SOIL MAPPING AND ADVISORY SERVICES
BOTSWANA

PHYSICAL PROPERTIES OF THE
SOILS OF BOTSWANA

FOOD & AGRICULTURE
ORGANIZATION OF THE
UNITED NATIONS

REPUBLIC OF
BOTSWANA

UNITED NATIONS
DEVELOPMENT
PROGRAMME

GABORONE, 1991

Soil Mapping and Advisory Services

Botswana

Physical Properties of the

Soils of Botswana

By

Willie D. Joshua
Soil Physicist

The conclusions given in this report are those considered appropriate at the time of its preparation.
They may be modified in the light of further knowledge gained at subsequent stages of this project.

CONTENTS

List of Tables

List of Figures

1. INTRODUCTION

The soils of Botswana were mapped under the Soil Mapping and Advisory Services Project of the FAO/UNDP. The different soil units were identified and classified according to the FAO Revised Legend of the Soil Map of the World (FAO, 1988). The soil units were mapped as either associations or complexes on a reconnaisance scale. Most of the soil profiles which were described were also sampled and characterized for their chemical properties. Measurements of physical properties were limited to some selected profiles because they involve both field and laboratory work and are time consuming. Only soil units which were agriculturally important or those which occur extensively were characterized for their physical properties. The physical properties which were measured are (a) Particle size distribution (b) Bulk density (c) Infiltration characteristics (d) Moisture retention and (e) Structural Stability of the surface soil. The results obtained from the measurements are stored in a computer data base for retrieval and interpretation. The measured soil physical properties are either directly interpreted or used to derive other properties which are essential for agriculture.

Particle size distribution, bulk density and structural stability are specific for each soil and therefore have to be measured directly. Infiltration rates and moisture retention properties are dependent to a large extent on the texture of the soil. But these properties are often modified by pore size distribution, bulk density, structural stability and other site specific conditions such as faunal activity and land use. Consequently, reliable estimates of infiltration and moisture retention properties are also obtained by direct measurement of the soil. Available soil moisture for plant growth, on the other hand, can be derived from moisture retention properties. If good correlations exist between sufficient measured data on soil physical properties and available moisture, then statistically significant regression equation can be established between these soil properties. Such functional relationship can be conveniently used to estimate available moisture holding capacity of soils from other measured soil physical properties.

The soil physical properties are interpreted both in relation to soil classification units as well as to textural classes so that the data can be used conveniently for agricultural planning and development in the country. Soil physical properties of some selected soil units and the interpretation of the measured data are given in the annex as Technical Papers.

2. PHYSICAL PROPERTIES OF SOILS

2.1 Materials and Methods

Soil physical properties were measured on seventy profiles covering various soil units in Botswana. The soil units were selected on the basis of recommendations made by the Soil Survey team which was responsible for identifying and mapping the soils of Botswana.

Infiltration measurements and soil core sampling for bulk density and moisture characteristic were carried out in the field. Soil structural stability indices and moisture retention were measured in the laboratory. The soil pits were described and sampled for chemical analysis. The same sites and soil pits were used for soil physical measurements. However, adjacent soil horizons which were similar in texture, structure and compactness were grouped together for the measurements of soil physical properties. Although some soil horizons are separated on morphological differences which are important for classification purposes, they do not differ markedly in their physical properties if they are similar as indicated above. The methods used are described in detail in the manual prepared by the Project for the measurement of the physical properties. (Joshua 1990)

All the soil units which were broadly similar in their overall profile characteristics were grouped together for the purpose of interpreting their physical properties. Nine such groups were identified as follows:

1.   Arenosols
2.   Ferric Luvisols and Lixisols
3.   Luvisols - light textured (clay < 20% above 120cm depth)
4.   Luvisols - heavy textured (clay >20% in one or more horizon
               above 120cm depth)
5.   Calcisols
6.   Saline and Alkali soils
7.   Vertisols
8.   Gleysols/Gleyic phaeozems
9.   Regosols

The following terminology is used in the rest of the report to refer to some of the above groups of soil units.

