Hydrological characteristics and properties of soils in Southern Africa 2: Soil water retention models

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Abstract

Following definitions of three soil water retention constants, viz. porosity, field capacity and wilting point, simplified generally applicable water retention equations for soils in Southern Africa are given. Clay distribution models for use with the retention equations are presented and typical texture classes are derived from the clay distribution models for the 501 soil series identified to date in Southern Africa. Finally, a comparison between estimated water retention constants derived by models from Southern Africa and the USA indicates a high degree of similarity.

Introduction

The amount of water retained in a soil has upper and lower bounds determined respectively by inherent properties of the soil and by plant extraction. It is this retained soil water which may be redistributed under saturated conditions by drainage (with a primarily vertical downward component) or under unsaturated conditions by movement up or down (depending on the relative wetness of respective soil horizons) and by plant root extraction.

In this second paper on hydrological characteristics of soils in Southern Africa soil water retention constants used commonly in hydrological models are first discussed and defined. Methods of estimating fractions of water held in the soil at field capacity and wilting point are described next. Water retention equations developed from Southern African data are then given. Soil water retention being largely a function of clay content and its distribution within the soil profile, clay distribution models applicable to Southern African soils are outlined and typical water holding fractions for the various models and submodels are then calculated from equations presented. Finally, Southern African soil series are classified by textural class and this enables a comparison to be made between estimated water retention constants derived by models from Southern Africa and the USA.

Definitions of soil water retention constants

Soil water analysis amounts to the arbitrary division of water in soils into a number of categories which are useful in assessing the amount of water available for plants, the storage capacity of soil and many other characteristics of hydrological and engineering importance (Rawls, Brakensiek and Saxton, 1982).

Definitions of three soil water retention constants are necessary.

Porosity

Porosity, PO, is the percentage soil volume occupied by voids, i.e. the maximum soil moisture storage or saturation. The matric potential at saturation is 0 kPa.

Field capacity

Field capacity is the soil water condition reached when water has been allowed to drain naturally from the soil until drainage ceases and the water remaining is held by capillary forces that are great enough to resist gravity. Field capacity, FC, is therefore often described as being the wet limit of the moisture available to plants. This theoretical definition has drawbacks when applied to soils in nature and FC can be described as the soil moisture content below which the hydraulic conductivity is sufficiently small for redistribution of moisture due to hydraulic head gradient to be ignored. A definition in terms of matric potential is difficult owing to the fact that FC may vary with texture, but it is traditionally taken to fall somewhere between − 5 and − 33 kPa, with a present-day value tending away from the − 33 kPa towards the − 5 kPa matric potential value. In this paper a value of − 10 kPa is used as the matric potential representing FC because very few data for − 5 kPa are available. It should, however, be noted that the retentivity curve is steep in this region and that small differences in matric potential may represent large differences in soil water content.

Wilting point

This is taken as the dry limit for water available to plants. At the stage of wilting point, WP, the hydraulic conductivity is so low that water cannot move over even short distances to the roots fast enough to satisfy the transpirational demand. The matric potential at this point is usually accepted to be − 1 500 kPa.

Using these definitions one can define plant available water, PAM, as PAM = FC − WP.

Estimating soil water contents for different retention constants

The hydrological processes occurring within the upper and lower bounds of the soil water store necessitate the estimation of values, for use in models, of porosity, field capacity and wilting point.

Traditionally, available moisture has been estimated only after time-consuming and expensive laboratory analyses of the soil. The association of the three retention constants with soil physical properties has long attracted the attention of soil scientist and hydrologist alike, and many relationships have been published. These have been reviewed recently hy Hutson (1984), who states that these efforts have met with partial success only, and considering the complex and variable nature of soil, little im-

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provement in such relationships can now be expected. It is not possible, he maintains, to characterize retentivity solely in terms of soil type and composition as so many factors influence retentivity, for example, particle shape, bulk density, clay mineralogy, organic matter content, structure, degree of aggregation, and other factors. Some of these factors defy precise quantitative description; consequently their effect on retentivity may be assessed in qualitative terms only.

