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Soil saturated hydraulic conductivity assessment from expert evaluation of field characteristics using an ordered logistic regression model

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ABSTRACT

The knowledge of the soil saturated hydraulic conductivity (K_s) is essential for irrigation management purposes and for hydrological modelling. Several attempts have been done to estimate K_s in base of a number of soil parameters. However, a reliable enough model for qualitative K_s estimation based on the expert assessment of field characteristics had not been developed up to date. Five field characteristics, namely macroporosity (M), stoniness (S), texture (T), compaction (C) and sealing (L), in addition to tillage (G) were carefully assessed according to three classes each, in 202 sites in an agricultural irrigated area in Eastern Mediterranean Spain. After the evaluation of field characteristics, a single ring infiltrometer was used to determine the K_s value as the solution of the infiltration equation when the steady state was reached. The distribution of the K_s was assessed and five classes with 10-fold separations in class limits were defined accordingly. The relationships among site characteristics and K_s were analyzed through a correspondence analysis (CA). Next, an ordered logistic regression model (OLRM) for the prediction of the K_s class was developed. The CA revealed that, though tightly related, the set of six site characteristics should not be simplified into a smaller set, because each characteristic explains a significantly different aspect of K_s. Consequently, the OLRM was based on the six characteristics, which presented the following order of importance: L > M > G > T > C > S. According to the cross-validation of the OLRM the hit probability for the prediction of the K_s class attained an average value of 50%, which increased to 63% for the highest class of K_s. Moreover, wrong estimation of the K_s class exceeded the ± 1 range only in 3% of sites. Therefore, a reliable enough assessment of K_s can be based on the expert assessment of field characteristics in combination with an OLRM.

1. Introduction

Saturated hydraulic conductivity (K_s), as a measure of the ability of soil to transmit water, is essential in infiltration-related applications such as irrigation and drainage management (Wu et al., 1999; Radcliffe and Rasmussen, 2002) and for modelling the hydrology of the landscape. This parameter is obviously related to the hazard of ponding and to the potential of soils for tile drainage, which can affect the production of certain crops (McKeague et al., 1982).

Ring infiltrometers are often used for measuring the water intake rate at the soil surface. The total flow rate into the soil from a single-ring infiltrometer is a combination of both vertical and horizontal flow. Wu et al. (1997) found that the infiltration rate of a single-ring infiltrometer was related to the one-dimensional (1-D) infiltration rate for the same soil. For a relatively small ponded head, the 1-D final infiltration rate of a field soil is approximately equal to the field K_s, which is valuable information for computer modelling and irrigation management.

Even with improved equipment, the K_s measurement is time consuming, and thus, models are recommended. Several attempts (Rawls et al., 1982, 1998; Tietje and Hennings, 1996; Dexter and Richard, 2009) have been made to estimate the K_s from readily available analytical soil data such as particle size distribution, bulk density and organic matter content by means of pedotransfer functions or by physical modelling of the pore size distributions. However, all these estimation methods exhibit large differences between predictions and measurements of K_s (Tietje and Hennings, 1996; Landini et al., 2007), or the hydraulic conductivity close to water saturation could not be estimated based only on the usually available estimators (Weynants et al., 2009). Models based on soil characteristics such as bulk density and pore size distribution give better predictions as shown by Mbagwu (1995), who estimated K_s

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from bulk density, macroporosity, mesoporosity and microporosity. Since these models are generally high data demanding and need cumbersome laboratory determinations, the applicability for farmers in irrigation management is reduced. To avoid this, qualitative models based on the expert assessment of morphological characteristics of soil could be an alternative approach to model the K_s. This idea of qualitatively describing water flow through soils has been credited to the Soil Conservation Survey (Norton, 1939). Since then, several models for the qualitative classification of soil ease to permit water flow have been developed. Mason et al. (1957) developed such a model based on the expert assessment of 14 soil morphologic characteristics in order to classify 900 soils in an ordinal scale of seven permeability classes, defined as the ease with which pores of a saturated soil permit water movement. They attained a hit probability of 30%, and suggested that 95% probability of making a correct prediction could be achieved by using only three to five permeability classes.

McKeague et al. (1982) developed guidelines for estimating the class of saturated hydraulic conductivity of soil horizons from observations of soil morphology in 78 soil horizons ranging in texture from sandy to clayey. The major factors contributing to high K_s values were abundant biopores, textures coarser than loamy fine sand, and strong, fine to medium blocky structure. The lowest values were associated with clayey horizons that had been compressed or puddled by cultivation. The guidelines presented, though incomplete and subjective to some degree, improved the estimates of K_s in limited testing by pedologists. The results also indicated that it was not feasible to assign a unique K_s estimate to near-surface horizons of cultivated soils of a particular series. Tillage practices and current land use have a major effect on soil structure, porosity and density, and hence on K_s.

