ESTIMATION OF SOIL HYDRAULIC PARAMETERS TO SIMULATE WATER FLUX IN VOLCANIC SOILS

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ABSTRACT

Determining soil hydraulic parameters is necessary for accurate simulation of water movement. However, few data exist for key hydraulic parameters required to run such simulation models for volcanic soils. The aim of this study was to obtain hydraulic parameters for sandy volcanic soils (Vitric Orthic Allophanic under the New Zealand system) that are irrigated with wastewater from Rotorua, New Zealand. We measured drainage characteristics, soil water retention, and hydraulic conductivity at three plots and used a simulation model, SOIL. The drainage process was simulated for 20 days and model output was compared with measured water contents and total drainage. The model output was in excellent agreement with measured results from one of the three profiles (less than 1% error in the prediction of the cumulative drainage at 1 m depth). However, the agreement was poor for the other profiles (35% and 138% over-estimation of the drainage) when water retention curves determined from soil cores were used. We repeatedly ran the model using new values of the Brooks & Corey coefficients, until the best agreement between simulated and measured data was achieved for the two profiles with poor comparisons. Residual water content was found to be large (about 25%). Finally, we constructed a three-layer soil profile for the upper 1 m of these soils, with common soil hydraulic parameters in each layer. Simulation results indicated that the uppermost 1-m layer of local volcanic soils may be adequately simulated as a profile with three layers for prediction of water fluxes and drainage. However, these parameters have to be tested on other soil profiles in order to evaluate their generality.

Keywords: soil physical parameters; soil water modelling; allophane soils; residual water content; soil water movement.

INTRODUCTION

Soil hydraulic properties can be measured either directly in the field or in the laboratory. They are convenient to measure on core samples in the laboratory. However, using only

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laboratory methods is not recommended, as the volume of soil cores is generally less than a representative elementary volume, the vertical continuity of pores is restricted, and large macropores can be deformed during sampling (Kutílek & Nielsen 1994). The main advantage of field methods is that the connection of big pores can be kept undisturbed, whereas the main disadvantages are the cost and the fact that only a small part of the water retention curve is determined, usually in the wet range (Kutílek & Nielsen 1994). Soil water characteristics can then be estimated by relating unknown parameters in a specific function to the available data. Many empirical functions are available for this purpose (e.g., Brooks & Corey 1964; Campbell 1974; van Genuchten 1980).

Volcanic soils have distinctive properties which distinguish them from other soils: low bulk density and high water contents at field capacity and wilting point (Maeda *et al.* 1977). Another factor making the soils hard to understand is that irreversible changes in hydraulic properties occur during drying (Maeda *et al.* 1977). The aim of this study was to obtain soil physical parameters for volcanic soils near Rotorua, New Zealand.

MATERIALS AND METHODS

Site Description

The study area was Rotorua Land Treatment System, which is located in Whakarewarewa Forest near Rotorua in the North Island of New Zealand (38°10′S, 176°16′E). The area is irrigated by tertiary municipal effluent from Rotorua in an effort to reduce nutrient loadings to Lake Rotorua. The wastewater is applied by sprinkler on a weekly rotation, with average applications of about 56 mm/week. The mean annual precipitation of 1500 mm is therefore supplemented with about 2900 mm of wastewater irrigation per year. The area is forested by *Pinus radiata* D. Don and dense understorey vegetation (*Rubus fruticosus* L. agg. and grasses) completely covers the ground.

Soil Properties

The soil types are Whakarewarewa and Ngakuru sandy loams, which are both derived from volcanic tephra deposited during the past 20 000 years. Both soils are classified as Vitric Orthic Allophanic soils under the New Zealand system (Hewitt 1993). A distinctive feature is a coarse lapilli deposit "Rotorua Tephra" which is found at depths ranging between 0.5 and 2.5 m. The thickness of the "Rotorua Tephra" deposit is between 0.5 and 2 m. It comprises loose pumice sand, gravel, and stone varying in diameter from 1 to 100 mm (Cook *et al.* 1994). Above and below this layer are sandy tephric deposits with significant amounts of allophane clays, about 9% (Cook *et al.* 1994; Tomer *et al.* 1997).

Field Drainage Trials

Three flood plots measuring 1.5 × 1.5 m were established on level, undisturbed, upland sites in irrigation blocks 4, 11, and 15 of the Rotorua Land Treatment System which are in the northern, south-eastern, and western portions of the irrigated area, respectively (Tomer *et al.* 1997). Two plots, 4 and 11, were established in 1996 and plot 15, which was similar but not identical to these plots, was established earlier, in 1987 (Cook *et al.* 1994).