2.   Ferric Luvisols and Lixisols - Ferric Luvisols
3.   Light textured Luvisols - light Luvisols
4.   Heavy textured Luvisols - heavy Luvisols
5.   Gleysols and Gleyic phaezems - Gleysols

The soils units included in the different groups are as follows:

Group 1.   Arenosols:- A22a, A40, A40c, KS03, KSO9
Group 2.   Ferric Luvisols:- A11, D05b, D07, G02d, G09, G10b,
                              S07
Group 3.   Light Luvisols:- A09d, A15a, G06b, G13a, G14a
Group 4.   Heavy Luvisols:- A07, A7, A16, A44, B06c, B07, G02e,
                              G09, G10a, G13, G14
Group 5.   Calcisols:- A04b, A04d, A09, L14
Group 6.   Saline and Alkali soils:- A09, A5, A37, L02a, L05
Group 7.   Vertisols:- A01, L25.2, L25.b1
Group 8.   Gleysols:- A31, A47, L07
Group 9.   Regosols:- G02a

All profiles having numbers in the 900 series of the Botswana Soil Database have been characterized for their physical properties. Some of the relevant properties for all soils are given in the appendix for ready reference.

Results from moisture retention measurements were statistically analyzed to establish their best possible correlation with texture, bulk density and organic matter content. For this purpose, the soil horizons were grouped into five categories based on texture and organic matter as follows:

(a)   All Soils
(b)   Light textured soils - clay < 40%
(c)   Heavy textured soils - clay > 40%
(d)   Soils with high organic matter - org. carbon >0.5%
(e)   Soils with low organic matter - org. carbon < 0.5%

Simple and multiple regression analysis were carried out with field capacity, wilting point and available moisture as dependent variables and total sand, coarse sand, fine sand, clay, bulk density and organic matter as independent variables. Field capacity for the heavy and light textured were defined as moisture content at 0.3 and 0.1 bar tensions respectively. Wilting point was assumed to be the moisture content at 15 bar tension. Available moisture was taken as the difference in moisture content between field capacity and wilting point.

2.2 Results and discussions

2.2.1. Particle size distribution

Particle size analyses to determine the proportion of the different size fractions was carried out by a combination of sedimentation and seiving procedures. The different size fractions are very coarse sand, coarse sand, medium sand, fine sand, very fine sand, coarse silt, fine silt and clay. As the different sand and silt fractions did not have any significant influence

separately on other physical properties, they were grouped into broad classes as total coarse sand (TCS), total fine sand (TFS), total silt (TSI) and clay for comparison and characterisation of the nine groups of soil units.

Table 1. Average particle size distribution for different soil groups – surface (A), sub-surface (B)

Soil Group		Coarse sand%	Fine sand%	Silt%	Clay%
Arenosol	A	6.3	61.9	5.5	5.4
	B	6.5	62.7	2.4	4.6
Luvisol-ferric	A	26.1	25.6	6.4	17.3
	B	25.6	20.9	5.8	22.3
Luvisol-light	A	18.5	40.9	10.1	15.6
	B	24.1	36.9	6.8	15.1
Luvisol-heavy	A	15.1	35.0	8.2	24.65
	B	17.0	28.4	8.0	31.4
Calcisol	A	9.7	47.3	10.3	19.9
	B	13.6	37.0	10.3	25.4
Saline and	A	18.3	35.8	7.9	21.9
Alkali soils	B	15.9	25.7	9.7	35.7
Vertisol	A	10.6	10.0	10.2	61.3
	B	7.5	6.7	7.1	66.8
Gleysols	A	1.3	33.5	16.7	41.7
	B	1.2	30.7	12.4	48.7

Table 1 shows the average percentages of the particle size fractions for the horizons of the different groups of soil units. The total of the different size fractions will not sum to 100 percent and should not be used to infer clay movement in the profile.

