Prediction of hydraulic conductivity of soils from particle-size distribution

Debashis Chakraborty[1,*], Abhishek Chakraborty[1], Priyabrata Santra[2], R. K. Tomar[1], R. N. Garg[1], R. N. Sahoo[1], S. Ghosal Choudhury[3], M. Bhavanarayana[1] and Naveen Kalra[1]

[1]Division of Agricultural Physics, Indian Agricultural Research Institute, New Delhi 110 012, India
[2]CAZRI, Regional Research Station, P.O. No. 63, Jaisalmer 345 001, India
[3]Central Agricultural Research Institute, P.O. Box 181, Port Blair 744 101, India

The study deals with the prediction of hydraulic conductivity, *K*, as a function of water content (θ) of 12 soils of Andaman Islands, India, three each in clay loam, sandy clay loam, sandy clay and clay textures, from their particle-size distribution (PSD) data using the Arya–Paris model. Pore-size distribution of soils was derived from PSD data using the model and *K*(θ) was determined by the horizontal infiltration method. Twenty soils, five each with the above-mentioned textural classes were used to relate the pore flow rate (*q*) and the pore radius (*r*) using the parameters *c* and *x* as obtained from the Hagen–Poiseuille equation for an idealized porous medium. log(*c*) varied from –5.58 to 0.17 and *x* varied from 2.41 to 3.95, but no systematic trends were observed for the textural classes, except the value of *x* approaching 4 as the sand content in the samples increased. The model predicted unsaturated hydraulic conductivity with reasonable accuracy. The root mean square residuals (RMSR) of the log-transformed *K*(θ) for all textures ranged from 0.107 to 0.879. The intra- and inter-textural uncertainties in the prediction could be attributed to the heterogeneity in the observed (experimental) data, which originated from the difference in hydrophysical behaviour of the soils.

Keywords: Andaman Islands, hydraulic conductivity, particle size distribution, soil water content.

HYDRAULIC conductivity (*K*) of soil is the most variable quantity, both spatially and temporally. Direct methods of estimating it have limitations for practical use due to unavailability of infrastructural facilities in most places, time-consumption and difficulty in operation[1,2], which led to efforts in developing indirect methods of estimating the same. There have been attempts to estimate *K*(θ) (where θ is the water content) from routinely available taxonomic data like particle-size distribution (PSD), bulk density and organic carbon[3–5], which have shown several advantages over direct methods[2,6], thus gaining considerable attention[7].

Since the soil water characteristics curve is basically a pore-size distribution curve (with the exception for some fine-textured soils), any hydraulic conductivity model based on pore-size distribution must require soil water function $\psi(\theta)$ and the saturated hydraulic conductivity K_s as the two most important input parameters[3,4,7–9]. Thus, it is likely that the hydraulic conductivity as a function of water content, $K(\theta)$ can also be related to the same basic soil properties[10] commonly used to characterize $\psi(\theta)$ and K_s. Pore-size distribution is directly related to PSD and hence $\psi(\theta)$ can be quantitatively derived from PSD data with considerable accuracy[5,7,10,11]. This is significant since PSD data are readily available and can be routinely determined in the laboratory. In the present study, PSD is the only available data on soil physical properties in areas like Andaman Islands, where no work has been carried out either to measure or predict $K(\theta)$ functions of the soils. Thus an attempt has been made to predict the $K(\theta)$ function of some soils of Andaman Islands based on the models proposed by Arya and Paris[11].

The model is based on the principle that flow in soil pore is a function of pore radius, with assumptions that only the completely filled pores contribute to the hydraulic conductivity at a given saturation, with negligible contribution from the partially drained pores. Hydraulic conductivity of the soil with its pore volume divided into *n* pore-size fractions (all filled with water) can be expressed, following the Darcy's law, as

$$K(\theta_i) = \frac{L}{(A\Delta H)}\sum_{i=1}^{n} Q_i \quad i = 1, 2, 3, \ldots, n \tag{1}$$

where $K(\theta_i)$ is the hydraulic conductivity (m s^{-1}) of the soil sample at moisture content θ_i, A is the cross-sectional area of the sample (m^2), $L/\Delta H$ is the reverse of the hydraulic gradient across the sample length L in the direction of flow and Q_i is the volume outflow rate (m^3 s^{-1}) contributed by the *i*th pore fraction and expressed as:

$$Q_i = q_i N_{pi}, \tag{2}$$

where q_i is the volume flow rate for a single pore i (m s^{-1}) and N_{pi} is the number of water-filled pores in the *i*th pore fraction.

