the grain size distribution curve (particularly of cobbles), the local soil cover, the upper soil layers depth and, when possible, the total soil unity depth.

As a comparison with *in situ* measurements, a falling head permeameter was considered reliable to estimate K_s in the laboratory for most of the soils. For this purpose almost undisturbed soil cores (diameter 0.10 m and height 0.14 m) with a volume of about 0.001 m^3 were collected at each experimental site, weighed and saturated in the laboratory. The samples were also used to measure the soil water content and the porosity, and to determine the grain size distribution curve (by wet sieving) and the soil-water retention relationship in the Richards apparatus. As an additional datum, the organic matter of some soil samples was determined by burning the oven-dried samples in a muffle furnace at temperatures of 440°C and 600°C according to ASTM standards.

Data treatment and assignment of a legend to the map of conductivity

Performing almost two different infiltration tests in each site, at natural and at modified soil water content, allows the guessing of a wide range of hypotheses about the physical phenomena taking place, and different falling head *vs* time curves can merge the hypotheses of different theoretical frameworks. The RE method is more suitable to be applied to the final part of the infiltration curve at natural soil water content. It needs, in fact, a reliable estimate of the initial water content and steady flow conditions. Moreover, the hydraulic head inside the infiltrometer is low and quasi-steady and the hypothesis of constant head can be realistic. The DA method, instead, is more suitable to be applied to the final part of the curve measured at modified soil water content. This method, in fact, requires the hypothesis of saturated flow and of uniform hydraulic head at the bottom of the infiltrometer. Once the local values of the hydraulic conductivity at saturation are estimated, an areal equivalent value is determined for each class. At surface saturation the vertical flow can be described as a parallel flow, and an arithmetic average between all the values belonging to the same class is suggested. As compared to, e.g. a geometric averaging, in which the relative importance of the different orders of magnitude is stressed, the arithmetic average focuses on the importance taken by more strongly permeable areas in the infiltration process and can be considered more realistic at describing the process for saturated soils. In some cases differential sedimentation or different age of the soil units can lead to systematically different conductivity values. In these cases it is recommended to divide the soil class into more homogeneous subclasses before averaging the conductivity values. As a result the conductivity map of the Mella River basin is proposed in Fig. 1(d). For this application the conductivity was determined on the basis of the RE method (for details on the values assigned to each class, see Barontini *et al.*, 2005).

DISCUSSION

The methodology focuses on the capability to provide reliable and quantitative surface conductivity maps of mountain soils after a preliminary map delineation and field and laboratory

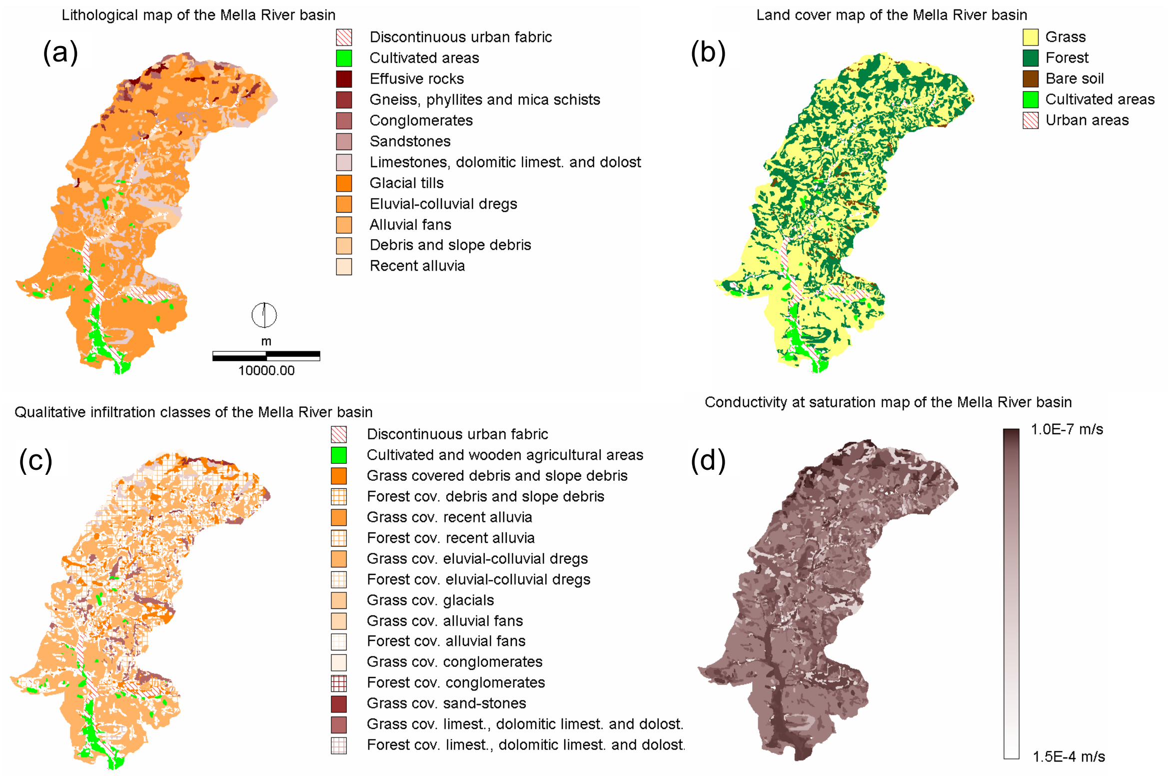

Fig. 1 (a) Lithologic map, (b) land cover map, (c) qualitative infiltration map and (d) map of the hydraulic conductivity K_s at soil saturation for the Mella River basin.

