On the estimation of hydraulic conductivity of layered vadose zones with limited data availability

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Vadose zone acts as a controlling agent for recharge and transport of contaminants into aquifers. Hence, for modelling and quantifying flow and transport processes in subsurface environments, hydraulic conductivity (K) of the vadose zone plays an important role. However, given the heterogeneity and anisotropy of subsurface systems, the *in-situ* measurement of K is a daunting task at a larger scale. The present study was conceived to evaluate the efficacy of salient pedotransfer functions (PTFs) to indirectly estimate the saturated hydraulic conductivity (K_s) of a lateritic vadose zone of eastern India. Also, *in-situ* hydraulic conductivity along with basic soil physical properties was determined in different vadose-zone layers at three locations (bare plot, cultivated field and orchard). Four PTFs [Campbell, Rawls–Brakensiek/Cronican–Gribb (R–B/C–G), and Models 2 and 3 of Rosetta] were selected to estimate K_s and their performances were evaluated. Based on the statistical indicators, it is concluded that Model 3 of Rosetta is capable of predicting relatively close values of K_s for the lateritic vadose zones to some extent. To generalise the findings of this study, it is recommended that such field-based studies should be carried out at a larger scale in lateritic terrains with varying land use/land cover.

Keywords. Lateritic vadose zone; saturated hydraulic conductivity; field-saturated hydraulic conductivity; pedotransfer functions; vadose-zone characterisation.

1. Introduction

Vadose zone is the intrinsic part of the water cycle that essentially controls the interrelationship between different water balance components such as precipitation, infiltration, evapotranspiration and groundwater recharge. It controls water and contaminant transport from the surface to groundwater and vice versa, acting as a buffer zone between land surface and underlying aquifer (Nimmo 2005). The physical and hydraulic characteristics of the vadose zone are generally poorly known due to its relative inaccessibility (in comparison to soil) and the comparative lack of historical

research in this area at a larger scale (Dann *et al.* 2009).

Increasing concerns regarding the environmental impacts of different land use and development activities on groundwater resources have led to a considerable focus on the development of flow and transport models to understand, analyse and predict flow and contaminant transport processes in the vadose zone. These models require knowledge on soil hydraulic properties such as hydraulic conductivity, among other inputs, for evaluating the impact of past, present or proposed agricultural practices and environmental factors on groundwater systems. Given the importance of

hydraulic conductivity, some direct methods have been developed for the determination of hydraulic conductivity in laboratory and field (Bouwer 1966; Libardi *et al.* 1980; Daniel 1982; Elrick *et al.* 1989; Reynolds and Elrick 1989; Bagarello *et al.* 2012). In spite of several comparative studies related to the determination of soil hydraulic conductivity for varying soils in the past (e.g., Lee *et al.* 1985; Gupta *et al.* 1993; Zhang *et al.* 2007; Jačka *et al.* 2014; Balfour 2015; Hangen and Vieten 2018), it is still a very difficult task to acquire appropriate data for specific applications as the field and laboratory methods are expensive, cumbersome and time consuming. To overcome this problem, indirect methods such as pedotransfer functions (PTFs) are used. Concerns in the last few decades regarding the contamination of groundwater due to agricultural and other man-made activities have led to a greater interest and more focused site-specific research on the estimation of hydraulic parameters in the field of vadose-zone hydrology.

In recent years, PTFs have been developed and used by many researchers across the world to estimate the hydraulic conductivity using easily available or measurable soil properties and also they have evaluated the performance of PTFs for various soils and regions (e.g., Wösten *et al.* 1995; Tietje and Hennings 1996; Pachepsky *et al.* 1999; Minasny and McBratney 2000; Sobieraj *et al.* 2001; Wagner *et al.* 2001, 2004; Cronican and Gribb 2004; Ungaro *et al.* 2005; Li *et al.* 2007; Manyame *et al.* 2007; Balland *et al.* 2008; Rasoulzadeh and Yaghoubi 2011; Duan *et al.* 2012; Puhlmann and von Wilpert 2012; Wang *et al.* 2012; Yao *et al.* 2015; Zhao *et al.* 2016). However, to date, no single PTF is available which can be used universally for varying soil types (Zhang *et al.* 2007). For example, Minasny and McBratney (2000) evaluated the predictability of eight PTFs against various field and laboratory measured saturated hydraulic conductivity values for a wide range of Australian soils. They found that the PTFs by Cosby *et al.* (1984), Dane and Puckett (1994) and Schaap *et al.* (1998) perform best for sandy, loamy and clayey soils, respectively. For all soil-textural classes of Germany, Wagner *et al.* (2001) reported that the PTF developed by Wösten (1997) performed the best among eight other well-known PTFs for predicting unsaturated hydraulic conductivities. In another study, Wagner *et al.* (2004) found the same PTF suitable for the deeper ground sediments (up to 100 m depth) of the Molasse basin in Germany. Manyame *et al.* (2007) found the van Genuchten

model to be the most accurate method among three PTFs including Campbell and Vauclin for predicting the unsaturated hydraulic conductivity of the sandy soils at two villages in Niger. On the other hand, Li *et al.* (2007) developed a location-specific PTF for the Fengqiu County soils (sand, loamy sand, sandy loam, silty loam, silty clay loam and silty clay) sampled at seven different soil profiles of North China Plain. They compared the estimated saturated hydraulic conductivity values with those obtained by four existing PTFs, and found that the developed PTF performed the best for the study area when validated against the field-measured hydraulic conductivity. Likewise, Duan *et al.* (2012) evaluated the three existing PTFs (Campbell 1985; Saxton *et al.* 1986; Smettem and Bristow 1999) for the lawn soils of Texas and reported that these PTFs underestimated saturated hydraulic conductivity when compared to the field-measured hydraulic conductivity values measured at three cities of Texas with fully established grass. Similarly, Yao *et al.* (2015) conducted experiments in two coastal salt-affected farming areas in north Jiangsu Province, China. They assessed the predictability of 12 PTFs against lab-measured saturated hydraulic conductivity values and identified Ahuja and Vereecken PTFs as the best estimators for saturated hydraulic conductivity in the coastal reclamation farming area.