Detailed and precise retentivity measurements provide insight into the manner in which various soil properties influence retentivity and add to the data base from which useful generalizations may be drawn. The gradual accumulation of a store of accurate data has reduced our dependence on measured data for immediate application and *ad hoc* problem solving. This enables soil water research facilities to be used more effectively and directed into areas where it is most needed (Hutson, 1984).

In Southern Africa, Hutson (1984) has undertaken a range of analyses from a large data base to determine the extent to which retentivity of local soils can be predicted from a knowledge of soil type, composition and bulk density and secondly, to develop and determine the range of parameters of a retentivity function to facilitate the mathematical description of retentivity for modelling purposes.

Using data from a wide spectrum of physical environments, Hutson (1984) developed a general model, in equation form, based on percentages of clay and silt together with bulk density, which may be applied to Southern African soils.

The model, applicable to "stable" soils, i.e. non-vertic soils and soils without prismacutanic, pedocutanic and gleycutanic horizons (MacVicar *et al.*, 1977), takes the general form

$$\Theta_\psi = \beta_1 + \beta_2 \mathrm{Cl} + \beta_3 \mathrm{Si} + \beta_4 \rho_b$$

in which

Θ_ψ = water retention in mm.mm^{-1} for a given matric potential

with

ψ = − 5 to − 30 kPa at field capacity and − 1 500 kPa at wilting point,
Cl = per cent clay (<2 μm),
Si = per cent silt (2-20 μm),
ρ_b = bulk density in Mg.m^{-3}, and
β_{1-4} = regression coefficients.

Regression coefficients with goodness of fit statistics for Hutson's (1984) general model for stable soils are given in Table 1.

The example below illustrates the use of the model, if results of a mechanical analysis of the soil are available:

Soil: Loam with 15% clay
25% silt
Bulk density 1,6 Mg.m^{-3}

Water content (volume/volume) at FC:

$$\Theta_{-30} = -0{,}015 + 0{,}0576 + 0{,}143 + 0{,}074$$
$$= 0{,}260 \pm 0{,}055 \text{ mm.mm}^{-1}$$

Water content (volume/volume) at WP:

$$\Theta_{-1500} = 0{,}0602 + 0{,}0483 + 0{,}077 - 0{,}0416$$
$$= 0{,}144 \pm 0{,}051 \text{ mm.mm}^{-1}$$

PAM = FC − WP = 0,116±0,051 mm.mm^{-1}
= 116±51 mm water per m soil depth

Since water retention for unstable soils differs from that of stable soils, Hutson (1984) has given similar regression equations for unstable soils at − 1 500 kPa. Thus, for

- vertic soils (with $r^2 = 0{,}472$):

  $$\Theta_{-1\,500} = 0{,}0293 + 0{,}00606\,\mathrm{Cl} + 0{,}00285\,\mathrm{Si} + 0{,}0384\,\mathrm{C}$$

  with C = per cent organic carbon, and

- for prismacutanic, pedocutanic and gleycutanic soils ($r^2 = 0{,}711$):

  $$\Theta_{-1\,500} = 0{,}01616 + 0{,}0052\,\mathrm{Cl} + 0{,}00222\,\mathrm{Si}$$

Problems associated with retention equations and simplifying assumptions

The retention equations presented in the previous section for stable and unstable soils found in Southern Africa include clay content, silt content, organic carbon content and bulk density as variables. Of these above four variables (NB others are also used) only classes of clay content are used by the binomial system of soil classification for Southern Africa (MacVicar *et al.*, 1977) to help distinguish between soil series within a given form. When applying Hutson's (1984) equations simplifying assumptions therefore have to be made in regard to silt content, organic carbon content and bulk density.

TABLE 1
REGRESSION COEFFICIENTS OF THE HUTSON (1984) MODEL FOR THE ESTIMATION OF SOIL WATER RETENTION VALUES OF MATRIC POTENTIAL FOR STABLE SOILS (SYMBOLS GIVEN IN TEXT).