Conceptualizing the flow in a single pore as capillary flow, the flow rate q_i is related to the pore radius r_i by the following equation:

$$q_i = c r_i^x, \tag{3}$$

where c and x are the model parameters which describe the shape, tortuosity and connectivity of pores along with fluid properties and degree of saturation[10]. The pore radius $r_i(m)$ can be obtained from the PSD curve using the following relation[11]:

---

*For correspondence. (e-mail: cdebashis@rediffmail.com)

$$r_i = 0.816R_i(en_i^{(1-\alpha_i)})^{0.5}, \tag{4}$$

where R_i is the mean particle radius for the ith particle size fraction (m), e is the void ratio, n_i is the number of equivalent spherical particles in the ith fraction and α_i is a scaling parameter[7].

N_{pi} can be computed using the following relation

$$N_{pi} = \frac{Ap_{\mathrm{e}}ew_i}{\pi r_i^2}, \tag{5}$$

where Ap_{e} is the total effective pore area exposed at the sample cross-section (m^2), and w_i is the particle mass fraction in the ith size fraction (obtained from PSD curve)[10].

For the flow under unit hydraulic gradient, the hydraulic conductivity function can be obtained as (after combining all the equations above)

$$K(\theta_i) = \frac{c\phi_e}{\pi}\sum_{c=1}^{n} R_i^{(x-2)} w_i [0.667en_j^{(1-\alpha)}]^{\frac{(x-2)}{2}}. \tag{6}$$

The above expression of $K(\theta_i)$ is thus related to the parameters of PSD and packing characteristics of the sample.

Undisturbed soil cores along with bulk soil samples were collected from different locations in the Experimental Farm of the Central Agricultural Research Institute, Port Blair, Andamans, India (11°40′N, 92°30′E). Soil in this area falls under Garacharma series (Tropofluvents). The parent material was shale and sandstone with different degrees of weathering. Average relief pattern of the study area was gentle with well-drained and moderate erosion potential[12]. Soil is dark reddish-brown (5YR), granular to sub-angular blocky in structure and sticky to moderately sticky. Particle-size analysis was carried out using International Pipette method[13] and textural classification was accomplished following International Society of Soil Science (ISSS) scheme[14]. Soil moisture retention at 0.03, 0.06, 0.1, 0.5, 1 and 1.5 MPa suctions was determined using pressure plate/membrane apparatus. Soil water diffusivity function $D(\theta_i)$ was calculated from experimental water content profile of undisturbed soil columns for different textural classes by horizontal infiltration method[15]. Finally, unsaturated hydraulic conductivity $K(\theta_i)$ was calculated using the relationship:

$$K(\theta_i) = D(\theta_i) \times C(\theta_i),$$

where $C(\theta_i)$ is the specific water capacity of soil at $\theta = \theta_i$ and is expressed as the inverse of slope of the experimental soil moisture-retention curve.

Pore size vs water content curves were obtained from the cumulative PSD curves for soils of four textural classes[7,11]. The parameters c and x were calibrated first by fitting observed $K(\theta_i)$ values to the flow model given by eq. (4) and then by plotting $\log(q_i)$ vs $\log(r_i)$ data for each of the textural classes[7,10]. The evaluated values of c and x were used in eq. (6) to predict $K(\theta)$ functions. In the process, 20 soils, five each with sandy clay loam, clay loam, sandy clay and clay in texture, and 12 soils, three each of the similar textures, were used for model calibration and testing respectively. The values of log c and x along with the log of the shape factor, S, for the experimental soils used for model calibration along with the goodness-of-fit are presented in Table 1. The values of S were calculated from the log c = log ($\pi\rho_w g/S\eta$) relationship, assuming viscosity of water 0.732×10^{-3} Nm s^{-1} at 30°C, as the other experimental data were obtained at this temperature[10]; ρ_{w} being density of water.

