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On Soil Retention Curves and Hydrological Forecasting in Ungauged Catchments

M. G. Anderson and S. Howes
University of Bristol, England

P. E. Kneale
University of Leeds, England

J. M. Shen
Geotechnical Control Office, Hong Kong

In many physically based hydrological models, there is the requirement to specify the suction-moisture curve of the soil system. This paper shows that where the suction moisture curve is known, then a model can be derived to predict groundwater rise. Secondly, it is shown that with only mapped soils data, relationships exist that allow suction-moisture curves to be predicted. This prediction scheme is incorporated into a forecasting model for ungauged catchments and results are presented to show the potential validity of the scheme for operational forecasting.

Introduction

Many physically based models of catchment hydrology require specification of suction-moisture curves and of the hydraulic conductivity function. Frequently, an important pre-requisite in the model requirement is that it shall be capable of transfer to a range of catchments and not restricted in application to a single catchment. However, here lies a potential conflict in model formulation. In the latter case of establishing the conductivity function there has been a substantial number of investigations into methods that may be used to estimate unsaturated hydraulic conductivity from moisture retention functions. Childs and Collis-George (1950), Millington Quirk (1959), Green and Corey (1971) and Libardi et al. (1980) present several such methods, and Jackson (1972) makes some useful comparisons between certain of these approaches. However, the requirement to obtain suction-moisture curves in the context of soil water physics elements of hydrology models, has only been researched relatively recently. It is manifestly too costly to obtain field measurements of soil water retention data (as well, of course, as hydraulic conductivity) in all sites that may be considered necessary from the hydrology modelling standpoint. To overcome these difficulties *and* to comply with model operational requirements that they be 'portable' catchment to catchment, certain recent investigations have attempted to establish relationships between basic soils data (such as particle size distribution or simply soil type) and soil water retention data. Rawls et al. (1982) have shown the nature of relationships between Green and Ampt infiltration parameters and bulk density and organic matter, as well as other variables. A more comprehensive approach has, however, been undertaken by Rawls et al. (1982) and Brakensiek and Rawls (1983). In these studies, some 1,323 soils were used as the data base to explore soil textural associations with soil retention parameters. This is a most significant approach since it complies fully with the two requirements set out at the start of this paper. It is this line of research that is pursued here in the context of its potential for hydrological modelling investigations.

The above discussion emphasises the benefits to be obtained from procedures that predict suction-moisture curves. There are, however, certain analytical aspects relating to groundwater changes that can be determined from field suction-moisture curves alone that have not been developed hitherto. In selected cases pertaining to forecasting needs where 'worst' groundwater conditions are required, we aim to show that such groundwater forecasts can be made, with the sole inputs being rainfall and the appropriate suction-moisture curve. Of course, such a scheme has greatest relevance in the near-surface zone. The structure of the research reported here, therefore, hinges on three applications of soil retention data. Firstly, where the field suction-moisture curve is known, an analysis is presented that predicts groundwater changes. Secondly, it is shown that predictions of suction-moisture curves can be made from basic mapped soils data for potential inclusion in hydrology models. Finally, the utilisation of such a prediction scheme is examined in the context of hydrograph validation on an ungauged catchment.

Utilisation of Soil Retention Data to Predict Groundwater Rise

The suction-moisture curve gives, of course, a measure of volumetric moisture content at specified suctions. In the context of water table rise through vertical infiltration, it is therefore implicit that, given known soil water conditions in the profile to the water table, the amount of infiltration required to raise the water x metres, establishing a new soil water profile, can be estimated. Boersma et al.

(1970) have undertaken work of this type, seeking to characterise water table responses in Oregon soils with specific regard to trafficability. Their approach was entirely empirical, taking the field suction-moisture curves together with a 15-year rainfall series and evaluating the probability of water table rise. This paper, however, seeks to establish a universal approach to the problem by the establishment of an analytical scheme, based upon the Campbell (1974) approximation of the suction-moisture curve. To ease the method of computation and analysis, it is more convenient to consider a solution as estimated by drainage. Initial trials at estimation of a solution by wetting were not completely successful. To complete a solution by drainage, the following assumptions are made:

a) Infiltration takes place vertically, there being no other form of recharge.
b) The soil is homogeneous.
c) The water table is horizontal.
d) Both initial and final soil water conditions in the profile are hydrostatic.
e) The suction moisture content of soil can be described by a linear log-log plot (equation with coefficients *a* and *b*) as illustrated by Campbell (1974):

$$\log \psi = a + b \log \theta \tag{1}$$

f) Evapotranspiration and other losses are ignored.

There is therefore no hystereris and saturation occurs at 1 kPa (ψ is suction in kPa and θ the volumetric water content).

From an initial condition with the water table at the surface, assume that drainage from below lowers the water table by an amount H, then the amount of drainage (D) is given by

$$D = \int_{x=0}^{H} (\theta_s - \theta_x)\,dx \tag{2}$$

where θ_x is volumetric moisture content of the soil at a distance x metres below the water table.

Since (Eq. (1))

$$\log \psi = -(a + b \log \theta) \qquad (a \text{ and } b \text{ treated as positive})$$
$$= -(\log 10^{-a} + \log \theta^{-b})$$
$$= -\log 10^{a}\,\theta^{b}$$

then $\psi = (10^{a}\,\theta^{b})^{-1}$

or $$\theta = \frac{1}{10^{a/b}}\frac{1}{\psi^{1/b}} \tag{3}$$

At saturation ($\psi = 1$ kPa) then

$$\theta_s \equiv 10^{-a/b}$$

thus

$$\theta_s - \theta_x = 10^{-a/b} - 10^{-a/b}\,\psi^{-1/b}$$

Since, for hydrostatic equilibrium

$$\psi = \gamma_\omega \quad + 1$$

then

$$\theta_s - \theta_x = 10^{-a/b}(1 - (\gamma_\omega x + 1)^{-1/b})$$

Integrating the moisture loss over the entire depth from the soil surface (x = H) to the water table (x = 0) we have

$$\int_{x=0}^{H} (\theta_s - \theta_x)dx = 10^{-a/b} \int_0^H (1-(\gamma_\omega x+1)^{-1/b})dx$$

$$= 10^{-a/b}\left[x - \frac{1}{\gamma_\omega}\,\frac{(\gamma_\omega x+1)^{-1/b}}{1-\frac{1}{b}}\right]_0^H$$

$$= 10^{-a/b}\; H - \frac{(\gamma_\omega H+1)^{1-1/b}}{\gamma_\omega(1-\frac{1}{b})} + \frac{1}{\gamma_\omega(1-\frac{1}{b})}, \qquad (4)$$