ψ (kPa)	β_1	β_2	β_3	β_4	r^2	Standard error of estimate of Θ_ψ
− 10	0,0558	0,00365	0,00554	0,0303	0,681	0,066
− 30	− 0,0150	0,00384	0,00572	0,0463	0,764	0,055
− 100	0,0290	0,00361	0,00441	0,0049	0,769	0,059
− 500	0,1588	0,00347	0,00170	− 0,0838	0,823	0,047
− 1 500	0,0602	0,00322	0,00308	− 0,0260	0,785	0,051

Silt content

Hutson (1984), in an analysis of over 3 000 Southern African soil samples, found that 90,1% of the samples comprised sandy loams, sandy clay loams, clays, sandy clays, sands and loamy sands. If these classes are examined on the Southern African texture triangle it may be seen that the 0-13% silt content values pass through the above soil textural classes. Analyses also show that a 20% silt content is very seldom exceeded. A general silt content of 10% is therefore assumed in generalized water retention equations applicable to Southern African soils. It must be stressed that this is a very broad generalization which can lead to errors in estimating soil water retention and in projects where plant available water plays a critical role, for example, in any irrigation schemes, this approximation is too course and *in situ* analyses need to be undertaken.

Bulk density

From data presented by Hutson (1984, p 75), a bulk density of 1,3 $Mg.m^{-3}$ may be assumed for the topsoil horizon (this value also being used in agriculture for fertilizer recommendations) and of 1,5 $Mg.m^{-3}$ for subsoil horizons.

Organic carbon content

For vertic A-horizons, organic carbon content, C, is required in its water retention equation and numerous analyses have shown 1,3% to be a representative value. (For the other diagnostic topsoil horizons the following C values, while not used in Hutson's (1984) equations, may be assumed representative: humic 6%, orthic 0,6%, melanic 1,3%, organic 10%).

Simplified, generally applicable water retention equations for Southern Africa

Since clay content is the primary characteristic used in the present South African soil classification, generally applicable water retention equations either have to make use of the simplifying assumptions suggested in the previous section, or be based on regression equations with percentage clay as the only variable.

Equations based on simplifying assumptions

With the simplifying assumptions made above, Hutson's (1984) equations for stable soils may be rewritten as follows:

At *field capacity*

$\theta_{-10} = 0{,}1506 + 0{,}00365\ Cl$ for the topsoil horizon

and

$\theta_{-10} = 0{,}1567 + 0{,}00365\ Cl$ for subsoil horizons.

At *wilting point*

$\theta_{-1\,500} = 0{,}0572 + 0{,}00322\ Cl$ for the topsoil horizon

and

$\theta_{-1\,500} = 0{,}0520 + 0{,}00322\ Cl$ for the subsoil horizons.

For vertic (unstable) soils water retention has been determined only at wilting point (Hutson, 1984).

At *field capacity*, therefore,

θ_{-10} = assumed identical to values derived by the equations for stable soils

but

at *wilting point*

$\theta_{-1\,500} = 0{,}1077 + 0{,}00606\ Cl$, for all horizons.

For prisma-, pedo- and gleycutanic (unstable) soils corresponding values of

θ_{-10} = again assumed identical to values derived by the equations for stable soils

but

$\theta_{-1\,500} = 0{,}0384 + 0{,}00522\ Cl$, for all horizons.

Equations using only percentage clay

Hutson (unpublished results) has used the data set from his previous analyses to regress water retention in $mm.mm^{-1}$ against percentage clay only. Results are summarised below:

$$\theta_{-10} = 0{,}1387 + 0{,}00416\ Cl,\ r^2 = 0{,}548$$
$$\theta_{-30} = 0{,}0943 + 0{,}00428\ Cl,\ r^2 = 0{,}612$$
$$\theta_{-100} = 0{,}0582 + 0{,}00413\ Cl,\ r^2 = 0{,}694$$
$$\theta_{-500} = 0{,}0262 + 0{,}00447\ Cl,\ r^2 = 0{,}800$$
$$\theta_{-1500} = 0{,}0344 + 0{,}00381\ Cl,\ r^2 = 0{,}732$$

Differences in results using the above two approaches are illustrated and discussed in a subsequent section.