The relationship between logarithm of experimental pore flow rate, q_i, and logarithm of pore radius, r_i, for 20 Indian soils representing clay loam, sandy clay loam, sandy clay and clay soil is presented in Figure 1. The dotted line refers to the Hagen–Poiseuille pore flow rate, which was computed with the assumption that the pores are circular and straight capillary tubes (for cylindrical tube of uniform diameter, $x = 4$ and $S = 8$). For our calculations, we further assumed $\eta = 0.001\ \rho$ (viscosity of water at 25°C). The experimental pore flow rates were calculated from measured $K(\theta)$ data. It can also be observed that the regression line underpredicts the flow rates for heavy soils like clay. Similarly, when log q_i was plotted against logr_i for individual textural classes strong linear relationships were observed (Table 1 and Figure 2). The goodness-of-fit (R^2) values ranged from 0.91 to 0.96, for both sandy clay loam and clay loam; 0.83 to 0.92 for sandy clay, and 0.91 to 0.95 for clay soils. Soils in clay, clay loam, sandy loam and sandy clay loam textural classes, when considered together for their respective textural class, gave R^2 values of 0.90, 0.92, 0.87 and 0.89 respectively. The difference in the slope and intercepts of the regression lines explains the tortuosity of pores in the soils. The coefficient of regression of the straight-line equation relating log q_i and log r_i, represents parameter x of the flow model. For the textural class sandy clay loam, clay loam, sandy clay and clay, it varied between 3.229 and 3.953; 3.308 and 3.684; 2.969 and 3.495; and 2.414 and 3.483 respectively. The values of log c were observed to be negative for all the textural classes (except one for sandy clay loam) and ranged from –3.950 to +0.172, –4.860 to –3.702, –5.579 to –2.774 and –1.950 to –0.460 in sandy clay loam, clay loam, sandy clay, and clay soils respectively. The calculated values of log c, x and S are presented in Table 1. The values of x were lower than those for the Hagen–Poiseuille equation. When x was plotted against sand per cent, a linear relationship between them ($R^2 = 0.46$) could be observed. The value of x tended to be more close to $x = 4$ (in capillary flow) as the sand percentage was increased (Figure 3 *a*). The range of values of S for different soil textures is 7.4 to 13.2, which is in agreement with similar findings[10,16] and could be at-

Table 1. Sand, silt and clay fractions, and bulk density of soils used for model calibration along with model parameters c and x, goodness-of-fit (R^2), and the logarithm of shape factor (s)

	Sand	Silt	Clay					
Soil textural class		(%)		ρ_b (Mg m^{-3})	log c	x	R^2	log S
Sandy clay loam	69.2	5.5	25.3	1.41	–3.148	3.620	0.96	10.734
	65.0	5.0	30.0	1.44	–3.950	3.368	0.92	11.536
	71.5	6.5	22.0	1.39	0.172	3.953	0.93	7.414
	70.4	5.5	24.1	1.41	–3.241	3.395	0.91	10.827
	68.9	3.9	27.2	1.33	–2.910	3.229	0.92	10.496
Clay loam	65.9	11.0	23.1	1.38	–4.520	3.432	0.92	12.106
	65.1	12.0	22.9	1.27	–3.702	3.636	0.91	12.446
	62.3	12.4	25.3	1.30	–4.860	3.216	0.96	11.288
	65.9	13.1	21.0	1.29	–4.268	3.308	0.91	11.854
	60.0	12.0	28.0	1.27	–3.947	3.684	0.91	11.533
Sandy clay	65.3	2.5	32.2	1.25	–5.579	2.969	0.92	13.165
	59.9	4.0	36.1	1.25	–4.327	3.084	0.90	11.913
	62.5	7.5	30.0	1.30	–2.774	3.359	0.90	10.360
	64.9	5.0	30.1	1.27	–4.404	3.495	0.83	11.990
	62.9	4.0	33.1	1.24	–3.503	3.483	0.92	11.089
Clay	46.2	4.2	49.6	1.15	–1.95	2.891	0.92	9.536
	50.9	4.4	44.7	1.21	–0.588	3.483	0.95	8.174
	57.4	6.3	36.3	1.24	–0.460	3.070	0.93	8.046
	50.5	7.3	42.2	1.32	–1.504	3.208	0.91	9.090
	40.7	7.6	51.7	1.09	–1.589	2.414	0.93	9.175