Arenosols

From Table 1, it is clear that fine sand is the dominant size fraction in Arenosols, indicating the aeolian nature of the parent material. The profiles are quite uniform throughout the

depth. The total fine sand is generally more than 50 percent and very often it is greater than 75 percent. Clay and silt are less than 10 percent, often around 5 percent.

Luvisol – ferric

Coarse sand and fine fine sand fraction in the ferric Luvisols are more or less equally distributed and both are generally in the range of 20 -30 percent. Silt content is very low which is typical for all soils in Botswana except the Fluvisols. Average clay content is about 20 percent and seldom goes above 30 percent. Surface horizons are slightly lighter than the sub-surface horizon.

Luvisols – light

The light textured Luvisols have fine sand fractions higher than the coarse sand but not as marked as the Arenosols. Clay contents are higher than the Arenosols but slightly lower than the ferric Luvisols. The clay contents are generally in the region of 15 percent and silt contents vary between 5 and 10 percent.

Luvisols – heavy

The occurrence of heavy textured Luvisols are more than the light textured Luvisols. They are generally found in the mid and lower positions in the landscape. The fine sand fractions are more than the coarse sand. The amounts of coarse sand and fine sands are slightly lower than the light textured Luvisols.

Calcisols

The Calcisols do not appear to follw any noticiable trend in the particle size distribution, especially in respect of the coarse sand and the silt fractions. These fractions vary between as low as 0.5 percent to about 30 percent. The fine sand fraction is relatively high and is in the range of 30 percent to 60 percent while the clay content has an average value of 25 percent. Texturally the Calcisols resemble the heavy textured Luvisols more than any other soil units.

Saline and Alkali soils

These soils can be very variable depending on the parent material and the topographic position in which they occur. Soils on the lower topographic site or on areas of trapped drainage are generally heavy textured and are similar to the heavy textured Luvisols.

Vertisols

Vertisols are characterised by the high clay content, usually more than 50 percent.

Gleysols

These soils usually occurs in the lower aspects of the landscape and have an accumulation of finer particles such as silt and clay brought in from the run-off water from the adjoining lands. The coarse sand fraction is almost negligible and is seldom greater than 2 percent. The fine sand fraction, although dominant, is less and the silt and clay are relatively high as compared to other soil units. On an average, the silt content is about 15 percent and the clay content is about 45 percent.

2.2.2. Bulk density

The bulk density was determined by obtaining undisturbed soil core samples of known volume and dividing the oven-dry soil mass by the field volume of the sample. Bulk density is the density of in-situ field soil where the volume includes the pore spaces. The bulk density gives the measure of the relative proportions of the volume of solid particles and pore spaces in the soil. The spaces between individual soil particle and the spaces between soil ag-gregates determine the porosity and hence the bulk density. Thus, organic matter which causes good soil aggregation and texture are related to bulk density. The bulk densities of the surface soils are often slightly lower than the underlying horizons due to higher organic matter content. Table 2 shows average bulk den-sities of the surface and sub-surface horizons of the different groups of soil units in Botswana. The percentage of organic mat-ter is also shown for comparision.

Arenosols

The bulk densities of Arenosols vary between 1.5 and 1.6gm/cc. Most of the values are clustered around 1.5 and 1.55gm/cc. The organic matter content of the Arenosols are low (< 2%) and as a result, the differences in bulk densities between the surface and the sub-surface horizon are not appreciably different.

Luvisols -ferric

The bulk densities of the surface horizons of ferric Luvisols are higher than that of the lower horizons due to the compaction and hardsetting properties of the soils under cultivation. The

6

overall bulk densities of the horizons vary between 1.5 and
1.65gm/cc. The average bulk densities of the surface horizons of
cultivated soils are about 1.6gm/cc.