The experimental procedure of flooded field plots in this study involved ponding water on the soil surface, allowing sufficient infiltration time to bring the entire profile to a constant (steady state) water content, and then covering the plot to prevent evaporation. Soil water contents were monitored during drainage for 20 days. Initially, the soil water content profile was measured at frequent time intervals (hourly) but as drainage proceeded measurements were taken less frequently (2- to 5-day intervals).

Drainage in Plots 4 and 11 was conducted during August 1996. Dykes consisting of four wooden planks (1500 × 300 × 30 mm) were set vertically in the soil to 100 mm depth to establish the plot boundaries. A pit was excavated at the outside edge of each plot, the soil profile was examined, and the median depth of each horizon was determined. A horizontal surface was successively exposed at each such depth, upon which a 200-mm-diameter disc permeameter was placed to determine maximum hydraulic conductivity, K_m. This was obtained through measurement of water inflow at potentials near saturation (–0.01 and –0.05 kPa). A gravity flow was assumed as flow rates equilibrated quickly (within 10 minutes), and K_m was calculated as the flow rate per unit area (Perroux & White 1988). Soil water contents were measured by Time Domain Reflectometry (TDR) with 3-wire probes (Zegelin & White 1989). These probes were 180 mm long and were inserted horizontally at 100-mm intervals between 0.2 and 1 m depth. To install these probes, a vertical trough about 80 mm wide was excavated into the sidewall of the soil pit, so that it extended 300 mm into the drainage plot. TDR probes were installed along the back length of this trough to be away from the plot's edge. The trough and soil pit were back-filled and packed by horizons. Another probe 100 mm in length was inserted vertically at the soil surface. The TDR calibration equation was obtained by laboratory calibration carried out on large block samples with known water contents (Tomer 1999).

Plot 15 was investigated in 1987 as an isolated soil monolith with drainage conducted during spring. A detailed description of the methods used for plot installation and measurements has been given by Cook *et al.* (1994) and so only a brief summary is given here. The sides of the soil monolith were covered with plastic to 2.5 m depth to ensure 1-dimensional flow and the surrounding trench was back-filled with the excavated soil. A sealed frame was constructed to a height of approximately 200 mm above the soil surface. Soil water contents were measured with a neutron probe at 0.1-m intervals from depths 0.1 to 1 m. The neutron probe was calibrated by the method of Greacen (1981). A separate calibration study was performed for the surface 0.15-m layer.

Soil Core Measurements

Plots 4 and 11

Three soil cores (54 mm in diameter and 30 mm high) were collected from each horizon at the outside edge of each plot. The cores were used for laboratory measurement of soil water desorption. Water contents were measured at –0.2, –1.35, –5, –10, –34, and –102 kPa using a tension table (–0.2, –1.35 kPa), a tempe cell with hanging water column (–5 kPa), and a pressure chamber (–10, –34, and –102 kPa) (Klute 1986).

Plot 15

Two soil cores, each 100 mm in diameter and 70 mm high, were collected from each horizon via the soil monolith trench. Bulk and particle densities were measured by standard methods on one from each pair of cores and porosity was calculated. Portions of these cores were also used to determine water contents at matric potentials of –5, –10, –100, and –1500 kPa imposed using manometers and a pressure plate apparatus. The other core of each pair was used for measurement of K_m at a matric potential of –0.2 kPa using sorptivity tubes (Cook *et al.* 1994) (*see* Table 1).

TABLE 1–Maximum hydraulic conductivity, K_m, (mm/day) measured by disc permeameters (Plots 4 and 11) and measured on small soil cores (Plot 15).

Horizon	Plot 4	Plot 11	Plot 15
A	1109	274	206
BA		749	
Bw	547	3197	674
2AB			302
2Bwb	1670	2981	269
2E	1814		
3Bwb	346	763	206

Description of SOIL Model

A finite difference model, SOIL (Jansson & Halldin 1979; Jansson 1998), was used to simulate water flow in the soil profile. The water flow in the soil was assumed to be laminar and to obey Darcy's law. The general equation for unsaturated water flow was derived by combining Darcy's law with the law of mass balance (Richards 1931). The water retention curve and the unsaturated conductivity function were adapted to modified expressions of Brooks & Corey (1964) and Mualem (1976), respectively. The function of Brooks & Corey is given by

$$S_e = \left(\frac{\psi}{\psi_a}\right)^{-\lambda} \tag{1}$$

where ψ is the water potential, ψ_a is the water potential at air-entry, and λ is the pore size distribution index. Effective saturation (S_e) is defined as

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2}$$

where θ is water content, θ_s is the porosity, and θ_r is the residual water content. Estimation of the parameters λ, ψ_a, and θ_r was usually done by least squares fitting of Eq. (1) and (2) to experimental data. In order to get a good fit in the range close to saturation, i.e., from (θ_s – 0.04) m^3/m^3 to θ_s, a linear expression was used for the $\theta - \psi$ relation.