measurements. In this sense it allows us to merge the qualitative information coming from soil and land cover maps with the quantitative and localised one coming from experimental practice. Moreover it helps to design the experimental campaigns. As it can be seen in the example of Fig. 1(d), the averaged values obtained for each class are realistic and span three orders of magnitude. Particularly, for the Mella River basin, a higher variability of the conductivity values is evidenced in the higher part of the basin, with sensitivity to the lithologic class, while a lower variability was observed in the central and lower part of the basin. A key aspect of the procedure, because it can strongly affect the resulting map, is the choice of the theoretical framework to interpret the single ring infiltration test data to guess realistic conductivity values. The reliability and the applicability of the two methods previously introduced is discussed in the following. The Darcy method, which focuses the attention on the control volume inside the infiltrometer, does not account for the soil suction below. It is therefore highly expeditious for it does not need the soil water retention relationship to be determined. As compared to other methods of field data analysis, this approach can not be fully satisfactory and systematically seems to overestimate K_s. As an example in Fig. 2(a) a comparison between the DA and the RE approach is represented for the soils of Mella River basin. Analogous results were obtained for the investigated soils in the Toce River basin (Barontini *et al.*, 2005). On the other hand, the hypotheses of homogenous and isotropic soil, assumed also by the RE method, are sometimes strong in mountain areas, even at the scale of the soil volume investigated in the field operations. In fact mountain soils are often only a few decimetres deep and they are affected by intense erosive and sedimentation processes. Anisotropy between vertical and lateral conductivity, with lateral conductivity usually higher than the vertical one, is often expected joint to a decay of both vertical and lateral conductivity toward the vertical profile. In this case the steady water content patterns (cf. Chen & Gallipoli, 2004) are different from the bulbs of equal soil water content obtained for a homogeneous soil (cf. Wooding, 1968). The RE methods therefore provide a conductivity value for an equivalent homogeneous and isotropic soil in which the same infiltration test can be observed under the same initial conditions.

Accepting "conventional" conductivity values or looking for more realistic ones, by changing time by time the theoretical interpretative framework, means somehow to choose between standard or site-dependent interpretation of field data. Provided that the RE method describes a 2-D axis-symmetric unsaturated flow, and takes into account a number of experimental features, it can be proposed as a standard interpretative method. Moreover accounting for an observed good correlation between DA and RE estimates (Fig. 2(a)), a small number of experimental sites, large enough to fit the power law regression relationship, can be investigated with both the methods, and then DA values can be used to get more reliable RE estimates without determining the soil-water retention relationships at each site.

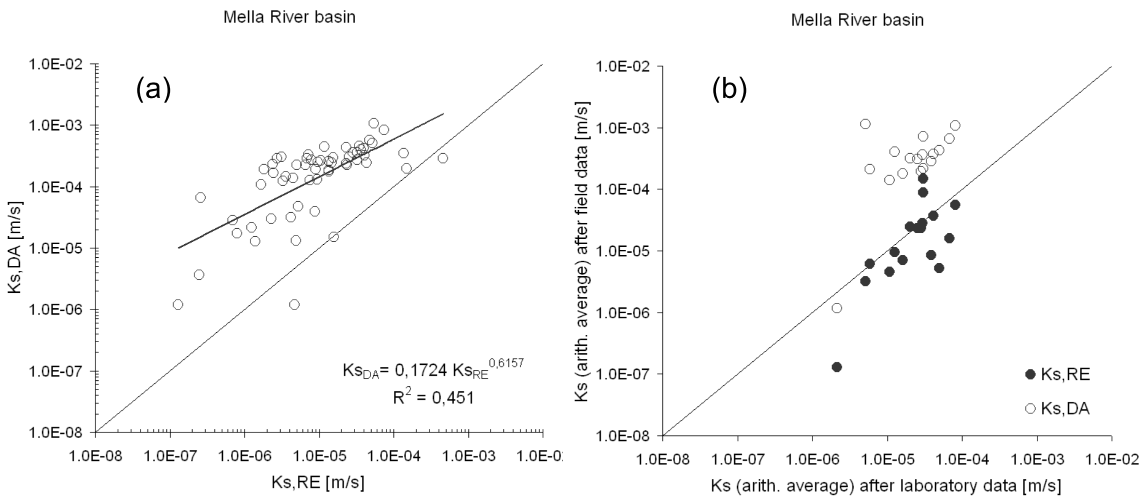

Fig. 2 Comparison between DA and RE method of estimating K_s (a). Comparison between arithmetic average of field and laboratory estimates K_s for different soil classes (b).