Eq. (4) gives the amount of water (metres) drained, in lowering the water table from the surface to depth H. Of course, the amount of water drained in this manner is equivalent to that water (infiltration) required to raise the water table from H to the surface. This can then be generalised to provide the infiltration, I (M), necessary to raise the water table from depth $H2$ to $H1$:

$$I = 10^{-a/b}\left[\left(H_2 - \frac{(10H_2)^{1-1/b}}{10(1-\frac{1}{b})} + \frac{1}{10(1-\frac{1}{b})}\right) - \left(H_1 - \frac{(10H_1)^{1-1/b}}{10(1-\frac{1}{b})} + \frac{1}{10(1-\frac{1}{b})}\right)\right] \qquad (5)$$

Thus, in $H2$ metres of soil (initial depth to water table) I metres of infiltration are

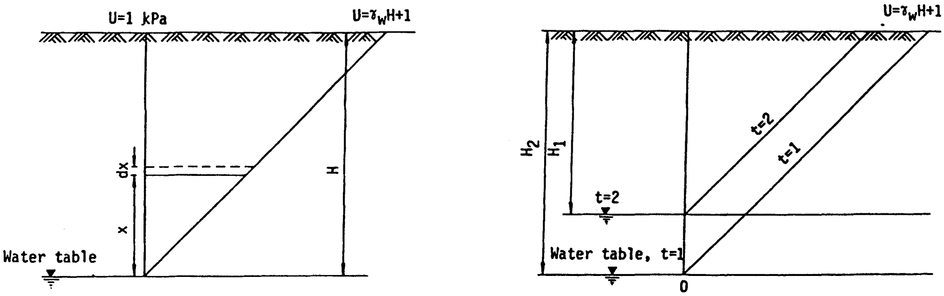


Fig. 1. Definition diagram for Eqs. (4-5).

required to raise the water table ($H2$ - $H1$) metres (see Fig. 1).

In Eq. (5) with respect to Eq. (4), $\gamma\omega H + 1$ is approximated by $10H$.

The next stage is the determination of the coefficients a and b. Data from Rawls et al. (1981), Campbell (1974), and McFarlane (1981) have been analysed such that these coefficients could be determined for all the soils presented in these papers.

From Fig. 2 it is seen that different soil types are grouped in different parts of the plot. This provides a classification of soil based on suction-moisture characteristics similar to Casagrande's plasticity chart based on soil consistency. A lower limit of all the points is conveniently represented by the line a = -1. It is

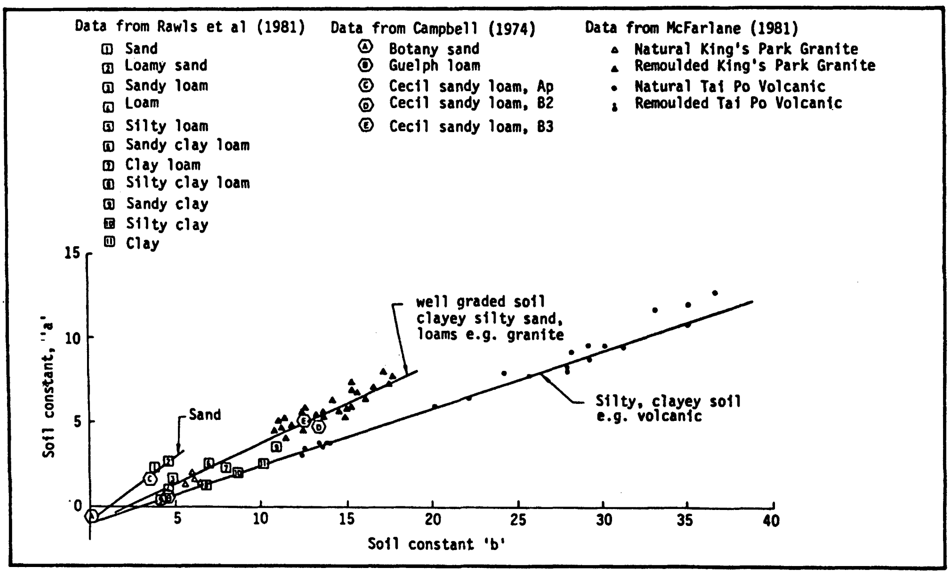


Fig. 2. Selected soils plotted on 'a' and 'b' coefficients (see Eq. (1)).

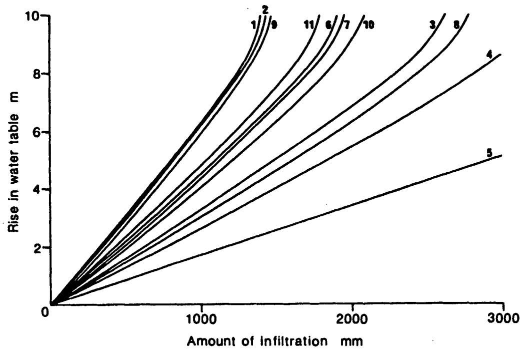


Fig. 3.
Water table rise predictions Eq. (5) for the soils of Rawls et al.(1981) in Fig. 2.

seen that soils of similar grading lie on a straight line, but that position on the line varies tremendously depending on soil structure.

In this analysis, it is assumed that the empirical equation derivations relating moisture content and soil suction exhibit correlation coefficients in excess of 0.95 since utilisation of Eq. (3) in the manner illustrated depends on using a regression equation as X on Y, although computed for Y and X.

Using Eq. (5) parameterised for specific soils by coefficients a and b from Fig. 2, then for an initial depth to water table ($H2$) of 10 m, Fig. 3 shows the response of selected soils to given amounts of infiltration.