The unsaturated conductivity (K) was calculated using the equation given by Mualem (1976)

$$K = K_s S_e^{\left(n + 2 + \frac{2}{\lambda}\right)} \tag{3}$$

where K_s is the conductivity at saturation and n is a parameter accounting for pore connectivity and flow path tortuosity.

Model Adaptation

The soil profiles were assumed to be unsaturated and a unit gravitational gradient was assumed as the driving force for the vertical water flows from the lowest soil compartments.

Neither lateral flow nor evapotranspiration was considered. Initial water storage in each soil layer was set according to the values measured at initiation of drainage.

The modelled soil profiles were divided into 10 discrete layers. The uppermost layers had a thickness of 0.15 m, and from 0.15 m down to 1.05 m the profiles were divided into layers of 0.1 m thickness. The value of the tortuosity factor was assumed to be 1 for all layers.

Practical Procedure

Step 1

The model was parameterised using measured retention data and saturated hydraulic conductivity and was run for 20 days of drainage. Analysis of residual errors, the difference between observed and predicted values, was used to evaluate model performance. Several such statistical measures are available (James & Burges 1982; Green & Stephenson 1986). We chose the two most-used measures, namely root mean square errors (RMSE) and modelling efficiency (EF). Simulated soil water contents in different layers were compared with measured values and RMSE and EF were calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \tag{4}$$

$$EF = \frac{\sum_{i=1}^{N}(O_i - \bar{O})^2 - \sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \tag{5}$$

where P_i are the predicted values; O_i are the observed values; N is the number of observations and $\bar{O}$ is the mean of observed values. If all predicted and observed values are the same, then RMSE will be zero (the lower limit), and EF will be one (the maximum value). However, any positive value of EF indicates an improvement over the use of the mean of the observations ($\bar{O}$) as the best estimator (Loague & Green 1991). Furthermore, the simulated cumulative drainage at 1 m depth was compared with the measured value.

If a close agreement was found, then Step 2 was omitted and the procedure continued with Step 3.

Step 2

The model was run repeatedly, modifying values of the coefficients in the Brooks & Corey expression each time, until the best agreement between model output and measurement was found.

Step 3

A simplified and robust common parameter set based on obtained parameter values (including porosity and saturated conductivity) was arranged and tested for the local volcanic soils.

RESULTS

Maximum Field Water Content and Possible Errors

The maximum field water content, θ_{fs}, varied between 0.53 and 0.74 (Table 2). However, comparison of θ_{fs} with those measured in the laboratory at pressure heads of 0 (θ_0), and –0.2 kPa ($\theta_{-0.2}$) revealed the uncertainty associated with θ_{fs} values.

With the exception of the surface layers, θ_{fs} was larger than θ_0 in Plot 15. Measured soil water contents during drainage also indicated that Plot 15 had the highest water contents and θ_{fs} at three of the four common horizons (Fig. 1). Only the A horizon at 0–0.15 m depth showed similar water contents. Haverkamp *et al.* (1984) pointed to the calibration error as

TABLE 2–Soil water content at field saturation (θ_{fs}) and at saturation and near saturation based on measurements on soil cores in the laboratory (θ_0 = saturation, $\theta_{-0.2}$ = water content at –0.2 kPa potential, nd = no data).

Horizon	Plot 4			Plot 11			Plot 15		
	θ_0	$\theta_{-0.2}$	θ_{fs}	θ_0	$\theta_{-0.2}$	θ_{fs}	θ_0	$\theta_{-0.2}$	θ_{fs}
A	nd	0.62	0.68	nd	0.69	0.68	0.68	0.57	0.62
BA				nd	0.58	0.68			
Bw	nd	0.57	0.62	nd	0.55	0.53	0.66	0.57	0.66
2AB							0.65	0.58	0.71
2Bwb	nd	0.59	0.60	nd	0.60	0.54	0.58	0.51	0.63
2E	nd	0.47	0.59						
3Bwb	nd	0.48	0.59	nd	0.55	0.53	0.70	0.59	0.74