From the literature survey, it is revealed that fewer studies related to layer-wise hydraulic characterisation of lateritic vadose zones (Behera *et al.* 2003; Garg *et al.* 2005; Nandagiri *et al.* 2006) have been reported in the past. Also, it is obvious that no studies have been attempted for evaluating the performance of existing PTFs to estimate the saturated hydraulic conductivity of the lateritic vadose zones considering both location and depth-wise variations. However, some studies have been conducted for deeper depths in specific soil types such as forest soils and sediments (e.g., Wagner *et al.* 2004; Puhlmann and von Wilpert 2012). Lateritic vadose zones, having typical characteristics, behave quite differently and hence significantly influence the groundwater recharge and transport processes. Laterites are prominent mainly within tropics of Cancer and Capricorn covering about one-third of the Earth's land area (Tardy 1997). In India, lateritic soils are found in Tamil Nadu, Andhra Pradesh, Odisha, West Bengal, and in Eastern and Western Ghats spreading over 248,000 km² (Raychaudhuri 1980). Despite the importance and typical nature of lateritic vadose zones, very

little information about the reliability of PTFs is available for the lateritic vadose zones. Needless to mention that such studies are of paramount importance for understanding the groundwater recharge (both natural and artificial) and contamination process through vadose zones. Although progress has been made in the development and use of PTFs to estimate soil hydraulic properties, in general, across the globe, to the best of our knowledge, there is little information on the assessment of PTFs for estimating the saturated hydraulic conductivity in the lateritic regions of eastern India. In this study, an attempt has been made to address some of the above-mentioned limitations of vadose-zone studies. To this end, the present study demonstrates the applicability and reliability of PTFs in estimating the hydraulic conductivity of vadose zone at different depths (beyond root-zone depth) and its spatial variation (from one location to another) under three different land management practices in a typical lateritic terrain of eastern India. Additionally, the basic physical properties of the vadose zone such as texture, bulk density and porosity were also determined as a function of depth and space. These findings of this study are very useful for better understanding of vadose-zone characteristics (both physical and hydraulic), which in turn can help in estimating the groundwater recharge and assessing groundwater vulnerability through the vadose zone.

2. Methodology

In the present study, three different locations were selected over the Experimental Farm of Agricultural & Food Engineering (AgFE) Department, IIT Kharagpur (figure 1) located in West Medinipur district of West Bengal, India. The study sites are located in a gently sloping drainage basin at 22°19'10.97"N latitude and 87°18'35.87"E longitude, and an altitude of 48 m above mean sea level. The soil of the region is dominated by lateritic sandy loam with 0.65% of organic matter (Machwal *et al.* 2006). This lateritic soil is rich in iron and aluminium, commonly found in hot and wet tropical areas.

2.1 Investigation sites

In this study, three investigation sites in the Experimental Farm were selected to represent three different land cover and management practices.

Of the three investigation sites, the first site (Site 1) is located in a bare plot, second site (Site 2) in a cultivated field 600 m away from the first site and the third site (Site 3) is located about 500 m away from the second site in the orchard area of Precision Farming Development Centre (figure 1). Vadose zone up to 2 m depth was considered at each site and the entire profile was divided into five layers, viz., 0–0.10, 0.10–0.35, 0.35–0.80, 0.80–1.30 and 1.30–1.70 m. Different physical and hydraulic properties of the soil of the vadose zone were determined at different depths representing these five layers at all the three sites.

2.2 Determination of physical properties

Soil texture, bulk density and particle density of the five different layers were determined in the 2 m deep profile of the vadose zone by analysing undisturbed core samples collected from each of the layers of the three investigation sites. Bulk density was determined from the undisturbed core samples, and the particle density was determined by pycnometer method in the laboratory. Thereafter, the percentage of sand, silt and clay was determined by the standard method in the laboratory and all the soil samples were classified into different texture classes following the United States Department of Agriculture (USDA) soil texture classification system. Cross-sections of the vadose zone at the three sites under study are illustrated in figure 2.

2.3 Determination of saturated hydraulic conductivity

2.3.1 Measurement of field-saturated hydraulic conductivity

Field-saturated hydraulic conductivity (K_{fs}) was determined by the Guelph Permeameter at all the three sites for the three layers (0.10–0.35, 0.35–0.80 and 0.80–1.30 m) of the vadose zone (figure 3a and b). Guelph Permeameter is a constant-head borehole technique and it is based on the assumption of three-dimensional steady-state flow from a cylindrical, uncased test/auger hole in the unsaturated soil (Reynolds and Elrick 1985). It measures combined horizontal and vertical field-saturated hydraulic conductivity (K_{fs}) at specified depths by determining the steady-state flow rate (Q) needed to maintain a constant depth of water in

Figure 1. Location of the investigation sites.