The original data from Rawls et al. (1982) used to estimate a and b on the suction-moisture curve (Eq. (1)) provide for moisture contents at 0.33 and 15 bars only. This is clearly not as high a data resolution as would ideally be considered suitable for practical applications. The impact of this is shown in Fig. 3 where, for example, sand and sandy loam are shown to exhibit relatively higher rises than might be expected. Nevertheless, the foregoing analysis is shown to exhibit useful water table rise information *providing* that the a and b coefficients can be obtained from sufficient original data on the suction-moisture curves over the appropriate suction ranges that are required by the application.

An estimation of water table rise can therefore be determined solely from the two coefficients of the soil water retention curve for the respective soil. This method may be most appropriate for certain design situations in which basic soil data is available, no groundwater level data has, or can be, obtained, and 'worst' groundwater levels are required. This latter aspect is, of course, an integral element in the above analysis, since it is assumed that the soil voids are instantaneously filled with the prescribed rainfall volume. It may well prove to be that the procedure outlined will be a most suitable method for determining landslide risk areas in regions of varying soil types, where groundwater monitoring methods cannot be continuously interrogated (Anderson 1983).

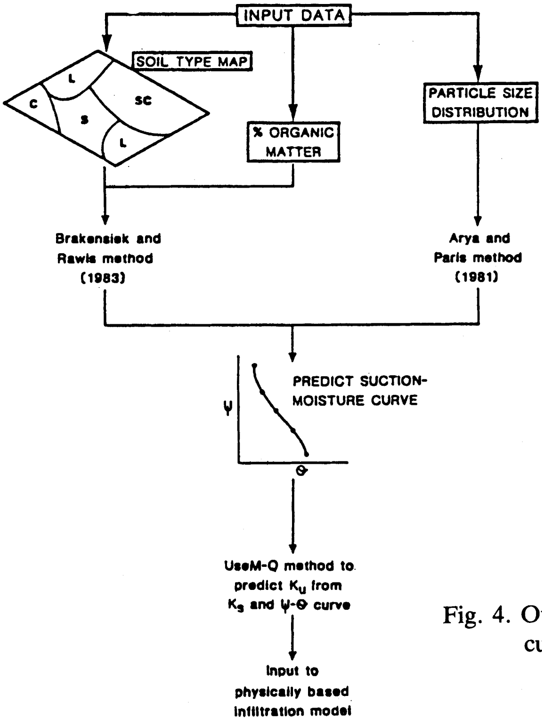
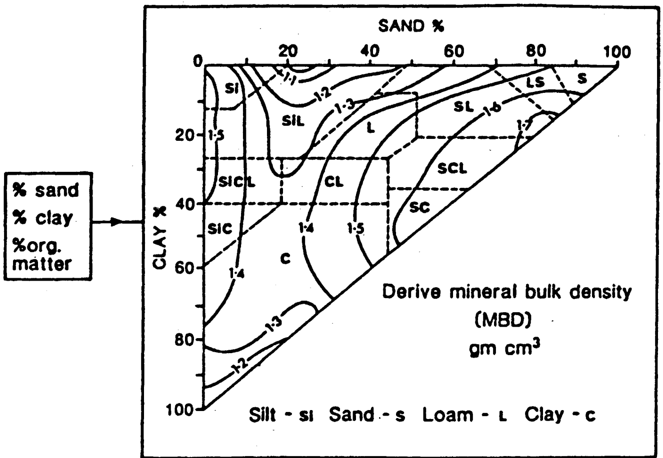


Fig. 4. Outline of data input, suction moisture curve and hydrology model relationships.

Predicting Suction Moisture Curves for Hydrology Models

The preceding analysis utilised the Campbell method for approximating the soil water retention curve. Other applications, however, such as hydrological forecasting, may require the prediction of the soil water retention curve itself, from basic soil data. Such methods have been discussed in the literature, most notably those methods attributable to Brakensiek and Rawls (1983) and Arya and Paris (1981). It may be appropriate to consider such methods as being capable of being interfaced with physically based infiltration models, as we suggest here (Fig. 4), or indeed with the groundwater rise model outlined above. In both cases the attraction is that of a minimal soil textural input (or particle size distribution (PSD), in the case of Arya and Paris) that is required – being data that is available for most hydrological forecasting applications. Such methods are especially appropriate for developing in the context of ungauged catchment hydrological forecasting, where available input data may well be of the form of soil textural mapping at a relatively coarse scale.

Theoretically, the Brakensiek and Rawls procedure for estimating the soil



Evaluates soil bulk density (SBD)

$$SBD = \frac{100}{\frac{\%\text{org. matter}}{0.224} + \frac{100 - \%\text{ org.matter}}{MBD}}$$

Table used to derive Θ for each given ψ using the regression equation :

$$\Theta = a_i + b_i(\%\text{sand}) + c_i(\%\text{clay}) + d_i(\%\text{org.matter}) + e_i(SBD)$$

Matric Potential - Bars	a	b	c	d	e	R^2
-0.20	0.4180	-0.0021	0.0035	0.0232	-0.0859	0.75
-0.33	0.3486	-0.0018	0.0039	0.0228	-0.0738	0.78
-0.60	0.2819	-0.0014	0.0042	0.0216	-0.0612	0.78
-1.0	0.2352	-0.0012	0.0043	0.0202	-0.0517	0.76
-2.0	0.1837	-0.0009	0.0044	0.0181	-0.0407	0.74
-4.0	0.1426	-0.0007	0.0045	0.0160	-0.0315	0.71
-7.0	0.1155	-0.0005	0.0045	0.0143	-0.0253	0.69
-10.0	0.1005	-0.0004	0.0044	0.0133	-0.0218	0.67
-15.0	0.0854	-0.0004	0.0044	0.0122	-0.0182	0.66

Suction - moisture curve

Fig. 5. Prediction of suction-moisture curve from soil type (after Brakensiek and Rawls 1983).

retention curve can be applied to any soil that can be assigned a known position on the soil texture triangle. It does not matter that the particle size criteria for given soil classes differ between countries, provided that the unique texture location can be made and this point transferred to its equivalent position on the USDA triangle. Fig. 5 outlines the Brakensiek and Rawls procedure in general terms.