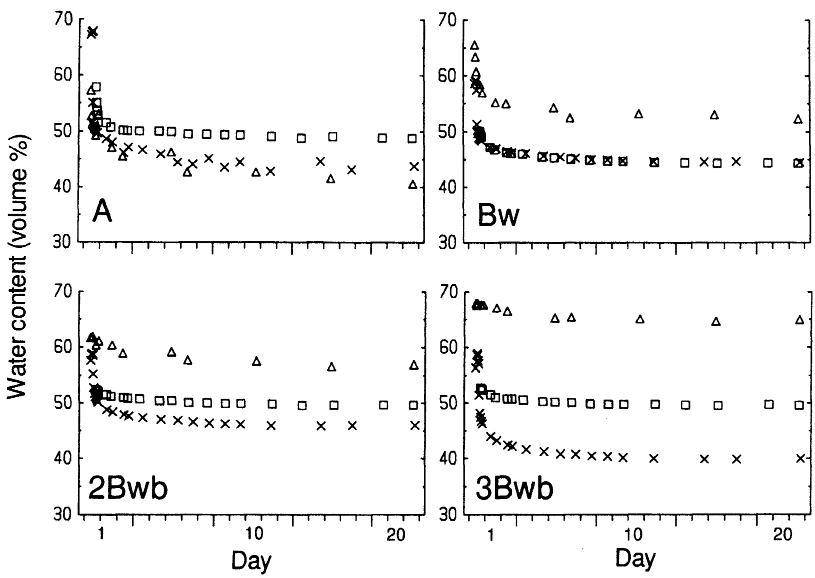

FIG. 1–Measured soil water content in the four horizons during drainage. Crosses represent Plot 4, squares Plot 11 and triangles Plot 15.

the main source of error in water content estimation by neutron probes. Whereas the neutron probe in the surface layer of plot 15 was calibrated against gravimetric measurements of water content, it was calibrated indirectly by the method of Greacen (1981), for sublayers of Plot 15. This difference in calibration method could be the main reason behind the higher "measured" porosity and water content in subsoil horizons of Plot 15.

In subsoil horizons of Plot 11, θ_{fs} was less than $\theta_{-0.2}$ (Table 2). This was probably because of the lower conductivity of the surface horizon in Plot 11 (Table 1) which might mean that subsoil layers never became fully saturated. It could also be the reason for the low amount of drainage in this particular soil profile (*see* the following section).

Step 1: Model Run using Parameter Sets Evaluated in Laboratory

The Brooks & Corey equation was fitted to the desorption points by regression at the different ranges of pressure heads, giving individual estimates of θ_r, λ, and ψ_a for each depth. The best fit was obtained when points measured in the range from –2 to –102 kPa were considered. Porosity was obtained from water content at initiation of drainage, θ_{fs}, for Plots 4 and 15 whereas it was obtained from water content of cores at –0.2 kPa potential for Plot 11 (Table 2). The saturated hydraulic conductivities were obtained from K_m estimated by flow measurements through disc permeameters for Plots 4 and 11 and cores for Plot 15 (Table 1).

The result showed different agreement between measured and simulated water contents in different plots and soil layers. Less agreement was found in Plots 11 and 15 whereas Plot 4 showed better agreement (Table 3, Fig. 2). A similar difference was obtained when comparing the measured and simulated cumulative drainage at a depth of 1 m. A total of 135, 63, and 123 mm of drainage was measured from Plots 4, 11, and 15 respectively during the simulation periods. The corresponding simulated values were 136, 150, and 212 mm, showing a prediction to within 1 mm for Plot 4 and over-estimation by 87 and 89 mm of measured drainage for Plots 11 and 15 respectively. However, Plot 15 was distinguished from the other plots by having the gravel-lapilli layer closest to the surface (Cook *et al.* 1994). It occurred at about 1.35 m depth in Plot 15 whereas it was more than 2 m below the surface in Plots 4 and 11. This layer has a large effect on redistribution of soil water at greater depths. For unsaturated flow, the Rotorua lapilli could act as an impedance resulting in higher water conditions in the layers above it. The constant high water content of the deepest layer at Plot 15 which belongs to the 3Bw horizon, 0.95–1.35 m (Cook *et al.* 1994), could thus be a result of impeded drainage caused by the underlying gravel-lapilli layer. If this is the case, then the assumption of a constant pressure head near saturation for the bottom layer would seem to be more realistic. We fixed the water potential of the bottom layer to –0.3 kPa and ran the model again for Plot 15. This resulted in a much better match for the 0.85–1.05 m layer, a small improvement for the 0.65–0.85 m layer, but no change for the other layers (data not shown). The simulated drainage became 166 mm, which was 46 mm less than in the previous simulation for Plot 15 but 43 mm more than the recorded drainage.

Step 2: Optimisation, Searching for the Best Agreement

We used the estimated coefficients in the Brooks & Corey equation for Plot 4, in particular air entry pressure, to improve the visual match between simulated and measured water contents for Plots 11 and 15.

TABLE 3–Root mean square error (RMSE, vol. %) and modelling efficiency (EF) for soil water contents in all three soil profiles and three parameter sets. Simulations for Plot 15 were made assuming a constant pressure head for the bottom layer and the common parameter set in Plot 15 was adjusted for θ_s.