Luvisols - light

The average bulk densities of the light textured Luvisols are
about 1.5gm/cc. These soils appear to have relatively high or-
ganic matter content in the surface horizons resulting in lower
bulk densities about 1.45 to 1.55gm/cc. The bulk densities of the
sub-surface horizons vary between 1.5 and 1.6 which is sig-
nificantly higher than the surface horizons.

Table 2.   Average organic carbon and bulk density for the
           different soil groups - surface (A), sub-surface (B)

Soil group		Org. Carbon %	Bulk density gm/c
Arenosol	A	0.20	1.49
	B	0.08	1.55
Luvisol-ferric	A	0.33	1.59
	B	0.21	1.54
Luvisol-light	A	0.66	1.45
	B	0.23	1.58
Luvisol-heavy	A	0.85	1.40
	B	0.37	1.50
Calcisol	A	0.43	1.60
	B	0.33	1.38
Vertisol	A	0.77	1.16
	B	1.05	0.80
Gleysol	A	4.22	1.09
	B	1.39	1.22

Luvisols - heavy

The heavy textured Luvisols have high content of organic matter
in the surface horizons and high content of clay in the entire
profile. Both these factors tend to cause these soils to have low
bulk densities. However, the organic matter content of the sur-

face horizons are often greater than 0.5 percent whereas the im-
mediately underlying horizons have relatively lower organic mat-
ter varying between 0.2 and 0.4 percent. Consequently, the sur-
face horizons are well aggregated and have lower bulk densities
than the sub-surface horizons. The bulk densities of the surface
horizons vary between 1.4 and 1.5gm/cc with a modal value of
about 1.45gm/cc. The bulk densities of the sub-surface horizons
gradually increase with depth from about 1.4 to 1.55gm/cc with
the modal value around 1.5gm/cc.

Calcisols

The high calcium carbonate content in the sub surface horizons
tend to increase the porosities of these soils. Consequently the
horizons with calcium carbonate have low bulk densities. The sur-
face horizons are generally non-calcareous and have higher bulk
densities varying from 1.55 to 1.7gm/cc and the bulk densities of
the sub-surface horizon range from 1.00 to 1.45gm/cc.

Saline and Alkali soils

The bulk densities of these soils can be very variable depending
on the texture. Bulk densities of the surface soils are higher
than those of the sub-surface horizons. Generally the heavy tex-
tured soils have bulk densities varying from 1.2gms/cc to
1.5gm/cc. The bulk densities of the light textured soils are on
an average about 1.6gm/cc.

Vertisols

Due to the continuous expansion of Vertisols on wetting, the bulk
densities decrease as the moisture content increases. Conse-
quently the bulk density of a Vertisol has to be reported with
the moisture content at which it was measured. In general, the
bulk densities vary from 1.0gm/cc in the wet range to about
1.3gm/cc at low moisture content near wilting point.

Gleysols

The high amounts of organic matter and clay in these soils give
rise to low bulk densities throughout the profile. The surface
soils have very high organic matter and consequently have low
bulk densities of the order 1.1gm/cc. The sub-surface horizons
have bulk densities varying from 0.5gm/cc to 1.4gm/cc depending
on the organic matter content.

2.2.3. Infiltration

Infiltration rates were measured by the double ring infiltrometer
method. At least three replicate measurements were made at each
location. Infiltration generally decreases from the initial rate
to a constant rate after some time. The constant rate is referred
to as the "basic infiltration rate" and is characteristic for the

soil. The initial rate and the time taken to reach the constant rate is dependent on the soil surface condition and the moisture status of the soil profile at the time of measurement. The infiltration characteristic of a soil can be adequately represented by the equation.

$$F = at^n$$

or in the logarithmic form

$$\log F = \log a + n \log t$$

Where F is the cumulative intake, t is the elapsed time and "a" and "n" are constants. The magnitude of "a" indicates the initial rate and "n" gives its rate of decrease. The measured values of "a", "n" and the basic infiltration rates are stored in the computer data base for the soil physical properties. Although the value of "a", "n" and the basic infiltration rates are very variable and site specific, the basic infiltration rates are indicative of the general infiltration characteristics of the soil unit.