Clay distribution models for use with retention equations

With soil water retention equations for field capacity and wilting point expressed in terms of clay content only, and with the binomial system of soil classification for Southern Africa containing clay content classes, water retention constants may be estimated for various horizons if the clay distribution down the profile is known. From an examination of the 41 soil forms and 501 soil series defined by MacVicar *et al.* (1977), five clay distribution models are proposed for Southern Africa. These are illustrated in Figure 1. Each clay distribution model is applied to the five classes of clay content of the B21 horizon as used by MacVicar *et al.* (1977) for soil series classification, in order to obtain typical values of topsoil and subsoil clay contents associated with any given soil series.

Model 1

In Model 1 clay distribution increases down the soil profile – a phenomenon common in well drained soils in which the process of illuviation has produced a translocation of the finer clay particles downwards. Consequently, clay values for a two-horizon profile are reduced from the middle value of a clay class for the topsoil horizon and increased for the subsoil horizon. In assigning topsoil and subsoil values of clay contents for the five classes of clay content used by MacVicar *et al.* (1977), cognizance was taken of Hutson's (1984) findings, namely that clay contents between A- and B-horizons varied but that the ratio of A to B increased with increasing clay content. Five submodels of Model 1, corresponding to the five clay content classes, are proposed. Their respective clay contents are given in Table 2.