Plot	Depth (m)	Parameter Set					
		Laboratory		Optimal		Common	
		RMSE	EF	RMSE	EF	RMSE	EF
4	0–0.15	3.95	–0.45	0.87	0.93	2.49	0.42
	0.15–0.25	3.55	–1.34	2.64	–0.29	2.13	0.16
	0.25–0.35	2.43	0.57	3.58	0.06	3.83	–0.07
	0.35–0.45	6.62	–1.16	5.62	–0.56	6.29	–0.94
	0.45–0.55	2.03	0.60	2.20	0.53	2.25	0.51
	0.55–0.65	2.44	0.10	2.49	0.06	2.40	0.13
	0.65–0.75	2.38	0.35	2.62	0.21	2.18	0.45
	0.75–0.85	5.15	–1.39	3.88	–0.35	4.32	–0.68
	0.85–0.95	2.70	0.43	2.09	0.66	4.22	–0.39
	0.95–1.05	5.26	0.21	5.60	0.10	4.78	0.35
	Median	3.12	0.15	2.63	0.08	3.16	0.14
11	0–0.15	4.23	–0.14	1.03	0.93	2.47	0.61
	0.15–0.25	5.98	–49.42	1.17	–0.92	1.63	–2.73
	0.25–0.35	10.04	–60.79	0.46	0.87	1.11	0.24
	0.35–0.45	7.21	–15.14	0.27	0.98	2.26	–0.58
	0.45–0.55	8.09	–9.12	0.54	0.95	1.43	0.68
	0.55–0.65	8.96	–16.21	0.73	0.88	1.24	0.67
	0.65–0.75	2.33	–3.75	0.29	0.92	1.28	–0.43
	0.75–0.85	2.71	–8.36	0.40	0.79	2.06	–4.41
	0.85–0.95	2.05	–0.49	0.43	0.93	2.39	–1.04
	0.95–1.05	4.71	–16.68	0.61	0.70	5.20	–20.58
	Median	5.34	–12.13	0.50	0.90	1.84	–0.50
15	0–0.15	1.91	0.88	1.58	0.92	2.36	0.82
	0.15–0.25	5.07	–0.41	1.35	0.90	2.68	0.60
	0.25–0.35	3.15	0.65	0.90	0.97	2.45	0.79
	0.35–0.45	4.45	0.56	4.19	0.61	4.60	0.53
	0.45–0.55	4.59	0.49	4.54	0.50	4.79	0.44
	0.55–0.65	6.33	–1.60	2.38	0.63	2.58	0.57
	0.65–0.75	8.46	–15.16	1.05	0.75	1.91	0.17
	0.75–0.85	4.47	–9.59	0.97	0.50	1.06	0.40
	0.85–0.95	1.58	0.61	1.06	0.82	3.75	–1.19
	0.95–1.05	1.99	–0.53	1.85	–0.32	1.74	–0.17
	Median	4.46	0.04	1.46	0.69	2.51	0.48

To improve the agreement in Plots 11 and 15, we calibrated the model by changing λ, ψ_a, and θ_r in such a way that new water-retention curves reasonably fitted the measured water-retention or were parallel to it.

After many simulations, we found the closest visual match, least RMSE, and largest EF values (Fig. 2, Table 3) as follows:

- Using measured hydraulic conductivities as in Step 1, except for the 0.35–0.65 m depth in Plot 15 where measured conductivity from the corresponding layer in Plot 4 resulted

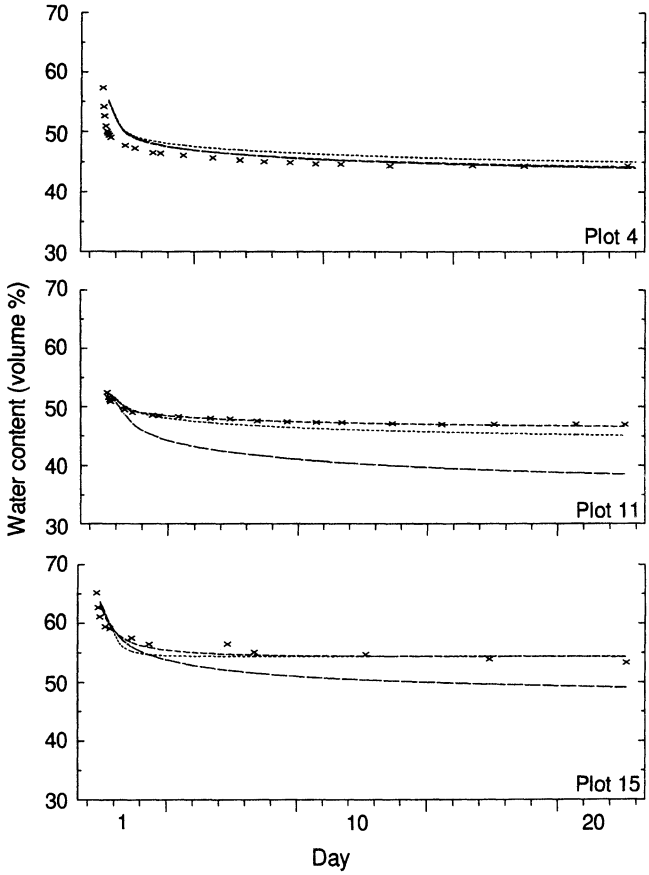

FIG. 2–Simulated (lines) and measured (crosses) soil water contents for the uppermost 1-m layer during drainage. Simulated values are represented by long dashed line for laboratory parameter set, medium dashed line for optimal parameter set, and short dashed line for common parameter set.

in a better match. It is worth mentioning that K_s in Plot 15 was measured on soil cores in the laboratory, which may not be representative of the field situation (Klute 1986).