As a comparison with the values obtained after field data analysis, laboratory experiments were performed over soil cores sampled in the same experimental sites. Also the laboratory analysis of surface soil cores can be affected by significant uncertainties due to the sampling operations, which can modify the structure of the soil. Uncertainties and soil disturbance are even more significant if the core is extracted from the socket punch to be put in the laboratory permeameter. The scatter between conductivity values obtained after field (RE method) and laboratory experiences is large, but not biased (Barontini *et al.*, 2005), and a rather good agreement was observed for average values (Fig. 2(b)). Also laboratory values, if not locally, at least on average can therefore be regarded as informative of the conductivity of the investigated class.

The reduction of K_s between the upper and the lower soil layers can be investigated after the infiltration tests performed at lower depth. The DA method applied in this analysis. After long imbibition and much water poured in the surrounding soil, in fact, a close to saturation state can be hypothesised in the soil downward of the infiltrometer. During our campaigns an exponential decay was used to fit the reduction of the conductivity with depth, obtaining a characteristic length of exponential decay L = 0.19 m and L = 0.12 m for the Toce and the Mella River basin, respectively.

CONCLUSIONS

An experimental methodology based on the use of the single ring infiltrometer to draw quantitative maps of vertical hydraulic conductivity at soil saturation in mountain basins was presented and discussed. The hypothesis is that the soil response to the rainfall process is widely influenced by its lithology and land cover was introduced in order to map the soil infiltration capacity. A standard protocol was designed to suggest an objective experimental approach and, at the same time, a realistic interpretation of the field infiltration data. Comparing the obtained field value of conductivity with laboratory measurements, the application of this methodology to three mesoscale basins in the Italian Alps provided quite encouraging results. The arithmetic average of experimental values was suggested as reference areal values for the infiltration classes.

Acknowledgements This research was partially funded within the projects "RAPHAEL" (Contract ENV4-CT97-0552), "Runoff and pollution production and propagation in river basins" (University of Brescia). The activity of two authors was partially funded within the project "Study of a hydrogeological system to assist flood control in the Red River Delta" (Italian Ministry of Foreign Affairs) and "Drought Forecast and Mitigation" (Italian Ministry of University and Research). The students who helped us to collect most of the data we analysed are gratefully thanked.

REFERENCES

Bogaert P. & D'Or, D. (2002) Estimating soil properties from thematic soil maps: the Bayesian maximum entropy approach. *Soil Sci. Soc. Am. J.* **66**, 1492–1500.

Barontini, S., Clerici, A., Ranzi, R. & Bacchi, B. (2005) Permeability and retentivity curves in mountain soils: from point to area estimate. In: *Climate and Hydrology in Mountain Areas* (ed. by C. de Jong, D. Collins, & R. Ranzi), 101–121. John Wiley & Sons, Chichester, UK.

Chen, G. J. & Gallipoli, D. (2004) Steady infiltration from buried point source into heterogeneous cross-anisotropic unsaturated soil. *Int. J. Numer. Anal. Meth. Geomech.* **28**, 1033–1055.

Clerici, A. & Cantoni, A. (2000) Misure in sito ed in laboratorio della velocità di infiltrazione e della permeabilità dei terreni superficiali nel bacino del Fiume Toce (Piemonte, Italia). *University of Brescia (Italy), Dep. of Civ. Eng. Tech. Report XIII/2000.*

Jenny, H. (1941) *Factors of Soil Formation. A System of Quantitative Pedology*. McGraw-Hill, New York, USA.

Lassabatère, L., Angulo-Jaramillo, R., Soria Ugalde, J. M., Cuenca, R., Braud, I., & Haverkamp, R. (2006) Beerkan Estimation of Soil Transfer Parameters through Infiltration Esperiments – BEST. *Soil Sci. Soc. Am. J.* **70**, 521–532.

Orlandini, S., Perotti, A., Sfondrini, G., & Bianchi, A. (1999) On the storm flow response of upland Alpine cathments. *Hydrol. Processes* **13**, 549–562.

Reynolds, W. D. & Elrick, D. E. (1991) Determination of hydraulic conductivity using a tension infiltrometer. *Soil Sci. Soc. Am. J.* **55**, 633–639.

Schloeder, C. A., Zimmermann, N. E. & Jacobs, M. J. (2001) Comparison of methods for interpolating soil properties using limited data. *Soil Sci. Soc. Am. J.* **65**, 470–475.

Smettem, K. R. J. & Smith, R. E. (2002) Field measurements of infiltration parameters. In: *Infiltration Theory for Hydrologic Applications* (ed. by R. E. Smith), *Water Res. Monogr. N.15*. AGU, 135–158.

USDA (1986) Urban Hydrology for Small Watersheds. *USDA, Nat. Res. Cons. Serv., Cons. Eng. Div., Tech. Rel. 55.*

Wooding, R. A. (1968) Steady infiltration from a shallow circular pond. *Water Resour. Res.* **4**, 1259–1273.

Zonn, S. V. (1986) *Tropical and Subtropical Soil Science*. MIR Publisher, Moscow, Russia.