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A comparative assessment of the estimates of the saturated hydraulic conductivity of two anthropogenic soils and their impact on hydrological model simulations

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MEASUREMENT TECHNIQUES

Field measurement techniques

Guelph permeameter (GP). Guelph permeameter is considered as one of the widely used methods for the Ks in-situ determination. It is a constant-head well method. Measurements using this instrument require borehole preparation within which a constant water level should be maintained (Reynolds & Elrick 1986). Measurements can be carried out using single head, double head or mixed head methods. Conversely to the laboratory techniques, the GP provides an equivalent Ks estimate, which accounts for both vertical and horizontal Ks in case the soil is anisotropic. According to the Eijkelkamp reference manual (Eijkelkamp 2011), measurements can be carried out at soil depth from 15 cm up to 75 cm below the soil surface with hydraulic conductivity ranging between 0.864 cm/day and 864 cm/day (10^{-4} and 10^{-7} m/s). This method may be used also to estimate the vertical variation of the equivalent K_s along the soil profile, which is very important for the characterization of layered soils. The main limitation of the GP use is that K_s can be underestimated due to soil compaction and smearing of the borehole (Mohanty *et al.* 1994 and Jačka *et al.* 2014).

In this study, using the Guelph permeameter, measurements were performed using two different constant hydraulic heads (5 cm and 10 cm). Within each test, one-head analysis has been applied to each of the two heads. The resulting K_s values were averaged to obtain one representative K_s of that location.

The duration of each test was variable from one measuring point to another from half of an hour (for the case of the agricultural fields in this study) up to 6 h (for the case of the compacted liner due the characteristic small conducitivity of this soil).

The K_s value was estimated based on the calculated total flow rate *Q* following the relationship presented by Reynolds *et al.* (1986):

$$Q = 2\pi \times H^2 \frac{K_S}{C} + \pi\alpha^2 K_S + 2\pi \frac{H\varphi_m}{C} \quad (1)$$

Where K_s is the saturated hydraulic conductivity (L/T), *H* is the depth of water maintained in the borehole (L), *Q* is the steady state discharge (L/T), α is the borehole radius (L), ϕ_m is the matric flux potential (L^2/T) and *C* is the well shape factor. The well shape factor C depends on well radius and head of water in the well, was calculated according to Zhang *et al.* (1998).

Double ring infiltrometer. The double ring infiltrometer provides an estimate of the topsoil hydraulic

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conductivity at soil saturation: it is composed of two rings; the outer ring allows to control the lateral flow since the aim is to measure the vertical K_s, which is estimated after data is collected in the inner ring (Bouwer 1986). This technique is considered as easy to be used and not expensive. Meanwhile, the measurements are carried out under water ponding conditions which in case of poor soil-ring contact may cause water leakage yielding an overestimation of K_s. The water ponding at the soil surface may cause also soil disturbance and air entrapment. This test was carried out only at Scarpino's site. The infiltration rate was calculated using the following equation:

$$f = \frac{\Delta Q}{A \Delta t} \quad (2)$$

Where f is the infiltration rate (L/T), ΔQ is the variation of water volume (L) and Δt is the time interval (T) and A is the cross section of the inner ring (L^2). The value of f is considered equal to the saturated hydraulic conductivity K_s when constant infiltration rate is reached after a quite long measurement time, under the assumption that the flow is considered of pure percolation.

Laboratory measurement techniques

Laboratory permeameter. Laboratory measurements are carried out using undisturbed soil samples. The hydraulic conductivity at soil saturation is estimated by means of a falling head or a constant head method (Klute & Dirksen 1986). Before starting the measurements, soil samples should be saturated. Then, K_s is determined by imposing 1D water flow through the soil sample. The main limitation of this kind of laboratory measurements is the size of the soil sample that should be representative of the tested soil under field natural conditions (Jačka *et al.* 2014). In this study we used the KSAT-UMS, this instrument is considered highly precise and allows measuring K_s ranging from 10^{-3} m/s down to 10^{-6} m/s (KSAT -UMS, Germany-2012). This device allows measuring the rate with which water flows through a 250 cm^3 saturated soil sample by constant-head and falling-head experiments. These methods are based on German standards (DIN 19683-9 and DIN 18130-1). For this study, both falling and constant head methods were tested. These methods gave comparable K_s values. The falling head method is considered as more preferable in particular for poorly conductive soils; hence, we decided to consider only this method as a laboratory estimate for landfill study site. Collected data from these experiments can be interpreted using different methods. Data interpretation was carried out using KSAT-VIEW software (KSAT-UMS, Germany-2012), specific for the KSAT-UMS device. This software automatically records the pressure drop. The K_s parameter was calculated from a fitted exponential function.

$$h(t) = h_0 \exp\left(-K_s \times \frac{A_{\text{bur}}}{A_{\text{sample}}} \times \frac{1}{L} \times t\right) = a \exp(-b \times t) \quad (3)$$

Where A_{bur} is the cross sectional area of the burette (L^2), A_{sample} is the cross sectional area of the sample (L^2), L is the length of the sample (L), K_s is the saturated hydraulic conductivity (L/T), $h(t)$ is the pressure (L) at a certain time t, h_0 is the pressure head at t = 0, (L). The coefficient b is determined through the fitting of the exponential function to the observed time series. The hydraulic conductivity at soil saturation is given by

$$K_S = \frac{A_{\text{bur}}}{A_{\text{Sample}}} \times L \times b \quad (4)$$

At each sampling points the measurements were repeated several times for the same tested sample.