- The porosity was the same as in Step 1 except for the 2Bwb horizon in Plot 11 and the A horizon in Plot 15 where it was obtained from θ_{fs} and $\theta_{-0.2}$ respectively.
- Using the pore size distribution index λ, air entry pressure ψ_a, and residual water content θ_r given in Table 4.

Finally, we simulated drainage for the soil profile in Plot 4 using optimised values of ψ_a, λ, and θ_r from Plots 11 and 15. Only some few adjustments were made for θ_r (Table 4). The agreement between the simulated and measured water content was as good as when the laboratory parameter set was used (Fig. 2).

The optimised parameter sets resulted in great improvement in predictions of cumulative drainage at 1 m depth in Plots 11 and 15 compared to parameter sets determined from

TABLE 4—Estimated air entry pressure ψ_a, pore size distribution index λ, residual water content θ_r, porosity θ_s, and saturated hydraulic conductivity K_s, through comparison of model output with the soil water contents measured in the field (optimal parameter set).

Depth (m)	Plot 4						Plot 11						Plot 15					
	Horizon	ψ_a (kPa)	λ (–)	θ_r (%)	θ_s (%)	K_s (mm/day)	Horizon	ψ_a (kPa)	λ (–)	θ_r (%)	q_s (%)	K_s (mm/day)	Horizon	ψ_a (kPa)	λ (–)	θ_r (%)	θ_s (%)	K_s (mm/day)
0–0.15	A	–0.77	0.18	17	62	1109	A/BA	–0.77	0.18	19	68	274	A	–0.77	0.18	15	58	206
0.15–0.25	A/Bw	–1.60	0.20	13	62	828	BA/Bw	–1.60	0.20	28	58	749	Bw	–1.32	0.43	43	66	674
0.25–0.35	Bw	–1.32	0.43	28	62	773	Bw	–1.32	0.43	37	56	3197	Bw	–1.32	0.43	40	66	674
0.35–0.45	2Bwb	–1.80	0.47	25	60	1670	Bw	–1.32	0.43	32	56	3197	2AB	–2.55	0.57	23	70	1670
0.45–0.55	2Bwb	–1.85	0.47	35	60	1670	Bw	–1.85	0.47	33	56	3197	2AB	–2.55	0.57	20	71	1670
0.55–0.65	2Bwb	–1.98	0.47	32	59	1670	Bw	–1.98	0.47	32	56	3197	2AB	–2.58	0.47	20	67	1670
0.65–0.75	2Bwb	–1.98	0.47	30	59	1670	2Bwb	–1.85	0.47	43	54	2981	2AB/2Bwb	–2.02	0.47	35	64	269
0.75–0.85	2E	–0.80	0.14	10	59	1814	2Bwb	–1.85	0.47	43	54	2981	2Bwb	–1.85	0.47	35	60	269
0.85–0.95	2E	–0.40	0.14	10	52	1814	2Bwb/3Bwb	–0.32	0.21	33	54	763	2Bwb	–1.00	0.47	19	64	269
0.95–1.05	3Bwb	–0.32	0.21	11	59	787	3Bwb	–0.32	0.21	40	55	763	3Bwb	–0.32	0.21	19	73	206

laboratory measurements. The simulated drainage was 136 mm for Plot 4, 66 mm for Plot 11, and 110 mm for Plot 15, which is within 3 mm of measured drainage for Plots 4 and 11 and an under-estimation by 13 mm for Plot 15.

Step 3: Construction and Test of a Common Parameter Set

A simplified, three-layer, soil profile was constructed based on optimal parameter sets. The profile consisted of a 0–0.25 m topsoil layer and two subsoil layers, 0.25–0.85 m and 0.85–1.05 m (Table 5). Model output agreed fairly well with field data from Plots 4 and 11 when the common parameter set was applied (Table 3, Fig. 2). The agreement was different for Plot 15. Except for the top layer where a good visual agreement was achieved, the simulated water contents were lower than the measured values (data not shown). Considering the fact that the neutron probes were calibrated against gravimetric measurements of water content only for the surface layer, it is very possible that the "measured" water content and porosity in subsoil horizons of Plot 15 were erroneous and the estimated porosity in the common parameter set was more realistic (*see* section on maximum field water content and possible errors). As we substituted the porosity in the common parameter set with the porosity from the optimal parameter set, we got much better agreement between the simulated and the "measured" water content (data not shown). The simulated cumulative drainage at 1 m depth was 130 mm for Plot 4, 83 mm for Plot 11, and 113 mm for Plot 15 (with adjusted θ_s). That was an under-estimation by 5 mm, an over-estimation by 20 mm, and an under-estimation by 10 mm of measured cumulative drainage in Plots 4, 11, and 15, respectively. Of the overestimation for Plot 11, 8 mm occurred at the 0.85 m depth.