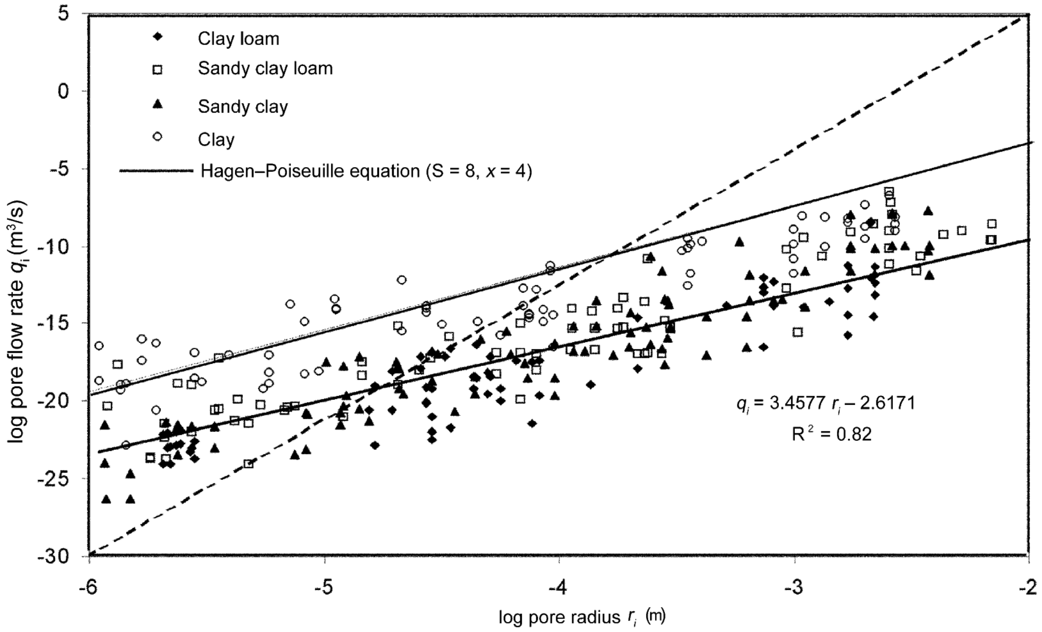

Figure 1. Relationship between pore flow rate (q_i) and pore radius (r_i) of 12 soils representing clay loam, sandy clay loam, sandy clay and clay textures.

tributed to the non-uniform pore geometry and pore-size distribution of the soils. These properties are likely to vary from one texture to another and so from one sample to another in the same textural class. The values for clay soils were close to those for the Hagen–Poiseuille equation, where $S = 8$, but no significant correlation between sand fraction and S could be obtained (Figure 3 *b*). Similar is the case when log c is plotted against sand per cent (Figure 3 *c*). These trends explain the complexity involved in describing the flow processes in soil. Nevertheless, the results indicate that macroscopic flow behaviour of soils can be predicted from the Hagen–Poiseuille model for flow in straight capillary tubes.

Comparison of logarithm of experimental vs predicted values of hydraulic conductivity on a 1 : 1 scale is presented in Figure 4. The regression lines between experi-