The following soil forms are classed for water retention pur-

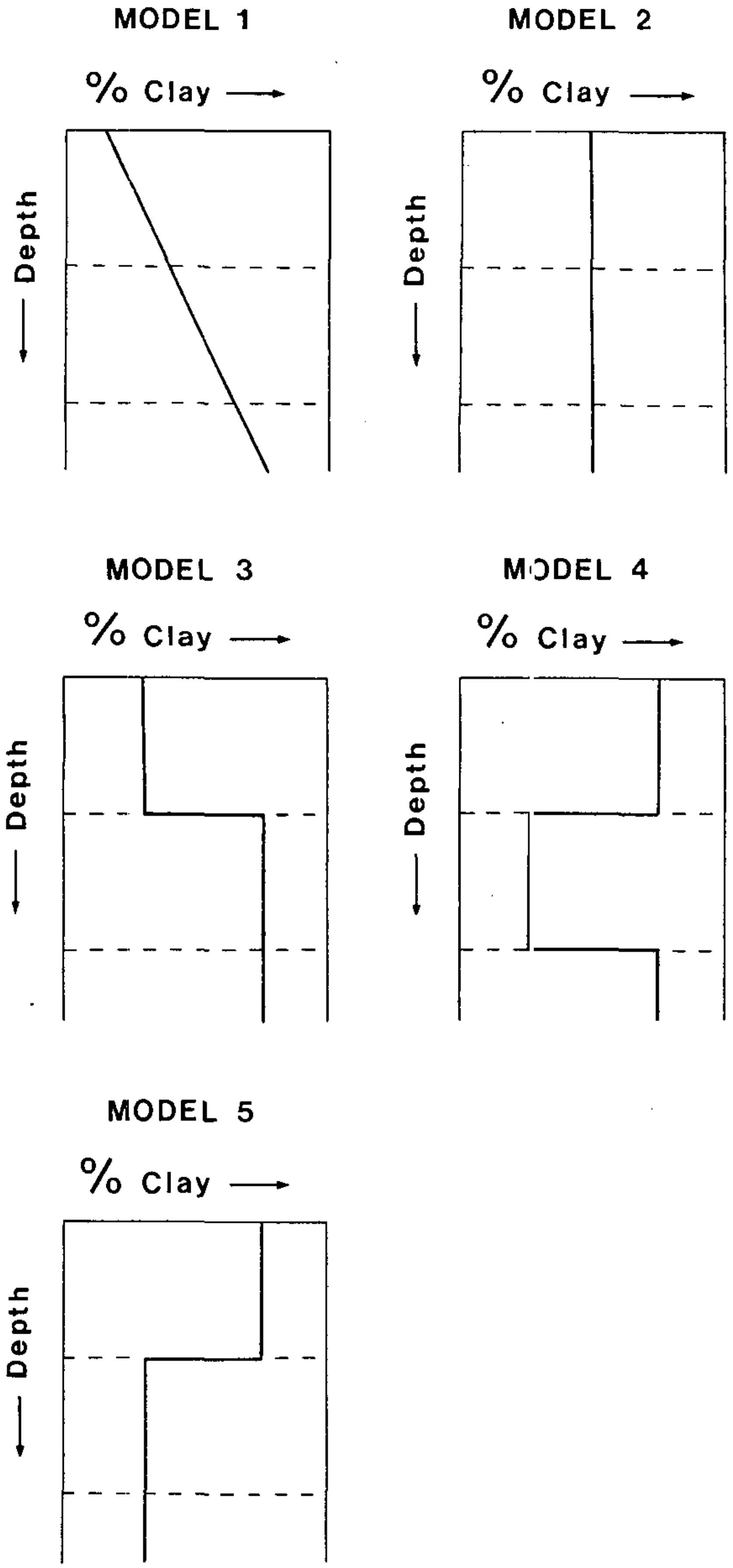

Figure 1
Clay distribution models for Southern Africa

TABLE 2
TOPSOIL AND SUBSOIL CLAY PERCENTAGES ASSIGNED TO THE SUBMODELS OF THE WATER RETENTION MODEL 1

Submodel	Clay class %	Typical clay % value	Assigned topsoil horizon clay %	Assigned subsoil horizon clay %
1a	0 – 6	3	2	4
1b	6 – 15	10	8	12
1c	15 – 35	25	17	33
1d	35 – 55	45	36	54
1e	>55	60	54	66

TABLE 3
TOPSOIL AND SUBSOIL CLAY PERCENTAGES ASSIGNED TO THE SUBMODELS OF THE WATER RETENTION MODEL 3

Submodel	Clay class (%)	Increase in clay % at transition	Assigned topsoil horizon clay %	Assigned subsoil horizon clay %	Existence in SA
3a	0 – 6	7	3	10	✓
b		15	3	18	✓
c		25	3	28	✓
3d	6 – 15	7	10	17	x
e		15	10	25	✓
f		25	10	35	x
3g	15 – 35	7	25	32	x
h		15	25	40	✓
i		25	25	50	x
3j	35 – 55	7	45	52	x
k		15	45	60	✓
l		25	45	70	x

poses as belonging to Model 1: Avalon, Bainsvlei, Clovelly, Fernwood, Glencoe, Griffin, Hutton, Inanda, Katspruit, Kranskop, Longlands, Magwa, Oakleaf, Pinedene, Shortlands, Swartland, Valsrivier and Westleigh.

Model 2
In Model 2 the clay distribution remains constant throughout the soil profile. Five submodels of Model 2 are proposed, in accordance with the five clay classes recognized in MacVicar *et al.* (1977), and the clay percentage assigned to the respective submodels are those shown in column 3 of Table 2.

The soil forms conforming to Model 2 are Arcadia, Bonheim, Champagne, Constantia (certain series), Dundee, Houwhoek, Inhoek, Lamotte, Milkwood, Mispah, Rensburg, Shepstone (certain series), Tambankulu, Vilafontes (certain series), Wasbank and Willowbrook.

Model 3
Model 3 soils display an abrupt textural (i.e. clay content) transition from the topsoil to the subsoil. Three "degrees" of abruptness were recognized, the least abrupt change increasing clay content by 7%, the middle class by 15% and the most abrupt change increasing clay content by 25%. The result is that 12 submodels of Model 3 can be distinguished theoretically. However, only six were found to exist in the 501 series in Southern Africa. Details of the submodels of Model 3 are given in Table 3.

Soil forms classified by clay distribution as belonging to Model 3 for water retention calculations are Constantia (certain series), Estcourt, Kroonstad, Shepstone (certain series), Sterkspruit and Vilafontes (certain series).

Model 4
The clay distribution down a profile indents in the E-horizon in Model 4 – a result of chemical reduction following periodic waterlogging and lateral flow of water causing a loss of clay particles.

Soil forms conforming to Model 4 are yet to be determined.