TABLE 5–Common soil hydraulic characteristics of the volcanic soils of Whakarewarewa Forest (common parameter set). ψ_a = air-entry potential, λ = pore size distribution index, θ_r = residual water content, θ_s = maximum water content, and K_s = saturated conductivity.

Depth (m)	ψ_a (kPa)	λ (–)	θ_r (%)	θ_s (%)	K_s (mm/day)
0–0.25	–1.20	0.20	20	62	720
0.25–0.85	–1.90	0.47	32	58	2400
0.85–1.05	–0.35	0.20	20	56	840

DISCUSSION

The visual agreement between the simulated and the measured soil water content can be split into two major parts: the rapid drop in the water content at the beginning of the drainage and the large, slowly draining, water content for the rest of the period. The model showed sensitivity to all three estimated parameters: λ, ψ_a, and θ_r. The former part was sensitive to ψ_a whereas the latter was sensitive to θ_r. The shape of the drainage curve in general was sensitive to λ.

The estimated θ_r was generally large and varied between 10% (2E horizon in Plot 4) and 43% (Bw- and 2Bwb horizons in Plots 15 and 11, respectively) (Table 4). It should be mentioned that θ_r estimated by use of soil cores also had a wide range: it varied between 0.3 and 25% in Plot 4, 0.3 and 33% in Plot 11, and 8 and 20% in Plot 15. Both the water retention curve and the conductivity were sensitive to θ_r. For the water retention curve, θ_r affected the curve at potentials less than ψ_a which is best shown in the Bw horizon in Plot 15 (Fig. 3). The higher water content for the potentials less than ψ_a was mainly due to the higher value of θ_r in the curve used to provide an optimal match with measured drainage. Considering the