From a study based on some 1,323 soils, they were able to derive two important relationships based on the percent sand, clay and organic matter. Firstly, a simple association of these elements with mineral bulk density, and, secondly, a suite of regression relationships for moisture content at nine specified suctions was also estimated. These relationships thus facilitate the establishment of a suction-moisture curve from the soil textural description alone, as Fig. 5 illustrates.

Hall et al. (1977) present a figure showing typical soil suction-moisture content curves for ten of the eleven soil classes on the British Soil Survey texture triangle. These were derived from sampling of some twenty-two soil groups in England. The soil suction-moisture curves have been calculated for each of these curves using the Brakensiek and Rawls method to compare with the curves reported by Hall et al. In each case the mid point of the texture class on the Soil Survey triangle was transposed to the USDA texture triangle and then to its equivalent position on the 'mineral bulk density triangle'.

In this context, it should be noted that errors may arise due to the problem of transferring from the texture equilateral triangle to the right angled mineral bulk density triangle, particularly at the clay and sand clay boundaries. For ease of working, the presentation of the mineral bulk density graph in Brakensiek and Rawls (1983) as an equilateral triangle would speed up analyses.

Figs. 6, 7 and 8 show the suction moisture curves obtained by the Brakensiek and Rawls method; it is the British Soil types that are referenced in these figures. With respect to the observed data given in Hall et al. (1977), the Brakensiek and Rawls method over-estimates the water content for clay and sand; under-estimates the water content for sandy clay loam, sandy loam, clay loam, loamy sand, sandy silt loam, and silty clay loam; while silty clay and silt loam are approximately correct.

The Brakensiek and Rawls estimation in Figs. 6-8 (as in Fig. 5) is not taken to saturation in these comparisons, as the measured data does not extend to suctions less than 60 cm. However, it will be seen in the application section following, that the Brakensiek and Rawls method does facilitate extension of the suction-moisture curve to saturation.

Arya and Paris (1981) describe a model that predicts the suction-moisture curve from the soil particle size distribution, bulk density and particle density. The model uses the particle size data to calculate the pore size distribution for the soil. It then cumulates the pore sizes to give a volumetric water content for each size range. Finally, the pore radii are converted to the equivalent soil water suctions using the equation of capillarity and making standard assumptions concerning

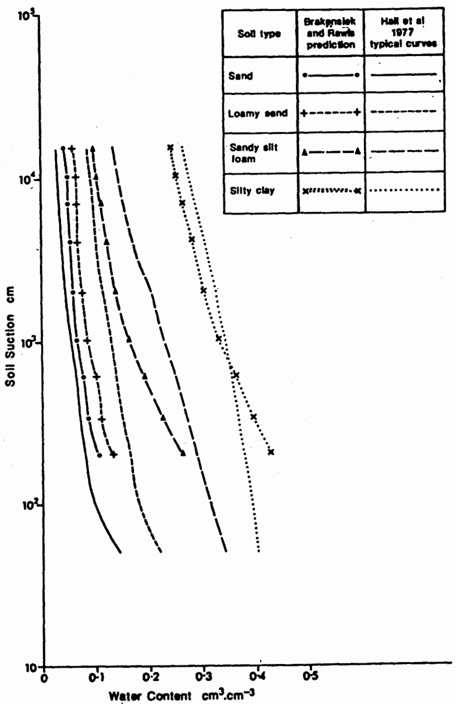


Fig. 6.
Comparison of Brakensiek and Rawls predictions (Fig. 5) with measured suction moisture curves of Hall et al. (1977).

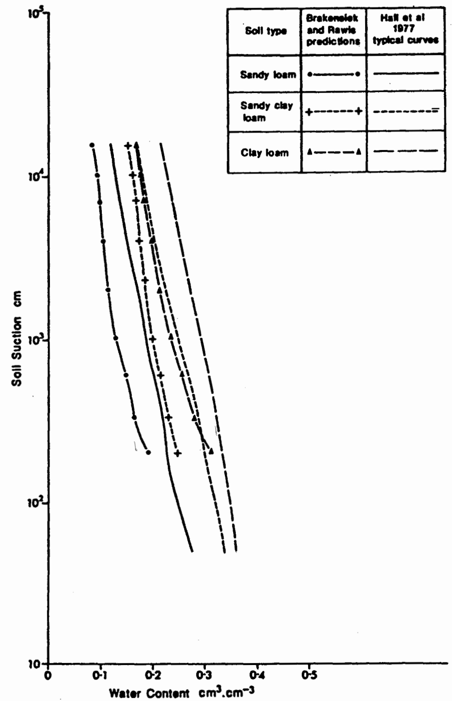


Fig. 7.
Comparison of Brakensiek and Rawls predictions (Fig. 5) with measured suction moisture curves of Hall et al. (1977).

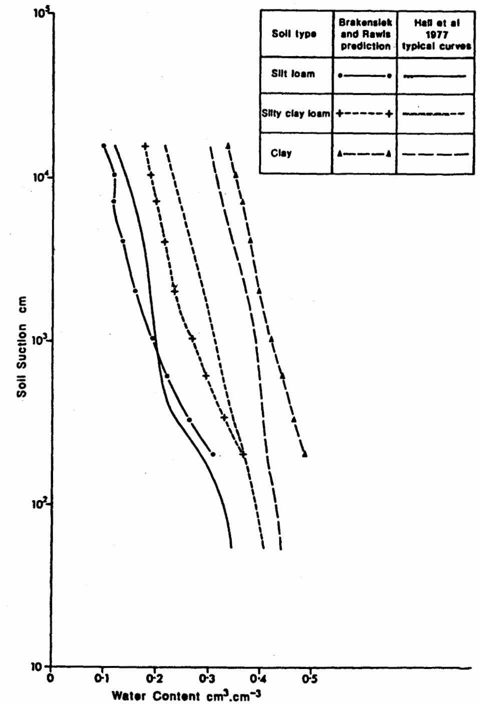


Fig. 8.
Comparison of Brakensiek and Rawls predictions (Fig. 5) with measured suction moisture curves of Hall et al. (1977).