the auger hole. In the present study, firstly the instrument was set at 20 cm depth to determine the hydraulic conductivity of the 0.1–0.35 m layer (figure 3a). The same auger hole was then excavated to the required depths in steps for measuring *in-situ* hydraulic conductivity in deeper layers (figure 3b). Great care was taken while preparing auger hole as it has a significant influence on hydraulic conductivity measurement (Bagarello 1997). At each depth, two sets of steady-state flow measurements were done for two constant heads (5 and 10 cm) in the auger hole. During this experiment, steady-state flow rates were obtained after

5–6 hr of the test. Using the field data, K_{fs} was calculated for each layer by using the following equation (Elrick *et al.* 1989):

$$K_{fs} = \frac{CQ}{(2\pi H^2 + \pi a^2 C + (2\pi H/\alpha^*))}, \quad (1)$$

where Q is the constant discharge, ($L^3 T^{-1}$); C is the shape coefficient which accounts for the interaction of capillarity and gravity in unsaturated flow; H is the constant head maintained in the auger hole, (L); a is the radius of the cylindrical auger hole, (L); and α^* is the capillarity factor, ($1/L$).

Figure 2. Cross-section of the vadose zone depicting five layers with their texture at the investigation sites.

The term field-saturated hydraulic conductivity is used mostly for field-measured hydraulic conductivity as the soil may not be fully saturated during measurements because of possible entrapped air within the soil pores. For this fact, the field-saturated hydraulic conductivity is generally lesser as compared to the saturated hydraulic conductivity. Therefore, the values of field-saturated hydraulic conductivity (K_{fs}) measured in the field were further converted into the corresponding saturated hydraulic conductivity (henceforth called measured K_s) values by using a multiplying factor of 1.5 and 2.0 (Youngs 1968; Stephens *et al.* 1984; Reynolds and Elrick 1985).

2.3.2 Estimation of saturated hydraulic conductivity by PTFs

As the determination of saturated hydraulic conductivity (K_s) of soil is cumbersome and time consuming, they were estimated by using some well-known PTFs based on the availability of data in the study area. Thus, four PTFs were used in this study, namely Models 2 and 3 of Rosetta, Campbell method, and Rawls–Brakensiek or Cronican–Gribb (R–B/C–G) method.

Rosetta software uses a neural-network approach to estimate the values of soil hydraulic parameters.

The neural-network approach of Rosetta allows for the best possible prediction of hydraulic properties of a large number of samples within the model's database (Hermsmeyer *et al.* 2002; Cronican and Gribb 2004; Sander and Gerke 2007). Considering the availability of data, Models 2 (required inputs: sand, silt and clay) and 3 (required inputs: sand, silt, clay and bulk density) of Rosetta software were used to estimate the saturated hydraulic conductivity of the five vadose-zone layers at each site.

As the third PTF, the equation suggested by Campbell (1985) was employed for estimating the saturated hydraulic conductivity of the five layers for all the three sites taking clay and silt fractions as inputs. The Campbell equation is given as follows:

$$K_s = C \exp(-6.9m_c - 3.7m_s), \quad (2)$$

where K_s is the saturated hydraulic conductivity in kg s/m^3 , which is equal to $3.53 \times 10^3 \text{ cm/h}$, m_c is the clay mass fractions, m_s is the silt mass fraction and C is constant (4×10^{-3}).

Moreover, the fourth empirical equation used was the Rawls and Brakensiek (1989) regression equation (henceforth called 'R–B method') that relates K_s to porosity (n) of the soil sample, and percentage of sand and clay particles in the soil

sample. This equation is expressed as

$$K_s = \exp \left[\begin{array}{l} 19.52348n - 8.96847 - 0.028212C + 0.00018107S^2 - 0.0094125C^2 \\ -8.395215n^2 + 0.077718Sn - 0.00298S^2n^2 - 0.019492C^2n^2 \\ +0.0000173S^2C + 0.02733C^2n + 0.001434S^2n - 0.0000035C^2S \end{array} \right], \quad (3)$$

(a)

(b)

Figure 3. (a) Guelph Permeameter installed at a shallow depth. (b) Guelph Permeameter installed at a deeper depth.

where K_s is the saturated hydraulic conductivity (cm/h) of the soil sample, n is the porosity expressed in fraction, C is the clay percentage in the sample and S is the sand percentage in the sample.

It should be noted that equation (3) is valid for soils with 5–70% sand-sized particles and 5–60% clay-sized particles. However, at some depths of the study sites, there exists greater sand percentage. For such samples, the equation developed by Cronican and Gribb (2004) was applied. This equation gives better results for sandy soils having >70% sand than Model 2 of Rosetta and equation (3). The Cronican and Gribb's equation (henceforth called 'C–G method') is given as

$$K_s = \exp(99.49815337 - 2.808839211S + 0.017873264S^2 - 0.019881556SC + 0.000268919S^2C), \quad (4)$$

where K_s is in cm/s. In this study, equation (4) was used for the vadose-zone samples of three locations having sand percentage greater than 70%.

2.4 Evaluation of pedotransfer functions

The values of saturated hydraulic conductivity (K_s) estimated by equations (2–4) as well as Models 2 and 3 of Rosetta were compared with the corresponding values of *in-situ* hydraulic conductivity. The performance of the four PTFs used in this study was evaluated using five statistical indicators namely, bias, mean absolute error (MAE), root mean square error (RMSE), geometric mean error ratio (GMER) and geometric standard deviation of the error ratio (GSDER) together with graphical indicators such as simultaneous plots of measured and estimated hydraulic conductivity values and 1:1 plot. A brief description of these statistical indicators is given below.