Constant head method was considered as the method used for determination of K_s of the agricultural field since it is considered as more adapted for highly conductive soils. The hydraulic conductivity at soil saturation is given by

$$K_S = \frac{Q}{A_{\text{Sample}}} \times \frac{L}{h} \quad (5)$$

with Q is the steady state flow rate from mariotte flask (L^3/T) and h is the hydraulic head difference between inlet and outlet level (L).

Laboratory evaporation method. A widely used method for the determination of soil hydraulic functions in the laboratory is the evaporation method. This method was suggested first by Gardner and Miklich (1962) and later improved by Wind (1966). Many researchers applied this method in order to determine the soil water retention curve parameters (Wind 1966; Becher 1970; Schindler 1980; Wendroth *et al.* 1993; Romano *et al.* 1995, Halbertsma 1996; Bertuzzi *et al.* 1997; Arya 2002). The method is based on monitoring the changes due to the evaporation both in the soil weight and in the soil matric potential due to the evaporation. The evaluation of these data relies on a fitting procedure of one of the

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existing soil-water constructive laws. In this work, Brooks and Corey (1964) and van Genuchten (1980) soil water retention relationships were used and coupled with Mualem (1976) predictive model of relative conductivity.

The evaporation method on undisturbed soil samples using HYPROP-UMS (Hydraulic Property Analyzer; UMS Munich, 2010). The device and soil sample preparation followed the instructions presented in the HYPROP-UMS manual. Intact soil samples (5 cm high and with a diameter of 8 cm) were saturated and placed afterwards on the HYPROP base containing two tensiometers at depth of (1.25 cm and 3.75 cm) from the bottom. The sample, closed on the bottom and open to the atmosphere at the upper side was placed on a balance: at each time step tensiometer pressure head and weight were recorded during the drying process caused by evaporation. The duration of a measurement of a soil sample lasted from 4 to 6 days. This method uses weight changes and the matric potential measurements on the samples to derive soil hydraulic functions. HYPROP-FIT software (Pertassek *et al.* 2015) was used to fit the measured HYPROP data to estimate the soil water retention curve and hydraulic conductivity functions. The software performs the nonlinear fitting of the soil water retention data using the Levenberg-Marquardt method (Marquardt 1963). The generated curve could be fitted to one of the parametric equations implemented in HYPROP-FIT: Brooks and Corey (1964), the constrained and unconstrained unimodal function of van Genuchten (1980), the unimodal function of Kosugi (1996) and the bimodal form of these equations (Durner 1994; Romano *et al.* 2011). For this study, we considered unimodal equations of van Genuchten (1980) and Brooks and Corey (1964). The first applied model was the unimodal Brooks and Corey with Mualem's (1976) conductivity are given by the following equations 6 and 7:

$$s(h) = \left|\alpha' h\right|^{-\lambda} \tag{6}$$

$$K = K_s s^{\frac{2}{\lambda}+l+2} \tag{7}$$

where s is the effective water content given by:

$$s = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \tag{8}$$

In eq (8) θ, θ_r are the actual and the residual volumetric water content and θ_s is the volumetric water content at saturation, respectively (L^3/L^3). The parameters λ, α' and *l* (eq. 7–8) are empirical parameters that represent pore size distribution index, the reciprocal of a bubbling pressure (*m*) and the Mualem's tortuosity parameter usually considered equal to 0.5. The unimodal van Genuchten-Mualam model is given by:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha'' h)^n\right]^m} \tag{9}$$

$$K(s) = K_S s^l \left[1 - \left((1 - s^{1/m}\right)^m\right]^2 \tag{10}$$

Where *l* represents Mualem's tortuosity factor, while α'', m and n are empirical fitting parameters. The value of parameter m was calculated with the constraint $m = 1 - 1/n$. This parameter has been considered within many studies as a free fitting parameter (Schwen *et al.* 2014; Peters & Durner 2008; shaap & Leij 2000). For the fitting procedure and in order to avoid getting negative values without a physical meaning, the tortuosity factor was fixed at 0.5 as recommended by Mualem (1976).