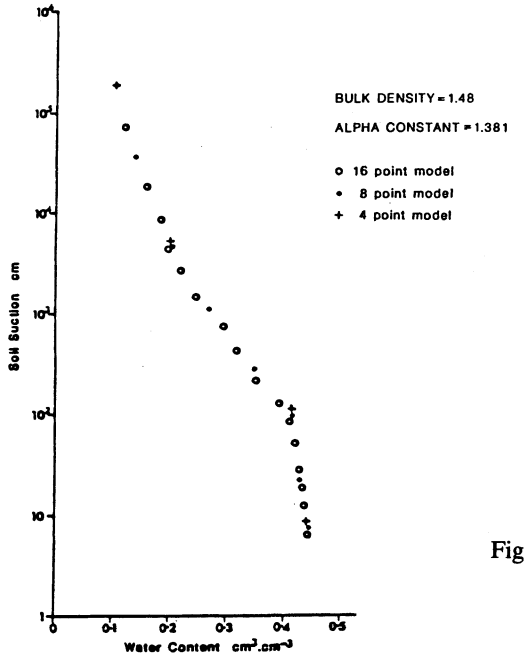


Fig. 9. Arya and Paris (1981) 16, 8 and 4 point models compared.

water temperature, surface tension and contact angles.

The Arya and Paris model has an important advantage over the Brakensiek and Rawls method. Because the calculations can be made for any number of divisions on the particle size curve, the shape of the suction-moisture curve can be more closely defined. However, a PSD curve is not always available for a given soil series. More often the best data available is the percent clay, percent silt and percent sand values, as, for example, in soil memoirs. However, it was felt that the model was worthy of comparison with the Brakensiek and Rawls method.

Initially, the Arya and Paris model was run using three points alone for comparison with an 8-point model. Arya and Paris divided their particle size graph into sixteen sections and thereby got a very good suction-moisture curve as compared with the field and laboratory determinations. The 8-point model plotted for comparison in Fig. 9 shows that the curve could be drawn just as satisfactorily from this more limited number of points. Reducing the model to 3-points is much less satisfactory because then there are no suction values less than -100 cm water. However, a fourth point can be obtained by summing the % data for sand, silt and clay, and subtracting from 100 to obtain a 'gravel fraction'. This gives a 4-point model with a suction-moisture content at ψ = -8 cm water, thereby defining the lower part of the curve with greater accuracy.

Figs. 10 and 11 plot two of the curves in the Arya and Paris paper, with the suction-moisture curve derived using the Brakensiek and Rawls method. The % clay value is taken as the % of particles < 2μm. There are a number of options when cumulating the % difference in the 20 to 200 μm range, the USDA fine sand range gives values of 48% sand (Fig. 10) and 60% sand (Fig. 11). Both these curves underestimate the water content of the soil for a given suction.

The use of organic matter at 0.0, or at 0.5 with consequent effect on bulk density, makes relatively little difference to the position of the suction-moisture curve. It is, however, important to use a bulk density value derived from Brakensiek and Rawls' procedure (Fig. 5) rather than the field measured bulk density. The best fit curve in both examples is that where BD is calculated from Brakensiek and Rawls (BD = 1.22 and 1.55 gm cm^{-3} respectively).

Khosla (1980) has reported data for a field determination of the suction-moisture curve of an alluvial sandy loam soil for which he also gives particle size and bulk density data. Both the quantitative methods of determining the suction-moisture curve described above were used and compared with the field derived curve.

The Brakensiek and Rawls method was used firstly by taking the values for % sand and % clay from Fig. 5 for a sandy loam soil. Bulk density was calculated assuming $OM \equiv 0$ and 1.0, and the curves were calculated and plotted on Fig. 12.

Secondly, the data for % clay and % sand were taken directly from the particle size analysis given by Khosla, and bulk density as measured in the field where OM = 0, and bulk density recalculated for OM = 1.0. The results are also plotted on Fig. 12.

The Arya and Paris equations were calculated by assigning a particle size of 2 μm to clay, 20 μm to silt, 200 μm to sand and then summing these percentages, subtracting from 100 and assigning this value to gravel at 1,000 μm. The upper part of the curve is as well defined here as by the other methods but the lower part is a problem. This is in part probably because of the wide particle range assigned to % sand in the texture analysis and the need to make assumptions about the middle particle size of the range. A smaller % sand size and a larger % gravel size would produce a suction-moisture curve that more truly reflects the field data than is produced here.

The above analysis has shown that two methods of estimating the suction moisture curve provide reasonable approximations to field observed curves. In particular, the Brakensiek and Rawls procedure performs well for all soil types (Figs. 6, 7, 8 and 12) and has a particular advantage in that only soil textural information is needed to initiate the estimation procedure (Fig. 5). From this evidence it would be appropriate to consider this procedure as an integral method for hydrological forecasting models where such models are designed for use in 'ungauged' catchments. Whilst the above analysis demonstrably makes this point, it is necessary to ascertain whether the accuracy of the soil retention curves undertaken in this manner is sufficient when used as input data for a hydrology model to predict flood hydrographs. It is this very point that a final analytical section of this paper is devoted to.

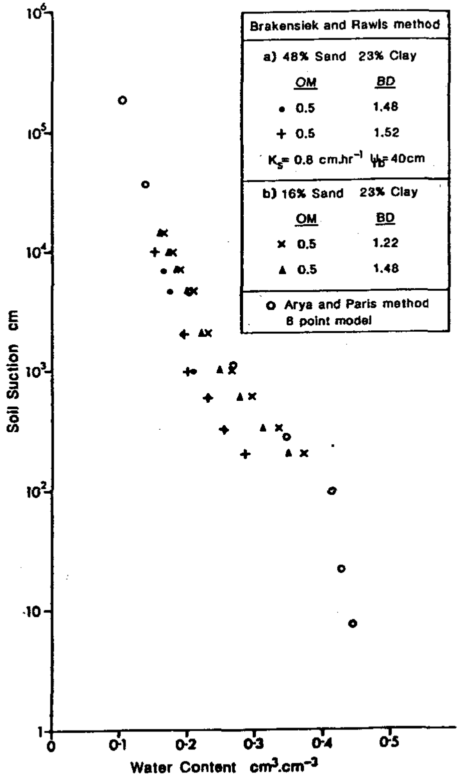


Fig. 10.
Brakensiek and Rawls and Arya *and Paris prediction* methods compared, for the data shown.