The performance of the models was assessed by comparing the bias in the predictions of K_s in each layer for three sites with the respective measured field-saturated hydraulic conductivity data by using the following formula:

$$\text{Bias} = (K_{mi} - K_{pi}), \quad (5)$$

where K_{mi} is the measured value of the field-saturated hydraulic conductivity in the i th layer and K_{pi} is the predicted value of the saturated hydraulic conductivity in the i th layer.

For evaluating the overall performance of the models, statistical indicators such as MAE and RMSE as well as GMER and GSDER were used. The expressions of MAE and RMSE are:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |K_{mi} - K_{pi}|, \quad (6)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (K_{mi} - K_{pi})^2}. \quad (7)$$

GMER and GSDER are special statistical indicators for the parameters such as hydraulic conductivity values, which are log-normally distributed. They are calculated based on the error ratio (ε), which is defined as the ratio of predicted hydraulic conductivity (K_p) to measured hydraulic conductivity (K_m) [equation 8]. These indicators GMER and GSDER are calculated using equations (9) and (10), respectively (Tietje and Hennings 1996; Wagner *et al.* 2001):

$$\varepsilon = \frac{K_p}{K_m}, \quad (8)$$

$$\text{GMER} = \exp \left(\frac{1}{n} \sum_{i=1}^n \ln(\varepsilon_i) \right), \quad (9)$$

$$\text{GSDER} = \exp \left[\left(\frac{1}{n-1} \sum_{i=1}^n [\ln(\varepsilon_i) - \ln(\text{GMER})]^2 \right)^{1/2} \right]. \quad (10)$$

The GMER value equals to 1 corresponds to an exact matching between the measured and predicted data; $\text{GMER} < 1$ indicates that the predicted values are underestimated, while $\text{GMER} > 1$ indicates a general over prediction. On the other hand, the GSDER equals to 1 corresponds to a perfect match and it grows with deviation from the measured data. Thus, the best performing model will have GMER value close to 1 and a small value of GSDER.

In addition to the afore-mentioned statistical indicators, graphical indicators such as 1:1 plot and simultaneous plots of the measured and estimated saturated hydraulic conductivity values

with respect to depth and location were also plotted to evaluate the performance of four PTFs.

2.5 Estimation of unsaturated hydraulic conductivity

Unsaturated hydraulic conductivity, $K(\theta)$, of the bare plot was evaluated from the water retention function, saturated hydraulic conductivity (K_s) and the soil hydraulic parameters predicted by Rosetta using measured bulk density and particle size, which is well known as the van Genuchten–Mualem model, and given as

$$K_u = K(S_e) = K_0 S_e^L \left\{ 1 - [1 - S_e^{n/(n-1)}]^{1-(1/n)} \right\}^2, \quad (11)$$

wherein S_e is given as

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha h)^n]^{1-(1/n)}}, \quad (12)$$

where $\theta(h)$ is the volumetric water content as a function of soil suction (h) (cm^3/cm^3), θ_r is the residual water content (cm^3/cm^3), θ_s is the saturated water content (cm^3/cm^3), α is the van Genuchten parameter related to the inverse of the air-entry pressure, n is the a measure of the pore-size distribution, h is the the soil-water pressure head (i.e., soil suction) (cm), K_0 is the fitted matching point at saturation (cm/day), S_e is the relative saturation and L is the empirical parameter.

3. Results and discussion

3.1 Soil physical properties of the vadose zone

The results of the texture analysis, bulk density and porosity determined for the five vadose-zone layers over the three study sites are summarised in table 1. It is apparent that mainly two types of soil textures (sandy loam and sandy clay loam) are dominant up to 1.7 m deep vadose zone of the study area, though there is a considerable variation of sand, silt and clay particles at individual depths of all the locations. Also, it is evident that the highest percentage of sand can be seen in all the layers at Site 2 as compared to the respective layers of other sites. On the other hand, greatest silt percentage can be seen at Site 1 up to 1.3 m depth, whereas greatest clay percentage occurs

Table 1. *Physical properties of five vadose-zone layers at three study sites.*

Description	Values of different vadose-zone layers				
	0–0.10 m	0.10–0.35 m	0.35–0.80 m	0.80–1.30 m	1.30–1.70 m
Site 1: Bare plot					
Sand (%)	67.00	70.00	53.00	53.00	52.00
Silt (%)	17.40	14.40	21.65	19.70	16.80
Clay (%)	15.60	15.60	25.35	27.30	31.20
Texture	Sandy loam	Sandy loam	Sandy clay loam	Sandy clay loam	Sandy clay loam
Bulk density (g/cm^3)	1.724	1.920	1.828	1.653	1.833
Porosity (%)	25.76	19.22	22.29	33.28	24.22
Site 2: Cultivated plot					
Sand (%)	88.01	92.01	82.03	74.01	66.10
Silt (%)	4.00	2.00	2.00	6.00	9.97
Clay (%)	7.99	5.99	15.98	19.99	23.93
Texture	Loamy sand	Sandy	Sandy loam	Sandy clay loam	Sandy clay loam
Bulk density (g/cm^3)	1.992	1.739	1.694	1.821	1.910
Porosity (%)	23.87	32.02	34.48	26.76	25.20
Site 3: Orchard					
Sand (%)	86.01	70.01	66.00	62.00	56.13
Silt (%)	8.00	10.00	14.00	6.00	25.92
Clay (%)	6.00	19.99	20.00	32.00	17.95
Texture	Loamy sand	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy loam
Bulk density (g/cm^3)	1.979	1.964	1.728	1.756	1.813
Porosity (%)	24.60	24.21	33.61	32.62	28.98

in three vadose-zone layers (0–0.10, 0.35–0.80 and 1.30–1.70 m) at Site 1.