Model 5
Model 5 represents a mirror-image of water retention Model 3, with an abrupt decrease in clay content in the subsoil. Unlike Model 4, however, the reduced clay content persists down the profile. In this Model, clay content of the subsoil horizon is re-

TABLE 4
TOPSOIL AND SUBSOIL CLAY PERCENTAGES ASSIGNED TO THE SUBMODELS OF THE WATER RETENTION MODEL 5

Submodel	Clay class (%)	Assigned topsoil horizon clay %	Assigned subsoil horizon clay %
5a	0 – 6	3	1,5
5b	6 – 15	10	5,0
5c	15 – 35	25	12,5
5d	35 – 55	45	22,5
5e	> 55	60	30,0

duced to half the topsoil horizon value, resulting in five submodels according to clay content classes. Suggested submodel clay percentages are listed in Table 4.

Water retention constants for the following soil forms should be estimated with values from Model 5: Cartref, Glenrosa, Mayo and Nomanci.

Each of the 41 soil forms described to date in Southern Africa was assigned to one (and in the case of certain forms, two) of the five clay distribution models and within each form individual soil series were allocated to a submodel. In this way the 501 soil series were classified by their diagnostic and clay distribution characteristics. Table 1 of the first of this series of two papers on hydrological characteristics of Southern African Soils (Schulze, 1985) lists this classification of each form and series by clay distribution submodel.

The generalized equations were applied to the assigned clay contents of all clay distribution submodels discussed above. By this procedure estimates of soil water content at field capacity and wilting point have been made for Southern African soil conditions and are presented in Table 5 for topsoil and subsoil horizons for both stable and unstable soil forms. A comparison from Table 5 of soil water content at field capacity and wilting by the two approaches used, namely simplifying the Hutson (1984) equations and secondly regressing a water retention for given matric potentials against percentage clay only, shows the second approach to result in a wider range of estimated moisture content. Estimations of PAM (i.e. FC – WP), however, are very similar with the simplified Hutson equations generally yielding slightly lower PAM by about 7 – 10 $mm.m^{-1}$ for topsoil horizons but for most clay distribution submodels somewhat higher PAM by about 3 $mm.m^{-1}$. Profile PAM estimates for soils in which the topsoil constitutes 1/3 and subsoil 2/3 of the effective soil depth would thus be very similar irrespective of which simplified approach was used.

Textural classes of Southern African soil series

Generalized values of retention constants have frequently been given for texture classes. Since a silt content around 10% may be assumed for most of Southern African soils (NB noting that this is a very coarse assumption), and since the binomial system of soil classification groups soil series by classes of clay content, each soil series may be grouped, in general terms, into a textural class, if the middle value of the clay class is assumed to be representative. By this approach the 501 soil series identified in Southern Africa were placed in textural classes, using the Southern African textural triangle given in MacVicar *et al.* (1977), on the following basis:

Series in the 0 – 6% clay class : loamy sands, except those with coarse sand fraction, then : sands
6 – 15% clay class : sandy loams
15 – 35% clay class : sandy clay loams
35 – 55% clay class : sandy clays
>55% clay class : clays

The textural classes of the 501 soil series are listed in Schulze (1985).

TABLE 5
ESTIMATES OF SOIL WATER CONTENT AT FIELD CAPACITY AND WILTING POINT FROM CLAY DISTRIBUTION MODELS USING (A) SIMPLIFIED VERSIONS OF HUTSON'S (1984) EQUATIONS AND (B) REGRESSION OF WATER CONTENT AGAINST % CLAY ONLY. (BRACKETED VALUES REFER TO UNSTABLE SOILS)

Clay *distribution* model	FC in $mm.m^{-1}$				WP in $mm.m^{-1}$			
	Topsoil		Subsoil		Topsoil		Subsoil	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
1a	158	147	171	155	64	42	65	50
b	180	172	201	189	83	42	91	80
c	213	209	277	276	112(127)	99	158(211)	160
d	282	288	354	363	173(226)	172	226(320)	240
e	348	363	398	413	231(320)	240	265(383)	286
2a	162	151	168	151	67	46	62	46
b	187	180	193	180	89	73	84	73
c	242	243	248	243	138(159)	130	133(169)	130
d	315	326	321	326	202(273)	206	197(273)	206
e	370	388	376	388	250(352)	263	245(352)	263
3a	162	151	193	180	67	46	84	73
b	162	151	222	214	67(54)	46	110(132)	103
c	162	151	259	255	67(54)	46	142(185)	141
e	187	180	248	243	89(91)	73	133(169)	130
h	242	243	303	305	138(169)	130	181(247)	187
k	315	326	376	388	202(273)	206	245(352)	263
4	–	–	–	–	–	–	–	–
5a	162	151	156	145	67	46	57	40
b	187	180	175	160	89	73	68	53
c	242	243	202	191	138	130	92	82
d	315	326	239	232	202	206	124	120