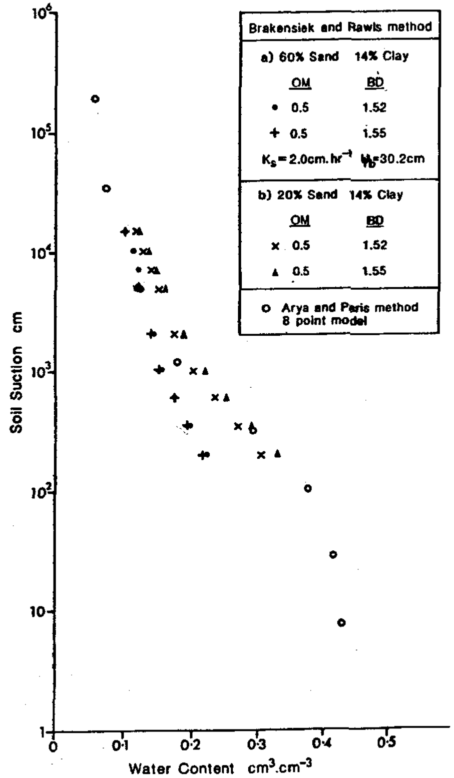


Fig. 11.
Brakensiek and Rawls and Arya and Paris prediction methods compared, for the data shown.

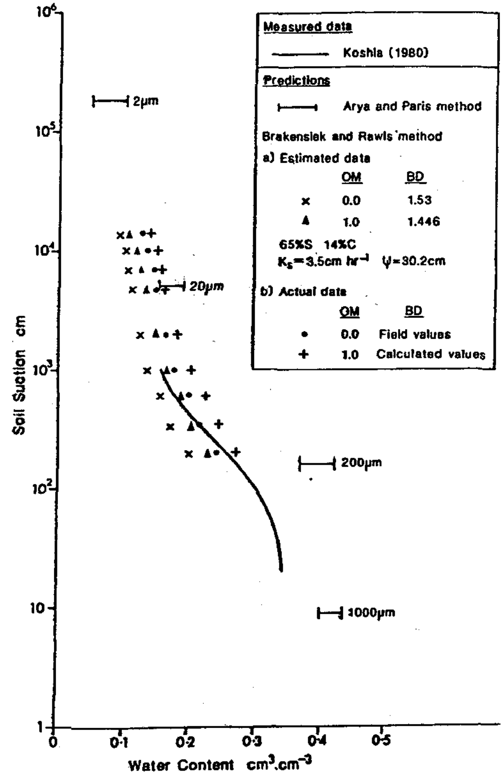


Fig. 12. Brakensiek and Rawls and Arya and Paris prediction methods compared with measured data from Koshla.

Applications of »HYMO« Model Using Derived Suction-Moisture Curves

A modified form of HYMO (HYdrology MOdel) is employed to evaluate the suitability of suction moisture curves derived by the Brakensiek and Rawls method, for catchment hydrology modelling. The original model structure is documented by Williams and Hahn (1973), and the version applied here by Anderson (1982), and Anderson and Howes (1984) is designed for prediction of the hydrologic response of the ungauged catchment. It is thus a watershed model; an event simulator whose parameters are deterministic in character, and are measured rather than calibrated. It is generally applicable to agricultural catchments, adequately representing the hydrologic response over a range of scales. It is distributed only to the degree that the whole watershed may be divided into a number of sub-catchments which are then assumed to exhibit similar hydraulic and hydrologic characteristics. Rainfall data for each sub-catchment is transformed into a runoff hydrograph which is routed down the channel network using a revised version of the variable storage coefficient flood-routing method (Williams 1969), and added to those produced from each of the other sub-catchments. When necessary, flood-routing through reservoirs is achieved by application of the storage indication method.

The transformation of rainfall information into the flood hydrograph is a standard two-stage procedure. Incremental runoff volume is determined from the rainfall data and is then convolved with the dimensionless unit hydrograph, which is derived for the sub-catchment area from physical basin characteristics. In the original HYMO, incremental runoff volume was determined by an empirical procedure, the Soil Conservation Service Curve Number method (USDA 1972). This, in the modified model, has been replaced by a more physically based infiltration simulation model, of the type documented by Hillel (1977), and outlined below.

Each major soil type in a sub-catchment is represented by a soil column which can be divided vertically in up to three distinct hydrologic layers, in order to replicate known field conditions. Each layer is divided into cells, between which the vertical movement of soil water is simulated. This flow occurs according to the Richards equations (developed from Darcy's law and the Equation of Continuity), which in one dimension becomes

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(K(\theta)) - \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial \psi}{\partial z}\right) \qquad (6)$$

where

θ – volumetric moisture content
K – hydraulic conductivity
Z – depth from surface (positive downwards)
t – time

To solve this equation for both saturated and unsaturated conditions, it is necessary to define the hydraulic conductivity function for each soil type in the soil column. This is numerically derived from the suction moisture curve using the equation presented by Jackson (1972). This is based upon that of Marshall (1958) and Millington and Quirk (1959), but is modified by the inclusion of a matching factor (the ratio of measured to calculated saturated conductivity). The pore interaction term (p) in the expression, is set to unity; this, Jackson found to optimally describe the relationship over a range of soils. The equation is as follows

$$K_i = K_s \left(\frac{\theta_i}{\theta_s} \right)^p \frac{\sum_{j=i}^{m} ((2j+1-2i)\psi_j^{-2})}{\sum_{j=i}^{m} ((2j-1)\psi_j^{-2})} \qquad (7)$$

where

K_i – hydraulic conductivity of ith water content increment (θ_i)
K_s – saturated hydraulic conductivity
θ_s – saturated volumetric water content
ψ_i – pressure head corresponding to water content midway between θ_i and $\theta_i + 1$ increment
m – number of increments of equal water content over which calculation is made

Water added to the soil column, at the surface, may infiltrate and accumulate on the surface when the infiltration capacity is exceeded. When the detention capacity (specified by the user) is exceeded, runoff occurs. Both during and after a storm, the model accommodates dynamic changes in its structure, by allowing both water tables and perched water tables to develop and fluctuate.