During the infiltration test, water flows through the soil under saturated conditions. Water flow is faster through the larger pores in the soil than in smaller ones. The proportion of the different soil particle size fractions influence the pore size distribution which in turn determines the infiltration rates. Therefore, the relative magnitude of the infiltration rates in a soil can be, to some extent, inferred from the texture of the soil. However, cracks, fanual activity and land use can modify the infiltration characteristics. Consequently the infiltration rates can be very variable for a textural class. Table 3 gives the average basic infiltration rates and the range for the different group of soils units for which infiltration was measured.

Table 3. **Trends in the basic infiltration rates of the different soil groups**

Soil group	Basic infiltration cm/hr	
	Average	Range
Arenosol	33.0	54.3 - 18.5
Luvisol - ferric	13.7	30.2 - 4.2
Luvisol - light	15.8	46.8 - 5.9
Luvisol - heavy	7.8	23.8 - 0.1
Calcisol	9.8	18.2 - 7.0
Gleysol	1.1	0.1 - 3.1

Arenosols

The infiltration rates in Arenosols can be considered as high to excessive. The modal values of the basic infiltration rates for these soils are in the range of 25 - 30cm/hr, with the initial rates being much higher. The high infiltration rates are in keeping with the sandy nature of the soil profile. In these soils, the run-off from rainfall can be expected to be minimal.

Luvisol - ferric

The ferric Luvisol, although having a higher clay content (17%) than the Arenosols, yet come under the category of light textured soils. Considering the high sand content, the infiltration rates can be expected to be high. However, the equal proportion of coarse sand and fine sand reduces the amount of large pores due to closer packing of the sand particles. Consequently the infiltration rates are much lower than the Arenosols. Due to surface sealing under rainfall and the hard setting properties of the soil, infiltration rates can be as low as even 1cm/hour. The low infiltration rates are usually associated with the heavier textured profiles and cultivated soils. Under natural vegetation and in uncultivated lands the infiltration rates are in the region of 10 -15cm/hr. It is best to obtain infiltration rates by measurements in these soils than to infer by other means.

Luvisol - light

The infiltration characteristics of the light textured Luvisols are very similar to that of ferric Luvisols. Presumably these soils are similar to the ferric Luvisols in texture and porosity. The modal values of the basic infiltration rates are usually between 15 and 20cm/hr and can be considered high to very high.

Luvisols - heavy

The high clay content in the heavy textured Luvisol is reflected markedly in their low infiltration rates relative to the ferric and the light textured Luvisols. The proportion of slow and non-conducting pores are high, thereby reducing the rate of water flow within the soil profile. Occasional high infiltration rates do occur in some profiles when cracks develop in the drying clays. The modal value of the basic infiltration rates is about 5cm/hr and the rates seldom exceed 10cm/hr. The infiltration rates can be classified as low to moderate.

Calcisols

Infiltration rates in the Calcisols are very similar to that in the heavy textured Luvisols. However, the average value tend to be slightly more due to the higher soil porosities. The basic infiltration rates vary between 18cm/hr and 7cm/hr.

Saline and Alkali soils

The infiltration rates in alkali soils are usually very low due to the dispersion of clay by the sodium in the exchange complex. The infiltration rates in saline soils can be very variable depending on the profile characteristics.

Vertisols

Due to the shrink-swell properties in the Vertisols, large cracks develop in dry soils. In such conditions, the infiltration rates are very high and almost infinite. On the other hand, in Vertisols when the cracks have closed, the infiltration rates are almost zero. Because of these reasons, infiltration measurements are seldom carried out on Vertisols.