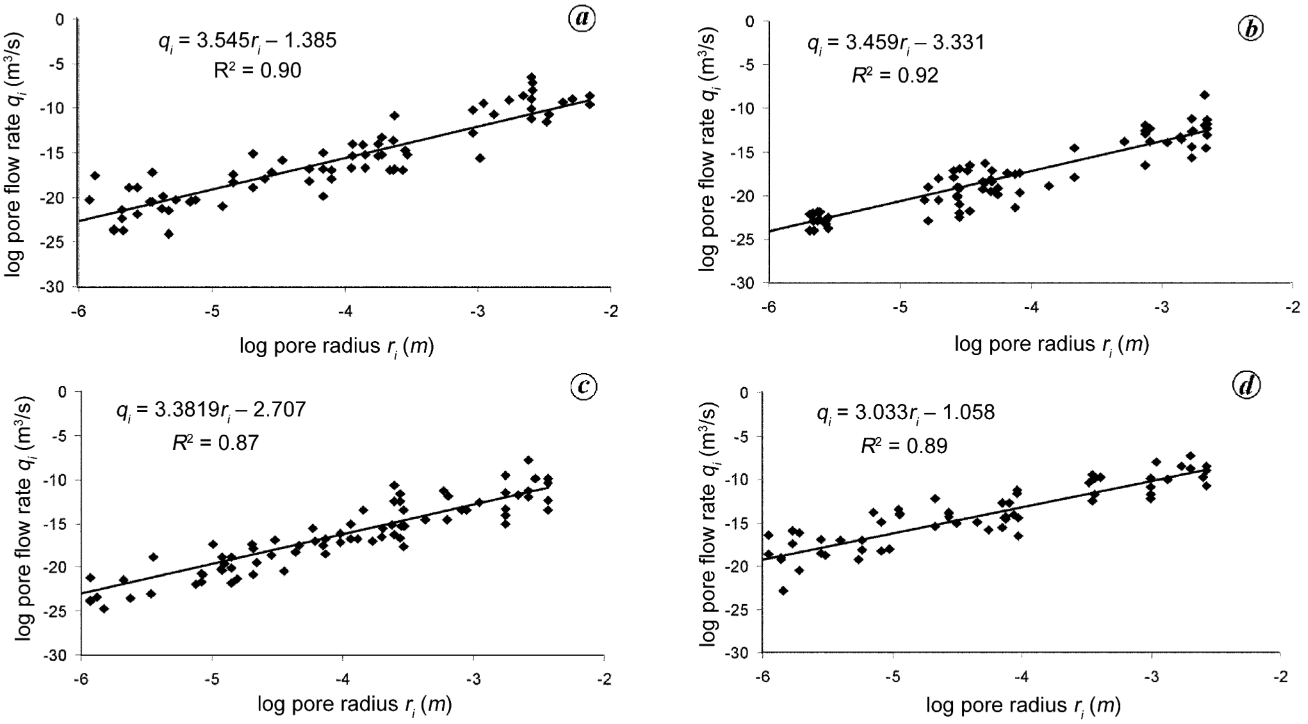

Figure 2. Relationship between pore flow rate (q_i) and pore radius (r_i) for (**a**) sandy clay loam, (**b**) clay loam, (**c**) sandy clay and (**d**) clay textures.

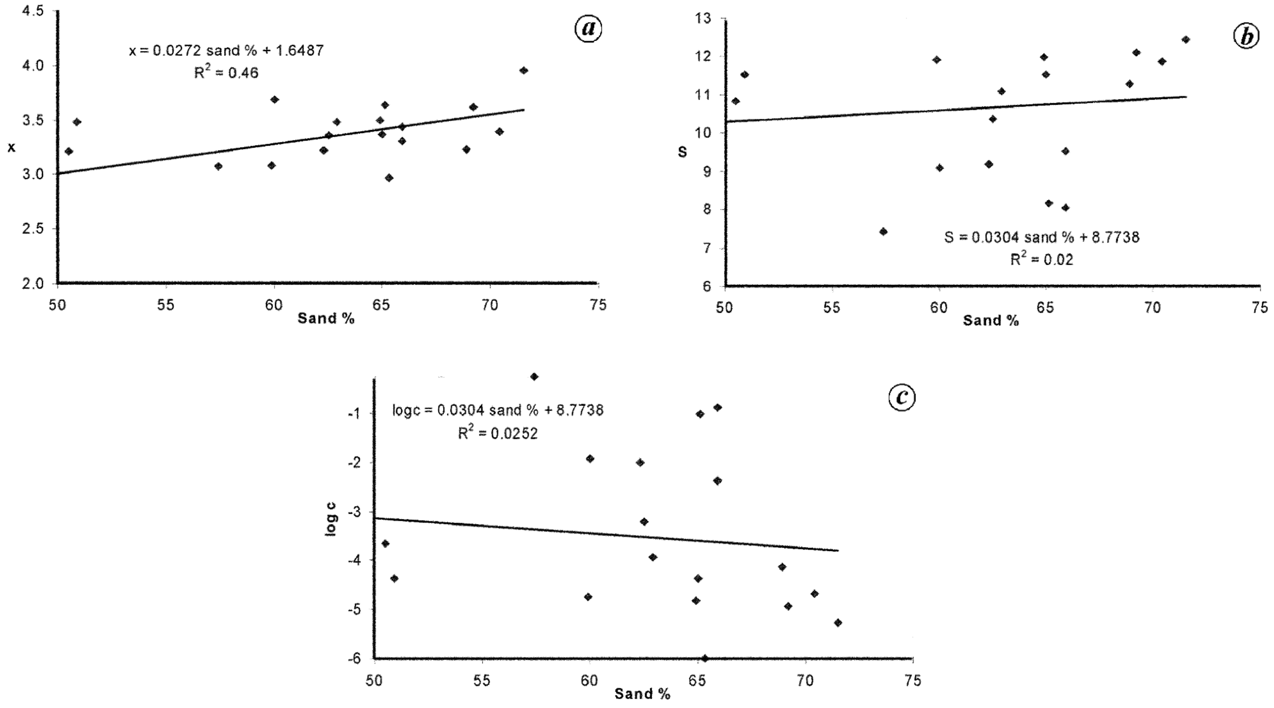

Figure 3. Relationship between sand % in soil and model parameter x (**a**), and shape parameter S (**b**) and log c (**c**).