This newly introduced infiltration model has undergone validation (Anderson and Howes 1984) which established that the computer program and its implementation are consistent with the mathematical model; infiltration acts rationally over a range of test conditions. An extensive sensitivity analysis also determined that the model is consistent with the quality of information commonly available for the ungauged catchment.

The data requirements for the modified HYMO are indicated in Table 1. Application of the model to the prediction of the hydrologic response of the North Creek catchment, Texas, to two storms, illustrates that the soil hydrologic parameters required by the model can be derived from the basic soil texture information provided by a soils map and the Brakensiek and Rawls relationships.

The North Creek (Fig. 13) has an area of 61.6 sq. km and is considered as one sub-catchment. The maximum elevation difference is 108 m and the main channel is 5.3 km long. It contains four major soil types, and the whole area supports

Table 1 – HYMO: Data requirements

	Parameter
For each sub-catchment*	Area Maximum height difference Length of main channel
	Land use
	Initial moisture conditions
	Number of major soil types and their percentage area
For each soil type	Depth of soil Numbers of layers and dimensions
For each layer	Suction-moisture curve Saturated moisture content Saturated hydraulic conductivity

* If catchment is divided into greater than one sub-catchment, in addition to tabulated data, and in order to apply the routing method, it is necessary to have either cross-sectional data or the rating curve for each sub-catchment outflow point.

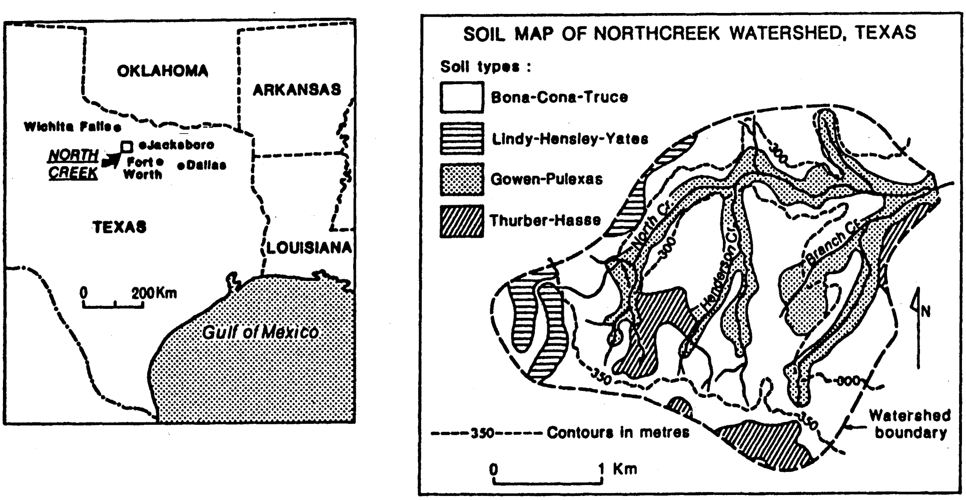


Fig. 13. Location details of North Creek Watershed, Texas.

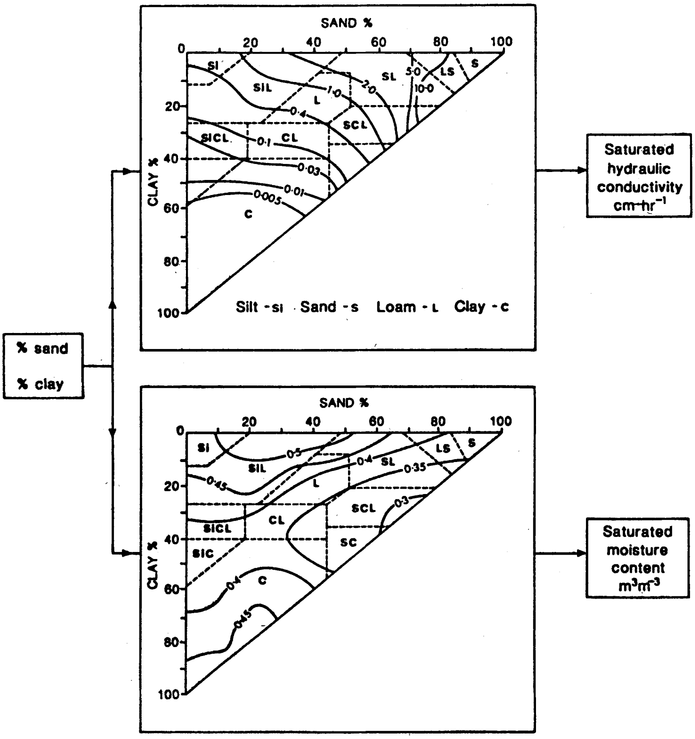


Fig. 14. Prediction of saturated hydraulic conductivity and saturated moisture content from soil type (after Brakensiek and Rawls, 1983).

rangeland. For each soil type, the suction moisture curve was determined from Fig. 5 as demonstrated in the previous section. Brakensiek and Rawls (1983) have also produced similar charts for deriving saturated moisture content and saturated hydraulic conductivity from % clay and % sand (Fig. 14).

One of the more critical areas on the suction moisture curve for this modelling application is that approaching saturation. The curves can be extended down to saturation by plotting the saturated moisture content for that soil texture class. A further point, the air entry value, can be derived from Table 2 in Rawls et al. (1982).

In this application, only soil texture class names were available for each soil, the exact % clay, % sand and % organic matter were not known. To generate the soil hydrologic data, therefore, the centroid values from the charts were assumed, and the corresponding values used to generate the required data. An organic matter content of 0.5% was assumed.