Saturated hydraulic conductivity can also be related to soil morphological criteria based on the expert assessment and the classes of the Factual Key (McKenzie et al., 2000). Lin et al. (2006) presented a vision that advocates hydropedology as an advantageous integration of pedology and hydrology for studying the intimate relationships between soil, landscape, and hydrology. Landscape water flux is suggested as a unifying precept for hydropedology, through which pedologic and hydrologic expertise can be better integrated. The discretization of continuous field measurements such as the K_s, is usually of high practical value to perform this integration. The indication of a class of K_s is, on the one hand, more informative, and on the other hand, more stable in space and time than the indication of an X% confidence interval derived from an ordinary least squares regression model.

Given a saturated hydraulic conductivity expressed in an ordinal scale, the datum to predict is not longer the actual value of K_s, but the probability of an observation to belong to a certain class of K_s. This can be adequately performed using logistic regression models (LRM). Logistic regression modelling has been previously used in soil research to assess water erosion from expert evaluation of site characteristics (Sonneveld and Albersen, 1999). The development of a LRM appears as an adequate methodology for predicting an ordinal variable from other ordinal variables, which to our knowledge has not been carried out up to date for the K_s assessment.

The objective of the present study was to develop a methodology for the estimation of the class of soil saturated hydraulic conductivity based on several field characteristics such as tillage, macroporosity, stoniness, texture, compaction and sealing. This main objective was split into two partial objectives: (i) the development of a methodology for the expert evaluation of the soil characteristics, and (ii) the development of an ordered logistic regression model for the K_s prediction on basis the six field characteristics.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) has 12,400 ha, of which approximately 6300 ha are agricultural irrigated lands. Citrus is the main crop with 53% of the irrigated area, followed by vegetables (mainly melon and watermelon) with 14%. Rice crop in lands with shallow watertables accounts for no more than 3% of the area. Citrus orchards and some vegetables are generally drip irrigated. Drip irrigation is used on 65% of the total irrigated area. The climate can be considered as semiarid following the UNESCO classification (De Paw et al., 2000), with annual rainfall of 500 mm and reference evapotranspiration (ET_0) of 1000 mm.

In regard on landscape features, three main areas, associated with soil types, can be distinguished: (i) the colluvial and glacis area, with soil materials moved, accumulated, removed or even replaced, especially when calcareous duricrusts can limit the effective soil depth for citrus crops; typical soils there are, respectively, aric Anthrosols and petric Calcisols; (ii) the floodplains and alluvial area, with more fertile finer-textured soils such as Luvisols, which are typically cultivated for citrus; (iii) the third area located near the coast, characterized by lacustrine fine-grained deposits from infilling of lakes and early used for rice and horticultural crops. In this last area, a watertable is present seasonally, and subsurface horizons of lacustrine soils often show visible greyish colours and prominent reddish mottles when oxidising conditions occur periodically by tile drainage.

2.2. Soil survey

The surveyed plots were selected according to a combined systematic and random point selection in agreement with De Paz et al. (2011), in order to have all soil types and crops represented according to their predominance in the area. The study was carried out during the irrigation season, and in days when the soil water content was close to field capacity, i.e., between 1 and 3 days after irrigation. In each of the 101 plots (Fig. 2), two separated points were selected for a total of 202 survey sites. In each site several 10 cm × 10 cm areas with no vegetation were delimited for the expert assessment of field characteristics, thereafter infiltration was measured in one of the areas.

2.3. Saturated hydraulic conductivity determination

The soil water infiltration rate was measured using a single head ring infiltrometer according to the method by Wu et al. (1999). The single-ring infiltrometer consisted of an infiltration ring 12 cm in diameter and 6.5 cm in height with a calibrated water supply column that maintains a constant water pressure head of 1 cm on the soil inside the ring (Fig. 3). The ring insertion depth in the soil was 5 cm. The cumulative infiltration at different times was measured by annotating the height of water in the water supply column. The time of measurement was sufficiently long to achieve a steady-state infiltration rate, which was usually 20 min. Calculations of saturated hydraulic conductivity were obtained from Eqs. (1)–(3) (Wu et al., 1999),

$$K_s = \frac{A}{(a f)} \tag{1}$$

$$f \approx \frac{H + 1/\alpha}{G*} + 1 \tag{2}$$

$$G* = \frac{d + r}{2} \tag{3}$$