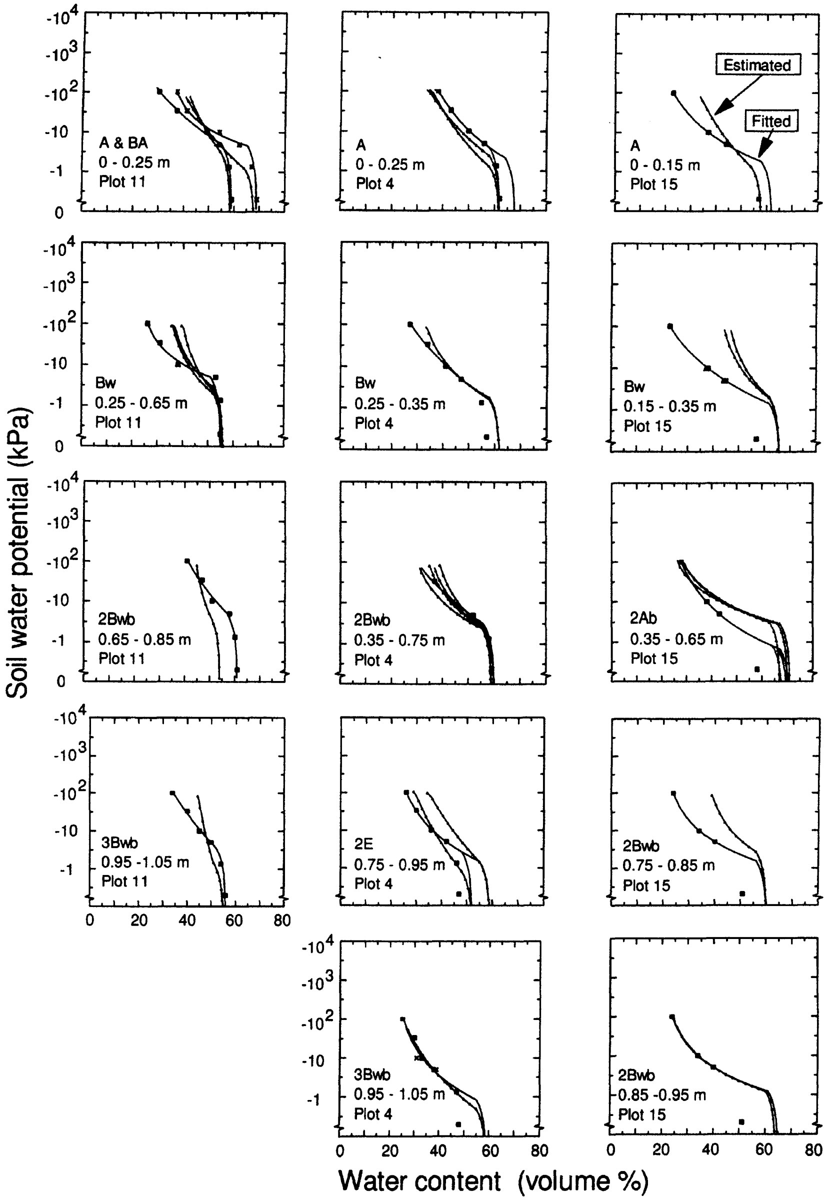

FIG. 3—Soil water retention curves fitted to values measured in the laboratory (fitted) and soil water retention curves estimated through comparison of model output with soil water contents measured in field (optimal parameter sets, estimated). Symbols represent values measured in the laboratory. The measured data points and fitted curves represent individual horizons, whereas estimated curves represent 0.1-m depth intervals.

conductivity, a larger θ_r caused a more rapid decrease in unsaturated conductivity (Fig. 4). These two important impacts indicate the key role of θ_r in simulation of the drainage.

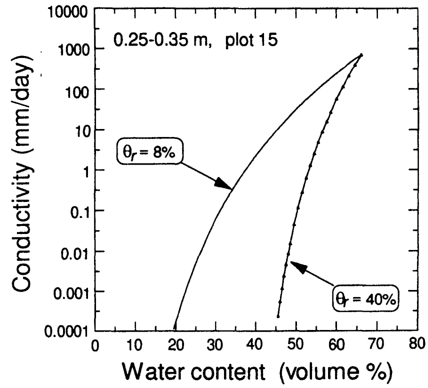

FIG. 4—Illustration of the effect of θ_r on the hydraulic conductivity curves.

The values of estimated θ_r may be related to the allophane clay content in these profiles. Maeda *et al.* (1977) reviewed physical properties of allophane soils and found in particular a higher wilting-point water content for allophane soils than for soils with crystalline clay minerals. They mentioned the large volume of small pores as the reason for the higher water content of allophane soils. No allophane content data were available for these profiles, but data from other profiles in the land treatment area (Tomer *et al.* 1997) showed that the estimated residual water content followed the variation of the allophane content in different horizons. For example the A horizon with 1.5% allophane content (Tomer *et al.* 1997) had an estimated θ_r of 17% (Table 4), whereas the Bw horizon with 9% allophane content had an estimated θ_r of 33%.

The model showed less agreement for Plot 11 compared to Plots 4 and 15 when the laboratory and common parameter sets were used (Table 3). This was probably because of the lack of soil homogeneity in this profile. A higher variation in water desorption data and maximum conductivity was found in this soil profile than in the other plots (Table 1). However, a large part of the variation in K_m might be accounted for by the error caused by the small number of K_m measurements. Repeated measurements at the same site would decrease the error as the values of hydraulic conductivity are spatially highly variable. The effect of vertical heterogeneity was probably amplified through the fact that parameter values represented individual horizons which were applied to more than one measured interval, whereas soil water contents were measured and simulated at 0.1 m depth intervals.

A problem in our study was the use of a different procedure for measuring water content and K_m in Plot 15 compared to that used in Plots 4 and 11. Using a similar procedure would make the measured parameters much more comparable. In 1987, however, TDR and disc permeameters were not generally available. Therefore, K_m values were based on laboratory measurements and water content was measured using a neutron probe.

The validity of the simulation may be restricted to wet conditions since the derived soil properties were estimated for such periods. However, it is likely that wet conditions will prevail as long as the present treatment continues. These soils receive more than 4000 mm of precipitation and wastewater irrigation, and this is evenly distributed throughout the year, with weekly applications of wastewater.

A logical continuation of this work may be a statistical evaluation of the generality of the common parameter set for the soils in the area. This may be done through applying of these parameters to a sufficient number of new soil profiles. Provided there is an acceptable generality, the common parameter set can be used in hydrological models to study the effects of wastewater irrigation on soils, groundwater, and vegetation in the land treatment area.

CONCLUSIONS

The uppermost 1 m layer of local volcanic soils may be adequately simulated as a profile with three layers for prediction of water fluxes and drainage. However, the generality of the common parameter set has to be statistically evaluated.

The estimated residual water content was large which might be related to allophane clay content in these profiles and to the unique hydraulic properties of these volcanic soils.

The position of the Rotorua lapilli layer is of importance in simulation of drainage. This gravel deposit acted as a barrier to unsaturated flow in the sublayers when we simulated drainage at Plot 15. Generally the lowest compartment in the simulated profile had a great impact on the simulated water movement in the overlying layers.

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