Gleysols

These soils have very low infiltration rates of the order of only 1 - 2cm/hr. Although the total porosity of these soils are high, the dominant pore sizes are in the micro-range which do not contribute to higher flow rates within the soil.

2.2.4. Moisture retention

Soil moisture retention can be described as the amount and the force with which water is retained in the soil pores. The moisture retention in a porous media such as soils, is largely determined by the pore size distribution. The water is retained in the pores due to surface tension and adsorptive forces. In large pores, the contribution by surface tension is more than that by adsorptive forces. As the pore sizes decrease, the influence of adsorptive forces in retaining water increases and in micro pores the water is mainly held by adsorptive forces. The magnitude of the force or the tension with which moisture is held in the pores is inversely proportional to the effective diameter of the pores. Thus, in very large pores, the water is held loosely as compared

to the smaller pores. When a progressively increasing force is applied on a saturated porous medium to extract water from the pores, the largest pore drains first followed by the smaller pores. In saturated field soils, gravity alone can drain off water from the large pores. The remaining water in the soil pores are held by forces greater than the gravitational force. It has been shown experimentally, that the amount of moisture held in soils against free drainage under gravity i.e. field capacity is equal to the moisture retained in soils against imposed tension of 0.1 bar for light textured soils (clay < 40%) and 0.3 bar for heavy textured soils (clay > 40%). The wilting point in a soil is equal to the moisture retained in the soil against an imposed tension of 15 bars. Since the pore size distribution in soils are related to texture, bulk density and organic matter content, the moisture retention values are also indirectly related to these properties.

Soil moisture retention was measured using the sand table for tensions less than 0.1 bar and the pressure plate apparatus for tensions greater than 0.1 bar. Measurement were made on undisturbed soil core samples for the lower range of tensions between 0 and 1 bar and on crushed samples passing through 2mm seive for tensions greater than 1 bar. Gravimetric moisture contents at 0.03, 0.05, 0.1, 0.3, 1.0, 3.0, 5.0 and 15 bar tensions were measured in duplicates. The mean gravimetric moisture content for each of the tension are stored in the computer data base of soil physical properties. The data for each horizon can be used to plot the graph of volumetric moisture content versus the corresponding tension which is referred to as the moisture characteristic curve or the PF curve. The soil moisture characteristic curve is of fundamental importance in agriculture for determining available soil moisture for plant growth and aeration status of soil. Figure 1 gives typical soil moisture characteristic curves for some soil units in Botswana.