As far as the variation of bulk density with depth is concerned, a usual trend of increasing bulk density is apparent in the deeper layers (0.35–0.80, 0.80–1.30 and 1.30–1.70 m) at Sites 2 and 3 (table 1). Exceptionally higher values of bulk density at shallow depths could be attributed to the local high compaction of the soil, whereas the existence of loosely packed soil layer or micro-pores could be the reason for relatively low bulk density values at deeper depths. Although the spatial variations of bulk density with depth and location are practically appreciable except at some depths (e.g., 0.1–0.35 and 0.35–0.80 m layers at Site 2, 0–0.10 and 0.10–0.35 m layers, 0.35–0.80 and 1.30–1.70 m layer of Site 3) as well as at some locations (e.g., Sites 2 and 3 in 0–10 and 0.35–0.80 m layers, Sites 3 and 1 in 0.10–0.35 and 1.30–1.70 m layers), they were not found to be statistically significant.

As far as the depth-wise variation of the bulk density of the vadose zone is concerned, at Site 1 it varies from 1.653 g/cm^3 (0.80–1.30 m layer) to 1.920 g/cm^3 (0.10–0.35 m layer), from 1.694 g/cm^3 (0.35–0.80 m layer) to 1.992 g/cm^3 (0–0.10 m layer) at Site 2 and from 1.728 g/cm^3 (0.35–0.80 m layer) to 1.979 g/cm^3 (0–0.10 m layer) at Site 3.

The second layer (0.10–0.35 m) of Site 1 and the first layer (0–0.10 m) of Site 2 are the most compacted layers, whereas both second (0–0.10 m) and third (0.10–0.35 m) layers are highly compacted at Site 3. The unusual compaction of shallow layers is attributed to local compaction and the type of land use.

On the other hand, physical property such as the porosity of the vadose zone shows little variation at some depths for all the sites (table 1). However, the range of porosity is from 19.22% (0.10–0.35 m layer) to 33.28% (0.80–1.30 m layer) at Site 1, 23.87% (0–0.10 m layer) to 34.48% (0.35–0.80 m layer) at Site 2 and 24.21% (0.10–0.35 m layer) to 33.61% (0.35–0.80 m layer) at Site 3. These variations of porosity are in agreement with the variation of texture and compaction level.

3.2 Saturated hydraulic conductivity

3.2.1 In-situ hydraulic conductivity of the vadose zone

Variation in the values of field-measured hydraulic conductivity (K_{fs}) with depth and location is illustrated in figure 4. It is apparent from figure 4 and table 2 that the K_{fs} values range from 0.39 to 6.77

Figure 4. Variation of *in-situ* hydraulic conductivity (K_{fs}) with depth and locations.

cm/day for the barren land, 0.031 to 19.79 cm/day for the cultivated land and 2.52 to 18.32 cm/day for the orchard area. Relatively higher values of the field-saturated hydraulic conductivity obtained in the orchard area may be due to the presence of deeper roots of horticultural plants in the vadose zone. It is interesting to note that despite the slightly higher bulk density of the 0.10–0.35 m layer in the barren land, a higher value of field-saturated hydraulic conductivity value is found in this layer, which could be attributed to localised effects such as the presence of macro-pores and their continuity. Although the variation in the K_{fs} of the study area due to different land uses is not statistically significant at 5% level of significance, the mean values of K_{fs} in the barren (mean K_{fs} = 3.72 cm/day), cultivated (mean K_{fs} = 7.26 cm/day) and orchard (mean K_{fs} = 9.45 cm/day) lands vary considerably from the practical viewpoint. In contrast, the depth-wise variation of K_{fs} in the study area was found to be statistically significant at 5% level of significance. It is obvious from table 2 that in the 0.10–0.35 m layer, the values of *in-situ* hydraulic conductivity range from 1.97 (Site 2) to 7.5 cm/day (Site 3), while they vary from 6.77 (Site 1) to 19.79 cm/day (Site 2) in the 0.35–0.8 m layer. The *in-situ* hydraulic conductivity of the 0.8–1.30 m layer varies from 0.031 (Site 2) to 2.52 cm/day (Site 3). Thus, the 0.35–0.8 m layer has the highest hydraulic conductivity and the deepest layer (0.8–1.30 m) has the lowest hydraulic conductivity with intermediate values in the 0.10–0.35 m layer. This trend is visible at all the sites under study, thereby

suggesting the presence of relatively low permeable layers at deeper depths. This has been confirmed from the field investigation that hard laterites are more prominent at deeper depths (beyond 0.8 m below the ground surface) in the study area.

As far as the field-saturated hydraulic conductivity values of various textural classes in the study area are concerned, it varies from 4 to 19.79 cm/day for the sandy loam, 0.031 to 18.32 cm/day for the sandy clay loam and 1.96 cm/day for the sandy soils. It is evident that despite having similar textured vadose-zone layers at the three locations (Sites 1–3), the variability of K_{fs} values in the same vadose-zone layers suggests more dependence of saturated hydraulic conductivity on other factors such as soil structure, bulk density, arrangement of particles, etc. Moreover, a comparison of the results of the study area with past studies also revealed that the saturated hydraulic conductivity values of similar textured soils vary significantly from the corresponding K_{fs} values obtained in this study. For example, in Fengqiu County, North China, Li *et al.* (2007) reported the values of *in-situ* saturated hydraulic conductivity for sandy loam and sandy soils to be 9.85 and 45.21 cm/day, respectively. In another study, Shin *et al.* (2012) found that the values of lab-measured saturated hydraulic conductivity range from 65.84 to 186.19 cm/day for sandy loam soils of Little Washita watershed in Oklahoma. Seki *et al.* (2015) reported the lab-measured hydraulic conductivity values to be 1132 cm/day for sand and 83 cm/day for sandy loam soil layer in Borneo

Table 2. Estimates of saturated hydraulic conductivity (K_s) by PTFs and in-situ method.