The initial moisture conditions of the soil are derived from daily rainfall totals for the five days preceding the storm. Detention capacity was assumed to be

Table 2 – Storm and Hydrograph Characteristics

Storm Characteristics

Storm date	27/07/1962	6/05/1969
Total precipitation (mm)	76.7	42.2
Storm duration (hrs)	9.0	8.75

Hydrograph Characteristics

	Measured	Simulated	Measured	Simulated
Runoff volume (mm)	13.74	17.5	20.4	27.3
Peak discharge (m^3s^{-1})	34.8	24.34	58.06	46.37
Time to peak (hrs)	7.5	9.25	6	6

minimal.

Details of the two storms used in this application, and the resulting simulated and measured hydrographs, are indicated in Figs. 15 and 16, and Table 2. For both, the rainfall data time increment was fifteen minutes, and the data was provided by the nearest recording rain gauge, seven miles to the south-east of the catchment.

To assess the adequacy of predictions, a number of numerical measures of the

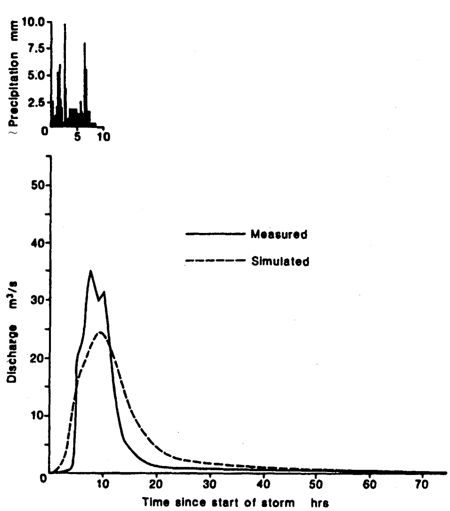


Fig. 15. Predicted and observed hydrographs for the storm of the 27 July 1962 (see Table 2).

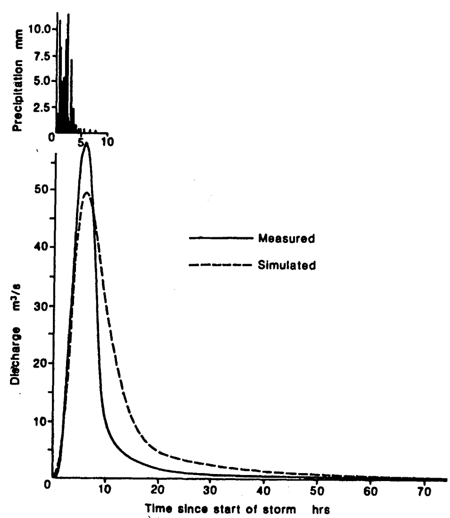


Fig. 16. Predicted and observed hydrographs for the storm of the 6 May 1969 (see Table 2).

Table 3 – Goodness of fit measures for the two storms simulated

	Storm 1 27/07/62	Storm 2 6/05/69
Time to peak error		
$(tp_m - tp_s) / tp_m$	0.2	0
Peak discharge error		
$(pq_m - pq_s) / pq_m$	0.3	0.2
Relative error		
$\sum_{i=1}^{n} \left[[q_m(i) - q_s(i)] / q_m(i) \right]^2$	9496	450
Relative error in magnitude of differences between consecutive items in series		
$\sum_{i=1}^{n} \left[\frac{(q_m(i) - q_m(i-1)) - (q_s(i) - q_s(i-1))}{q_m(i) - q_m(i-1)} \right]^2$	3436	499
McCuen and Snyder (1975)		
$\frac{1}{n} \sum_{i=1}^{n} \left[[\frac{q_m(i) - \bar{q}_m}{\sigma_{qm}}][\frac{q_s(i) - \bar{q}_s}{\sigma_{qs}}] \right]$	0.9	0.91

Note: All indices approach zero as the fit becomes perfect, except the McCuen and Snyder, which approaches unity.

Key to Table 3:

n – number of pairs of coordinates
m – measured
s – simulated
pq – peak discharge
tp – time to peak discharge
$\bar{q}$ – mean discharge
σq – standard deviation of discharge

performance of the simulated, with respect to the observed hydrograph, are presented in Table 3. Predictions of time to peak discharge, and the magnitude of this peak, appear to be acceptable. The other three measures, which consider the overall goodness of fit, reflect more the rather less satisfactory prediction of the recession limb.

From the two applications, it can be suggested that the soil hydrologic information derived from basic soil textural data together with the charts and relationships established by Brakensiek and Rawls, is of sufficient reliability to allow acceptable predictions of flood hydrographs to be made by the modified version of HYMO. The ease and simplicity with which the data can be assembled allows for the replacement in HYMO of the empirical curve number procedure for estimating precipitation excess with a more physically based model of the infiltration component; this new model configuration is still routinely applicable to the ungauged catchment.

Discussion

Since soil retention characteristics are an integral element in many physically based hydrology models, it is desirable that sufficiently accurate methods be devised for estimating such characteristics from basic soils data. This situation would enhance the basis of applications of hydrology models by rendering such models suitable for a larger number of catchments where mapped soils data alone is available. We have shown that the Brakensiek and Rawls (1983) and Rawls et al. (1981) procedure accomplishes this goal and accurately predicts suction-moisture curves throughout a range of soil types (see Figs. 6, 7 and 8). In addition, incorporation of this procedure into the HYMO streamflow forecasting model yields good estimates of flood flows (Figs. 15 and 16). Compatibility of suction-moisture curve estimation methods with other physically based models could now be undertaken to ascertain whether similar data input reductions in this area could be effected, without reducing prediction accuracy. Additional to this analysis, it has been shown that a simple approximation to the suction-moisture curve proposed by Campbell (1974) can be used in an analytical derivation to determine water table rise (under isostatic and zero loss assumptions) – Figs 1-3. It is suggested that in both of these aspects (groundwater rise and streamflow forecasting) further analysis of suction-moisture curve estimation methods may render selected hydrological forecasting methods to be increasingly appropriate to ungauged catchments.

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Address:

M. G. Anderson and S. Howes,
Department of Geography,
University of Bristol,
University Road,
Bristol BS8 1SS

P. E. Kneale,
School of Geography,
The University,
Leeds, LS2 9JT,
England

J. M. Shen,
Geotechnical Control Office,
68 Mody Road,
Tsim Sha Tsui East,
Hong Kong.