A comparison between estimated water retention constants derived by models from Southern Africa and the USA

Probably the most comprehensive set of retention values classified by textural classes, and based on several thousands of laboratory analyses, was published recently by Rawls, Brakensiek and Saxton (1982). A summary of some of their findings is given in Table 6.

TABLE 6
TYPICAL VALUES FOR RETENTION CONSTANTS, BASED ON SOIL TEXTURAL CLASSES (AFTER RAWLS *ET AL.*, 1982)

Textural class	Effective porosity (mm.m^{-1})	Water retained at −33 kPa potential (mm.m^{-1})	Water retained at −1 500 kPa potential (mm.m^{-1})
Sand	417	91	33
Loamy Sand	401	125	55
Sandy loam	412	207	95
Loam	434	270	177
Silt loam	486	330	133
Sand clay loam	330	255	148
Clay loam	390	318	197
Silty clay loam	432	366	208
Sandy clay	321 (?)	339 (?)	239
Silty clay	423	387	250
Clay	385 (?)	396 (?)	272

(?) Denotes apparent anomalies due to different sample sizes

The textural classification of Southern African soil series and the information contained in Tables 5 and 6 facilitate a comparison between estimates of water retention values by models developed in Southern African and the U.S.A. Comparative values are given in Table 7. For the Southern African values, averages of water retention estimates between the topsoil and subsoil from the simplifications of the Hutson (1984) equations were assumed for the typical clay contents of the five clay classes used in clay distribution Model 2 (Table 5). Table 7 shows that values compare very well with those derived from the highly generalized Southern African approximations, generally being slightly lower than approximations from the U.S.A. If, however, values of plant available water are examined, then the comparison shows very small differences in the cases of sandy loams, sandy clay loam and clay and somewhat bigger differences in the cases of loamy sand and sandy clay.

The implications of the above findings are important, since equations for the estimation of soil water content at saturation are not yet available for Southern African soils. Porosity values for soil textural classes from the U.S.A. (for example those listed in Table 6) may therefore be used in hydrological models in Southern Africa until local data become available. There are, however, anomalies apparent in Table 6 where for certain soils porosity values are smaller than those at field capacity.

Conclusions

For many years hydrologists in Southern Africa have experienced a genuine need for Southern African soils data to be used in their modelling exercises or hydrological designs. Two events have played a major role in the attempts in these papers at classifying Southern African soils for various practical purposes. The first was the publication by MacVicar *et al.* (1977) of the binomial system of soil classification for Southern Africa, by which soil forms and series can be diagnosed largely by visual, sequential characteristics with a high degree of accuracy in the field. The sytem is under revision at present. The second was the analytical work on hydrological properties of Southern African soils completed by Hutson (1984), which has enabled certain key hydrological variables (water retention values) to be estimated with confidence.

The results which have been presented, mainly in tabular form, in these two papers represent typical *initial working values* for the hydrologist. These values will be altered in time and refined as field experience is gained and further laboratory analyses of soils are undertaken. Certainly for detailed hydrological modelling and for irrigation planning the values and classifications given cannot replace detailed *in situ* examination of the soil or the attendant laboratory analyses necessary for in-depth understanding of the spatial and temporal variations of hydrological processes on a catchment.

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TABLE 7
COMPARISON OF WATER RETENTION VALUES BY SOIL TEXTURAL CLASSES

Soil textural class	Water retention (mm.m^{-1}) at					
	Field capacity		Wilting point		Plant available water	
	SA	USA	SA	USA	SA	USA
Loamy sand	165	125	65	55	100	70
Sandy loam	190	207	86	95	104	103
Sandy clay loam	245	255	135	148	110	107
Sandy clay	318	339	200	239	118	100
Clay	373	396	247	272	126	124

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