Site	Vadose-zone layers (m)	Values of K_s (cm/day) estimated by different PTFs					<i>In-situ</i> hydraulic conductivity	
		Rosetta model 2 (SSC)	Rosetta model 3 (SSCBD)	Campbell method	R-B/C-G method	K_{fs}	K_s	
Site 1 (bare plot)	0–0.1	29.94	13.17	60.67	4.17	NM	NM	
	0.1–0.35	32.25 (–28.25)	5.96 (–1.96)	67.79 (–63.79)	1.03 (2.97)	4.00	6.00	
	0.35–0.80	11.30 (–4.53)	2.98 (3.79)	26.46 (–19.69)	0.10 (6.67)	6.77	13.55	
	0.80–1.30	10.33 (–9.94)	6.69 (–6.30)	24.85 (–22.14)	1.90 (–1.51)	0.39	0.78	
	1.30–1.70	9.23	2.50	21.14	0.05	NM	NM	
Site 2 (cultivated plot)	0–0.1	200.05	44.38	168.40	117.34*	NM	NM	
	0.1–0.35	404.9 (–402.93)	214.46 (–212.49)	208.12 (–206.15)	611.39* (–609.42)	1.97	2.955	
	0.35–0.80	44.48 (–24.69)	38.69 (–18.90)	104.52 (–84.73)	35.74* (–15.95)	19.79	29.679	
	0.80–1.30	22.43 (–22.40)	8.96 (–8.93)	68.34 (–68.31)	2.50* (–2.47)	0.031	0.062	
	1.30–1.70	15.89	3.28	44.96	1.32	NM	NM	
Site 3 (orchard)	0–0.1	176.47	40.98	166.67	23.86*	NM	NM	
	0.1–0.35	21.78 (–14.28)	3.72 (3.78)	58.94 (–51.44)	2.60 (4.90)	7.5	15	
	0.35–0.80	21.09 (–2.77)	9.88 (8.44)	50.79 (–32.47)	17.26 (1.06)	18.32	36.64	
	0.80–1.30	13.80 (–11.28)	6.04 (–3.52)	29.83 (–27.31)	2.46 (0.06)	2.52	5.046	
	1.30–1.70	19.14	5.22	37.65	2.50	NM	NM	

* K_s estimated by the C–G method; NM: not measured; values in the parentheses are biases (‘–’ indicates overestimation and ‘+’ indicates underestimation).

Island of Indonesia. This clearly indicates the typical hydraulic characteristics of lateritic vadose zones.

3.2.2 Performance of the PTFs

(1) *Depth-wise performance*: Comparisons of depth-wise values of saturated hydraulic conductivity obtained by the four empirical methods/PTFs for the three sites with those measured in the field (K_{fs}) are shown in table 2 and figure 5(a–c). Among the empirical methods, the Campbell method monotonically overestimates K_s for all the depths and locations (figure 5a–c). In the 0.10–0.35 m layer, it overestimates K_s by 8–100 times with the bias ranging from –51.44 to –206.15 cm/day (table 2). Similarly, in the 0.35–0.8 m layer, it estimates K_s three to five folds greater than the corresponding measured values (bias varying from –32.47 to –84.73 cm/day), whereas in the deeper layer (0.8–1.30 m), K_s is overestimated by 12–1000 times (bias varying from –27.31 to –68.31 cm/day). Further, when compared with the measured K_s , in the 0.10–0.35 m layer, overestimation is by 4–70 times with the bias ranging from –43.9 to –205.2 cm/day. Similarly, in the 0.35–0.8 m layer, it estimates K_s one to four folds greater than the measured values (bias varying from –12.9 to –74.8 cm/day), while K_s is overestimated by 6–1000 times in the deeper layer (0.8–1.30 m) with bias values varying from –24.1 to –68.3 cm/day. The general over-predictability of the Campbell method in this study is in contrast with those reported by Wagner *et al.* (2001) and Duan *et al.* (2012).

Like the Campbell method, Model 2 of Rosetta overestimates the values of saturated hydraulic conductivity at all the depths for all the sites under study but in a smaller range. In the 0.10–0.35 m layer, the model prediction varies from three times with a bias of –14.28 cm/day (Site 3) to 200 times with a bias of –402.93 cm/day (Site 2). In the next layer, model moderately over predicts K_s with the lowest over prediction (about one fold) at Site 3 and the highest over prediction (about two folds) at Site 2. In the deeper layer (0.8–1.3 m), the model prediction varies from 5 times at Site 3 (bias = –11.28 cm/day) to 700 times at Site 2 (bias = –22.4 cm/day). However, when compared with the measured K_s values, Model 2 underestimates at two sites (table 2). In the shallow layer, the model prediction varies from 2 times with bias of –6.78 cm/day (Site 3) to 100 times with bias

Figure 5. (a–c) Comparison of K_s estimated by the PTFs with *in-situ* hydraulic conductivity (K_{fs}) and measured K_s for: (a) Site 1; (b) Site 2; and (c) Site 3.

of –401.95 cm/day (Site 2). In the intermediate layer, the model over predicts K_s by two times only at Site 2 (bias = –14.8 cm/day), while the lowest under prediction is within one order of magnitude with a difference of only 2.25 cm/day at Site 1.