mental and predicted $K(\theta)$ values almost matched the 1 : 1 line with R^2 of 0.93 for sandy clay loam and clay loam, 0.89 for sandy clay and 0.95 for clay respectively. When the same was plotted for all the soils the regression line was found to be close to the 1 : 1 line, with R^2 value of 0.92 (Figure 4 *e*). The root mean square residuals (RMSRs) of the log-transformed predicted and experimental $K(\theta)$ ranged from 0.322 to 0.647 for sandy clay loam, 0.237 to

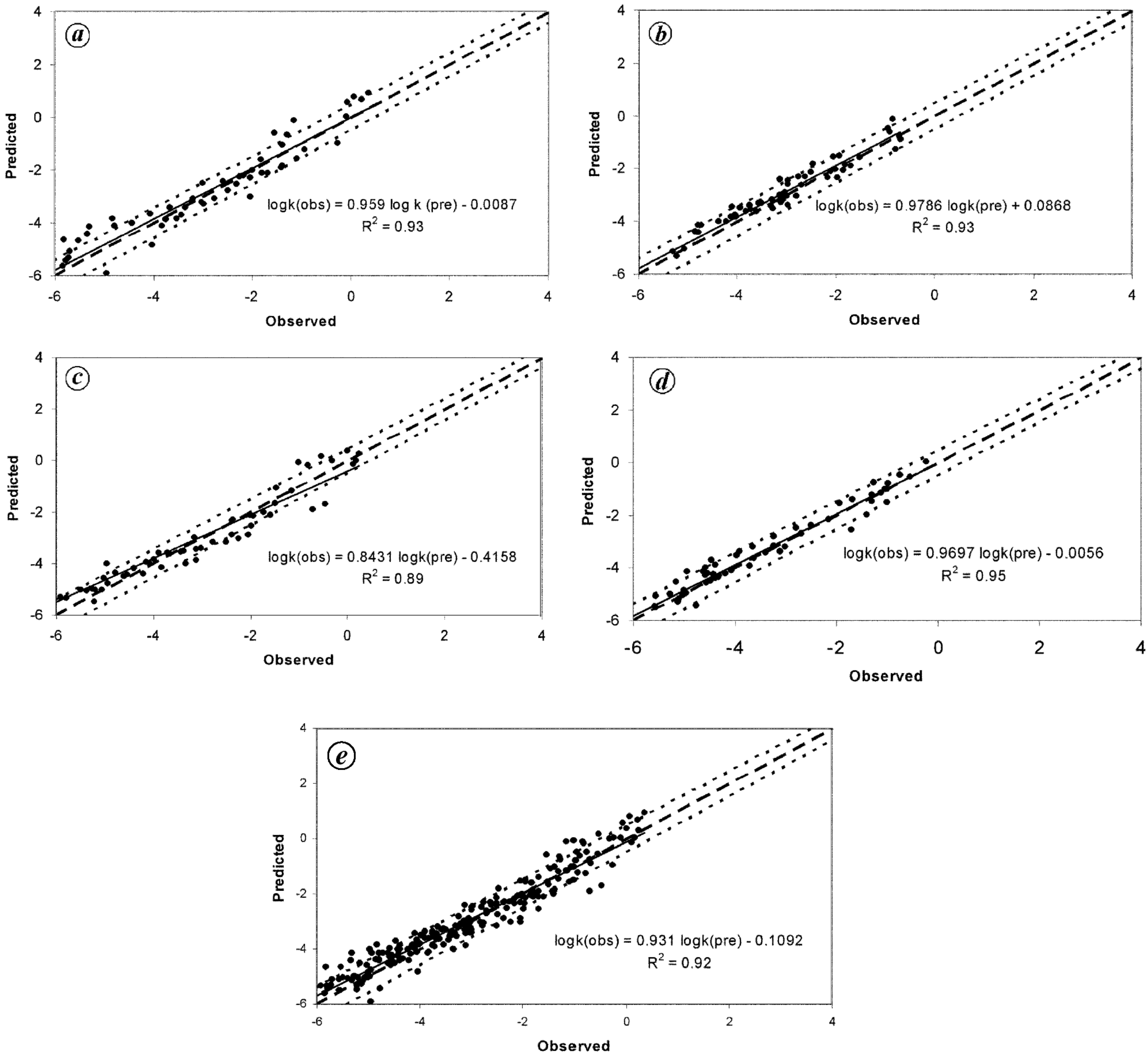

Figure 4. Observed vs predicted K(m/day) for (*a*) sandy clay loam, (*b*) clay loam, (*c*) sandy clay, (*d*) clay and (*e*) all textures pooled (dotted lines indicate ± 10% deviation from 1 : 1 line).

Table 2. Sand, silt and clay fractions, and bulk density of soils used for model testing along with root mean square residuals (RMSR) of log-transformed $K(\theta)_{\text{predicted}}$ and $K(\theta)_{\text{mean}}$ data

	Sand	Silt	Clay		
Texture		%		ρ_b(mg m^3)	RMSR
Sandy clay loam	65.9	6	28.1	1.34	0.322
	64.5	10.1	25.4	1.21	0.576
	62.4	13.4	24.2	1.40	0.647
Clay loam	52.2	17.7	30.1	1.31	0.334
	41	20.3	38.7	1.24	0.378
	44.9	18.9	36.2	1.25	0.237
Sandy clay	60	3.6	36.4	1.27	0.879
	64.9	4.2	30.9	1.31	0.437
	63.8	2	34.2	1.22	0.259
Clay	40.2	18.4	41.4	1.35	0.107
	43.7	4.4	51.9	1.33	0.257
	51.5	8	40.5	1.28	0.448

0.378 for clay loam, 0.259 to 0.879 for sandy clay and 0.107 to 0.448 for clay (Table 2). The average RMSR for all textures was 0.5228. The spread of data around the 1 : 1 line was obvious in view of the difficulty and complexity involved in estimating hydraulic conductivity of soils. Large differences between measured hydraulic conductivity could also be observed, even if the soil samples are of the same texture class, which is in agreement with the results of other workers[10,16]. Variations between predicted