Pedotransfer functions

Pedotransfer functions are relationships to estimate soil hydraulic properties (i.e. the parameters of the soil-water constructive laws) from other and more easily estimated from other soil properties such as the bulk density, the particle size distribution, and the organic matter content (Bouma 1989, Schaap & Leij 1998, Wösten *et al.* 1995; Rawls & Brakensiek 1989, Looy *et al.* 2017). PTFs are empirical relationships essentially based on statistical regressions, which are previously obtained from large data bases. PTFs provide an easy to use and less time-consuming tool to predict soil hydraulic properties. Although the wide adoption of these methods, the selection of a proper PTF for a given site is a complex task (Acutis & Donatelli 2003). In fact, in study areas different from the ones where these functions were obtained, the validity of PTFs should be tested and compared to field and laboratory measurements. K_s values depend on a wide range of soil properties while only some of them are also required as inputs for the PTFs. For this reason, many researchers considered that PTFs are not working well to estimate of the Ks and their implementation can lead to significant errors (Jarvis *et al.* 2013).

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References

Acutis M., Donatelli M. (2003): SOILPAR 2.00: software to estimate soil hydrological parameters and functions. European Journal of Agronomy, 18: 373–377.

Arya L.M. (2002): Wind and hot-air methods. In: Dane J.H., Topp G.C. (eds.): Methods of Soil Analysis, Part 4, Physical Methods. SSSA Book Series No. 5, Madison, SSSA: 916–926.

Becher H.H. (1971): Ein Verfahren zur Messung der ungesättigten Wasserleitfähigkeit. Zeitschrift für Pflanzenernährung und Bodenkunde, 128: 1–12.

Bertuzzi P., Voltz M. (1997): The Wind method: A standard laboratory method adopted by the French INRA laboratories. In: Workshop Proc. Use of Pedotransfer in Soil Hydrology Research, Oct 10–12, 1997, Orleans: 51–53.

Bouma J. (1989): Using soil survey data for quantitative land evaluation. Advances in Soil Science, 6: 177–213.

Bouwer H. (1986): Intake rate: Cylinder infiltrometer. In: Klute A. (ed.): Methods of Soil Analysis. ASA Monograph No. 9. Madison, ASA: 825–843.

Durner W. (1994): Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resources Research, 30: 211–223.

Eijkelkamp (2011): Operating instructions.09.07 Guelph Permeameter. Available at https://www.eijkelkamp.com

Gardner W.R., Miklich F.J. (1962): Unsaturated conductivity and diffusivity measurements by a constant flux method. Soil Science, 93: 271–274.

Halbertsma J. (1996): Wind's evaporation method, determination of the water retention characteristics and unsaturated hydraulic conductivity of soil samples. Possibilities, advantages and disadvantages. In: European Workshop on Advanced Methods to Determine Hydraulic Properties of Soils, Thurnau, June 10–12, 1996: 107.

Jarvis N., Koestel J., Messing I., Moeys J., Lindahl A. (2013): Influence of soil, land use and climatic factors on hydraulic conductivity of soil. Hydrology and Earth System Sciences, 17: 5185–5195.

Klute A., Dirksen C. (1986): Hydraulic conductivity and diffusivity: laboratory methods. In: Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. 2nd Ed., Madison, American Society of Agronomy: 687–734.

Kosugi K. (1996): Lognormal distribution model for unsaturated soil hydraulic properties. Water Resources Research, 32: 2697–2703.

Marquardt D.W. (1963): An algorithm for least-squares estimation of nonlinear parameters. SIAM Journal on Applied Mathematics, 11: 431–441.

Looy K.V., Bouma J., Herbst M., Koestel J., Minasny B., Mishra U. et al. (2017): Pedotransfer functions in Earth system science: challenges and perspectives. Reviews of Geophysics, 55: 1199–1256.

Pertassek T., Peters A., Durner W. (2015): HYPROP-FIT Software User's Manual, V.3.0. München, UMS AG.

Peters A. Durner W. (2008): Simplified evaporation method for determining soil hydraulic properties. Journal of Hydrology, 356: 147–162.

Rawls W.J., Brakensiek D.L. (1989): Estimation of soil water retention and hydraulic properties, In: Morel Seytoux H.J. (ed.): Unsaturated Flow in Hydrologic Modeling: Theory and Practice. NATO ASI Series, Boston, Kluwer Academic Publishers: 275–300.

Romano N., Nasta P., Severino G., Hopmans J.W. (2011): Using bimodal log-normal functions to describe soil hydraulic properties, Soil Science Society of America Journal, 75: 468–480.

Schaap M.G., Leij F.J. (1998): Database related accuracy and uncertainty of pedotransfer functions. Soil Science, 163: 765–779.

Wendroth O., Ehlers W., Hopmans J.W., Kage H., Halbertsma J., Wösten J.H.M. (1993): Reevaluation of the evaporation method for determining hydraulic functions in unsaturated soils, Soil Science Society of America Journal, 57: 1436–1443

Wösten J.H.M., Finke P.A., Jansen M.J.W. (1995): Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. Geoderma, 66: 227–237.

Zhang Z.F., Groenevelt P.H., Parkin G.W. (1998): The well-shape factor for the measurement of soil hydraulic properties using the Guelph permeameter. Soil Tillage Research, 49: 219–221.