In the 0.8–1.3 m layer, the model over prediction varies from 3 times at Site 3 (bias = -8.8 cm/day) to 300 times at Site 2 (bias = -22.4 cm/day).

The R-B/C-G method yields K_s values mostly with low bias when compared with both K_{fs} and measured K_s (table 2). It is apparent from table 2 and figure 5(a–c) that in the 0.10–0.35 m layer, the R-B/C-G method underestimates K_s values by three (Site 3) to four times (Site 1) with a lower bias (<5 cm/day) except for Site 2 where it yields exceptionally high value of K_s (611.39 cm/day). In the 0.35–0.8 m layer, it underestimates K_s at Sites 1 and 3 (the value of K_s at Site 3 is slightly less than the measured one), whereas it overestimates by about two times at Site 2 with a bias of -15.95 cm/day. Finally, in the deeper layer, this method overestimates K_s with a bias of -1.51 cm/day by about 5 times (Site 1) to about 80 times (Site 2) with a bias of -2.47 cm/day, whereas it yields K_s values closer to the measured one at Site 3. It is also obvious from table 2 that when compared with the measured K_s values, the R-B/C-G method predicts in a similar way as with the K_{fs} value.

Moreover, K_s value in 0.10–0.35 m layer estimated by Model 3 of Rosetta was found to be within one order of magnitude at Site 1 (bias = -1.96 cm/day), but it is overestimated by about 2 times at Site 3 (bias = 3.78 cm/day) to 100 times at Site 2 (bias = -212.5 cm/day). However, in the intermediate layer (0.35–0.8 m layer), it underestimates K_s values by two folds at Sites 1 (bias = 3.79 cm/day) and 3 (bias = 8.44 cm/day)], while K_s values are overestimated by approximately two times (bias = -18.9 cm/day) at Site 2. In contrast, in the deeper layer (0.8–1.30 m), it overestimates K_s values at all the locations with bias values ranging from -3.52 (Site 3) to -8.93 cm/day (Site 2). A comparison of the model prediction with the measured K_s values reveals that the prediction pattern remains similar in all the layers except the shallow layer (0.10–0.35 m) of Site 1 where the model predicted K_s is almost equal to the measured K_s (bias = 0.04 cm/day).

Based on the above results and discussion, it can be inferred that when the estimated hydraulic conductivity values are compared with the field-saturated hydraulic conductivity (K_{fs}), the R-B/C-G method generally performs somewhat better in estimating K_s of the deeper and intermediate layers where sandy clay loam type soil is prominent. In general, Model 3 of Rosetta estimates relatively closer K_s values than other PTFs, specifically

for coarse-textured soils when compared to both measured K_{fs} and K_s values. In contrast to that, Minasny and McBratney (2000) reported Model 3 of Rosetta giving best results for finer clayey soils of Australia. However, Sobieraj *et al.* (2001) reported Model 3 of Rosetta to be the best performing PTF for a tropical rainforest area of Peru dominated by sandy loam and loam type textures. Interestingly, all the PTFs yield highly overestimated values with very large errors in K_s estimates in the 0.10–0.35 m layer of Site 2 (soil texture: sandy). Also, all the PTFs predict K_s values with very high values of errors at all the layers of Site 2, where the higher sand percentages ($>70\%$) are evident than other two sites. This finding indicates that all of the PTFs completely fail to represent the field-saturated hydraulic conductivity of lateritic vadose zone having a higher sand percentage.

(2) *Overall performance of the PTFs:* In order to evaluate the overall performance of the PTFs for this lateritic terrain, salient global statistical indices were calculated using the entire data set and their values are summarised in table 3. It is obvious from the table that all the methods overestimate the values of saturated hydraulic conductivity as indicated by the GMER values exceeding 1. Based on the GMER values, the R-B/C-G method performs comparatively well with the GMER value of 1.86 followed by Model 3 of Rosetta (GMER = 4.24) when compared with the field-saturated hydraulic conductivity (K_{fs}). However, Model 2 of Rosetta and the Campbell method poorly predicts the saturated hydraulic conductivity with GMER values of 10.91 and 22.26, respectively. In contrast, the performances of the PTFs are somewhat improved when their results are compared with the measured K_s values as indicated by decreased GMER and error values with some exceptions (table 3). In this case also, the R-B/C-G method estimates the saturated hydraulic conductivity values best fit with the measured K_s values with GMER almost equal to 1 followed by Model 3 (GMER = 2.33). The GSDER values for the four PTFs, when compared with the measured K_s values, vary over a range from 8.27 to 19.71. Except for the R-B/C-G method, all the other PTFs have almost closer GSDER values. Surprisingly, the PTF with the least GMER has the highest GSDER value. On the other hand, Model 3 of Rosetta, which has the second least GMER value equal to 2.33, has a GSDER of 11.17. Also, the values of MAE and RMSE are the lowest for Model 3 (MAE = 31.66 cm/day;

Table 3. Goodness-of-fit statistics for the PTFs.

PTFs	MAE (cm/day)	RMSE (cm/day)	GMER	GSDER
1. Rosetta model 2 (SSC)	57.89 (56.47)	135.28 (134.75)	10.91 (6)	9.46 (9.66)
2. Rosetta model 3 (SSCBD)	29.79 (31.66)	71.35 (71.4)	4.24 (2.33)	11.09 (11.17)
3. Campbell method	64.26 (58.88)	84.17 (81.42)	22.26 (12.25)	8.26 (8.27)
4. R-B/C-G method	71.66 (74.54)	203.27 (203.03)	1.86 (1.02)	20.22 (19.71)

Values in parentheses indicate the error values when compared with the measured K_s values.