and observed hydraulic conductivity are extensively reported in the literature[10,16–18]. These variations emerge from the differences in PSD, bulk density, mineralogical compositions, structural properties and organic matter present in soils at the time of collection of samples and other physico-chemical characteristics, even within soils of the same textural class. In the present study, textural class average values of the model parameters c and x are used, which is likely to involve some errors in the prediction.

Nonetheless, the predicted hydraulic conductivity of soils of the study area based on the model as proposed by Arya and Paris[11], was in satisfactory agreement with the measured values of the same. Similar results have also been reported[16]. However, there is scope for further improvement of the model by introducing factors that influence flow processes in soil under unsaturated moisture regime.

The results show considerable success in predicting hydraulic conductivity from PSD data of soils. The average values of the model parameters for a particular textural class were used in the study. As there are variations among the soil samples even within a specific textural class, attributed to differences in bulk density, organic matter content and mineralogical composition, textural similarities could not necessarily be translated into hydrophysical similarities. Some degree of disagreement observed between the predicted and the measured data suggests that the model needs further improvement to include some parameters, which influence the flow behaviour of the soils. Besides the present model, other PSD models have also been proposed and hence attempts to quantitatively investigate the effect of the choice of a PSD model on the prediction of $\psi(\theta)$ and $K(\theta)$ curves have been suggested[19].