Figure 6. 1:1 plot for comparison of *in-situ* measured hydraulic conductivity (K_{fs} and K_s) with the saturated hydraulic conductivity values estimated by the PTFs.

RMSE = 71.4 cm/day) and the greatest for the R-B/C-G method (MAE = 74.54 cm/day; RMSE = 203.03 cm/day). Overall, the Campbell method tends to over-predict all the K_s values as shown in figures 5 and 6. Although it is difficult to conclude the best performing PTF from the graphical indicator i.e., 1:1 plot (figure 6) due to smaller data sets, based on the statistical indicators, it can be concluded that Model 3 of Rosetta provides better estimates of saturated hydraulic conductivity in the study area to some extent. The larger errors associated with the K_s estimated by the PTFs are due to the fact that the saturated hydraulic conductivity depends more on soil structural properties than the soil texture. Empirical nature of the PTFs as well as use of data sets from completely different geographic locations and

climatic settings may contribute to the larger error values when compared with the actual field data.

3.2.3 Limitations of the PTFs

Although some empirical models/PTFs provide successful approximations of the difficult-to-measure soil hydraulic properties to some extent, they are sometimes problematic and pose larger uncertainties. These larger uncertainties in the results of PTFs may arise because of several factors: inherent variability of the saturated hydraulic conductivity itself due to methods of measurement, representative sample volume, measurement error or its spatial variability (Minasny and McBratney 2000). The accuracy of some PTFs highly depends

Figure 7. Variation of unsaturated hydraulic conductivity, $K(\theta)$, in five vadose-zone layers of bare plot.

upon the quality of input data. For instance, the particle-size distributions should be as detailed as possible for the Campbell model (Campbell 1985) as the information about only three fractions (sand, silt and clay) may result in the reduction of its performance (Wagner *et al.* 2001; Manyame *et al.* 2007). Moreover, the results of this study as well as past studies highlight the limitations of PTFs' applicability in the regions having different climatic settings, hydrologic conditions and data availability. Thus, the performance of the PTFs used in this study is limited to the lateritic soils as well as other locations having similar soils, hydro-climatic conditions and land management practices. Nevertheless, all of the PTFs used in this study can be applied to other locations/terrains for examining their performances considering location-specific calibrations, if possible.

3.3 Unsaturated hydraulic conductivity

Unsaturated hydraulic conductivity depends not only on soil moisture content, but also on the number, size and continuity of the soil pores. The unsaturated hydraulic conductivity, $K(\theta)$, curves obtained for the five vadose-zone layers of the bare plot are shown in figure 7. The wetter the soil, the greater is the conductivity of the soil. The hydraulic conductivity values of the top and

bottom most layers are comparatively lesser among all the vadose-zone layers, while the highest value was found in the root zone (layer 2: 0.1–0.3 m). Compactness of both the layers may play a vital role behind this. In low moisture range, the hydraulic conductivity value of top layer (sandy loam) is greater than that in the bottom most layer, while in high moisture range, the hydraulic conductivity is higher in the bottom most layer (sandy clay loam). Much steeper $K-\theta$ curves in low moisture range are also apparent from figure 7.

4. Conclusions

The field investigation carried out in the lateritic vadose zone of the study area revealed that the K_{fs} values range from 0.39 to 6.77 cm/day for the barren land, 0.031 to 19.79 cm/day for the cultivated land and 2.52 to 18.32 cm/day for the orchard area. Although the effect of different land uses on the K_{fs} of the study area is not statistically significant, the mean values of K_{fs} in the barren land (mean $K_{fs} = 3.72$ cm/day), cultivated land (mean $K_{fs} = 7.26$ cm/day) and orchard area (mean $K_{fs} = 9.45$ cm/day) vary considerably from a practical point of view. In contrast, the depth-wise variation of K_{fs} in the study area was found to be statistically significant. Moreover, the depth-wise performance assessment

of the PTFs revealed that the R-B/C-G method can predict somewhat better in deeper lateritic-vadose-zone layers mostly having finer 'sandy clay loam' type texture, while Model 3 of Rosetta performs well to some extent in shallow layers mostly having coarse-textured soils. The performance of the PTFs varies considerably for the vadose-zone layers even for similar textured layers. This finding implies that the importance of bulk density and effective porosity should not be ignored for estimating the saturated hydraulic conductivity. Based on the statistical indicators, it is concluded that Model 3 of Rosetta is capable of predicting relatively close values of saturated hydraulic conductivity for the lateritic vadose zones to some extent. However, all the PTFs used in this study generally fail to yield reasonable values of *in-situ* hydraulic conductivity of lateritic vadose zones.

The findings of this study emphasise the urgent need for considering both spatial and depth-wise variation of hydraulic and physical parameters of the vadose zone while studying groundwater recharge and contaminant transport processes through unsaturated porous media. Finally, to generalise the findings of this study, such field-based studies should be carried out in future at a larger scale considering larger data sets and more number of locations with varying land use/land cover. Future attempts should also be made to develop more reliable PTFs for lateritic vadose zones. Also, creating additional data of the lateritic vadose zones such as organic matter content and soil water retention parameters at a larger scale will be useful for the rigorous evaluation of existing sophisticated and data-intensive PTFs. These future studies will be helpful in better planning and management of land and water resources at a watershed/catchment scale. In future, further studies may be carried out to evaluate the performance of PTFs in other alluvial terrains and hard-rock terrains.

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