1. Shao, M. and Robert, H., Integral method of soil hydraulic properties. *Soil Sci. Soc. Am. J.*, 1998, **62**, 585–592.
2. van Genuchten, M. Th. and Leji, F., On estimating the hydraulic properties of unsaturated soils. In Proceedings of the International Workshop on Indirect Method of Estimating Hydraulic Properties of Unsaturated Soils (eds van Genuchten, M. Th. *et al.*), 11–13 October 1989, US Salinity Laboratory and Department of Soil and Environmental Science, Univ. of California, Riverside, 1992, pp. 1–14.
3. Mualem, Y., A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.*, 1976, **12**, 593–622.
4. van Genuchten, M. Th., A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.*, 1980, **44**, 892–898.
5. Tyler, S. W. and Wheatcraft, S. W., Application of fractal mathematics to soil water retention estimation. *Soil Sci. Soc. Am. J.*, 1989, **53**, 987–996.
6. Van Dam J. C., Stricker, J. N. M. and Droogers, P., Inverse method for determining soil hydraulic function from one-step outflow experiments. *Soil Sci. Soc. Am. J.*, 1992, **56**, 1042–1050.
7. Arya, L. M., Leij, F. J., van Genuchten, M. Th. and Shouse, P. J., Scaling parameter to predict the soil water characteristic from particle-size distribution data. *Soil Sci. Soc. Am. J.*, 1999, **63**, 510–519.
8. Marshal, T. J., A relation between permeability and size distribution of pores. *J. Soil Sci.*, 1958, **9**, 1–8.
9. Dirksen, C., Unsaturated hydraulic conductivity. In *Soil Analysis, Physical Methods* (eds Smith, K. and Mullins, C.), 1991, Marcel Dekker, NY, pp. 209–269.
10. Arya, L. M., Leij, F. J., Shouse, P. J. and van Genuchten, M. Th., Relationship between the hydraulic conductivity function and the particle-size distribution. *Soil Sci. Soc. Am. J.*, 1999, **63**, 1063–1070.
11. Arya. L. M. and Paris, J. F., A physicoempirical model to predict soil moisture characteristics from particle-size distribution and bulk density data. *Soil Sci. Soc. Am. J.*, 1981, **45**, 1023–1030.
12. Singh, N. T., Mongia, A. D. and Ganeshamurthy, A. N., *Soils of Andaman and Nicobar Islands*, CARI Bull. 1, Central Agricultural Research Institute, Port Blair., 1988, p. 28.
13. Gee, G. W. and Bauder, J. W., Particle size analysis. In *Methods of Soil Analysis, Part 1, Agronomy Monograph No. 9* (ed. Klute, A.), ASA and SSSA: Madison, WI, 1986, pp. 383–412.
14. Jalota, S. K., Khera, R. and Ghuman, B. S., State properties of soil. In *Methods in Soil Physics*, Narosa Publishing House, New Delhi, 1998, pp. 41–43.
15. Bruce, R. R. and Klute, A., The measurement of soil moisture diffusivity. *Soil Sci. Soc. Am. Proc.*, 1956, **20**, 458–462.
16. Chaudhary, S. K. and Batta, R. K., Predicting unsaturated hydraulic conductivity functions of three Indian soils from particle size distribution data. *Aust. J. Soil Sci.*, 2003, **41**, 1457–1466.
17. Mishra, S., Parjer, J. C. and Singhal, N., Estimation of soil hydraulic properties and their uncertainty from particle size distribution data. *J. Hydrol.*, 1989, **108**, 1–18.
18. Tamari, S., Wosten, H. M. and Ruiz-Suarez, J. C., Testing an artificial neural network for predicting soil hydraulic conductivity. *Soil Sci. Soc. Am. J.*, 1996, **60**, 1732–1741.
19. Hwuang, S. I. and Powers, S. E., Using particle-size distribution models to estimate soil hydraulic properties. *Soil Sci. Soc. Am. J.*, 2003, **67**, 1103–1112.

Received 8 September 2005; revised accepted 31 January 2006

Impact of tsunami on terrestrial ecosystems of Yala National Park, Sri Lanka

Prithiviraj Fernando[1,2,*],
Eric D. Wikramanayake[1,3] and
Jennifer Pastorini[1,4]

[1]Centre for Conservation and Research, Rajagiriya, Sri Lanka
[2]Center for Environmental Research and Conservation, Columbia University, New York, USA
[3]Conservation Science Program, World Wildlife Fund United States, Washington DC, USA
[4]Anthropologisches Institut, Universität Zürich, Zürich, Switzerland

Yala National Park in southeast Sri Lanka, lay in the direct path of the December 2004 tsunami, hence afforded a rare opportunity to study tsunami impacts on a natural ecosystem. We surveyed the impacted area and studied the damage caused to vegetation, early response of vegetation, and effects on animals. Tsunami incursion was patchy, much of the coast being protected by sand dunes. Although impact on vegetation within inundated areas was intense, survival and resiliency of the flora were high. Recovery of vegetation will be rapid and mainly a process of regeneration

---

*For correspondence. (e-mail: pruthu62@gmail.com)