Arenosols

Although the Arenosols have high porosity of about 40 percent, all pores are large and freely draining. Consequently these soils are poor in moisture retention. They could retain only 5 -8 percent of moisture by volume at field capacity. Even this moisture is easily released under relatively low tension and at 15 bar tension, the moisture content is often less than 2 percent.
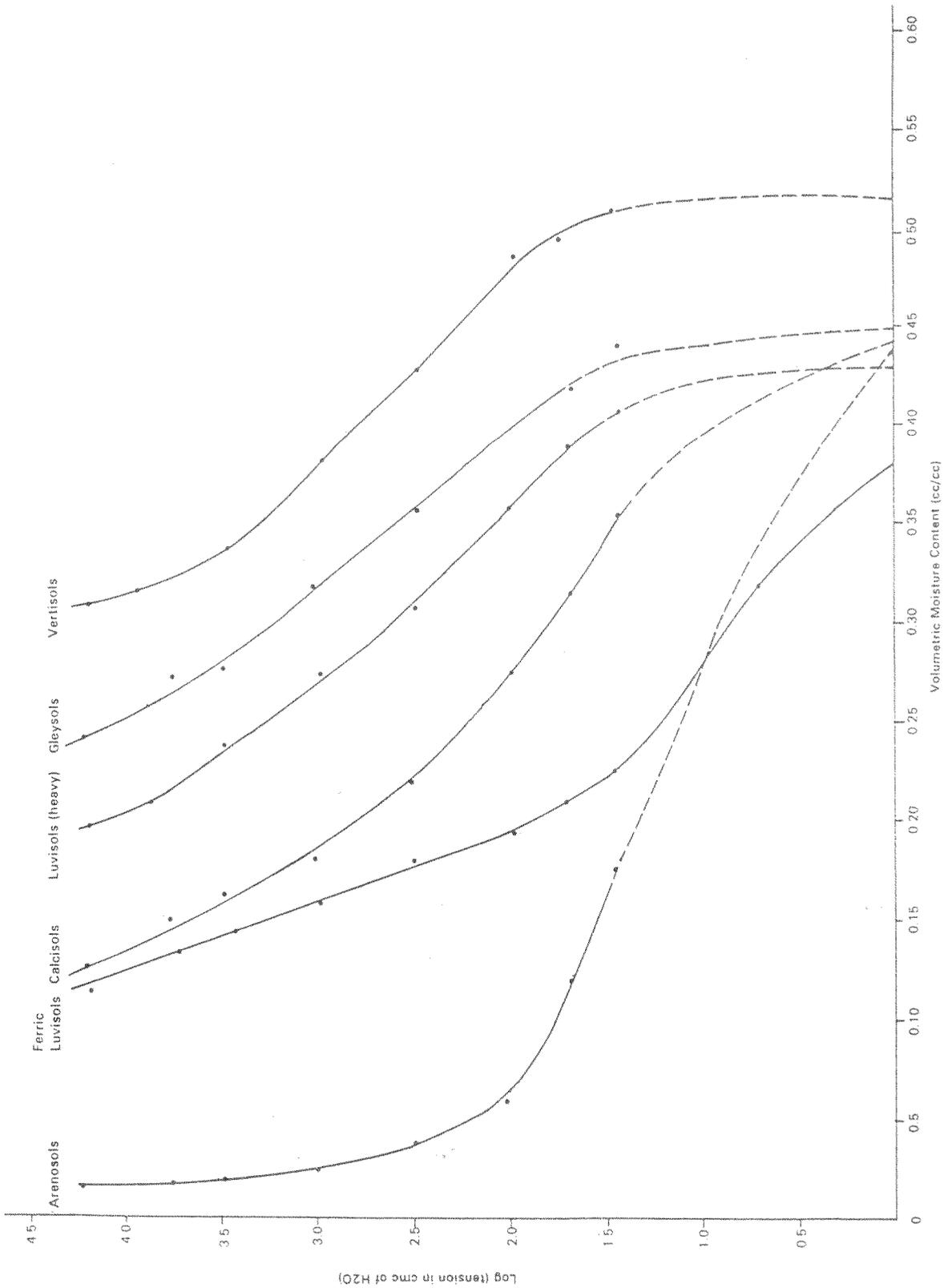
FIGURE 1 : MOISTURE CHARACTERISTIC (pF) CURVES OF SOME REPRESENTATIVE SOIL UNITS IN THE DIFFERENT GROUPS OF SOILS IN BOTSWANA

Luvisol – ferric

The total porosities of the ferric Luvisols are similar to those of Arenosols (40%) but the pore size distribution is such that it imparts better moisture retention properties to these soils. The ferric Luvisols could retain about 20 percent moisture by volume at field capacity, thus about half of the moisture at saturation is freely draining. At 15 bar tension, about 9 percent moisture is retained indicating the presence of higher proportion of micro pores in these soils than Arenosols.

Luvisols – light

The light textured Luvisols are very similar to the ferric Luvisols in their moisture retention properties.

Luvisol – heavy

The heavy textured Luvisols have very good moisture retention properties, in that, they tend to retain maximum amount of moisture against free drainage. These soils hold about 45 -50 percent of moisture by volume at saturation and only 10 -15 percent of moisture drain under gravity. Due to the higher clay content in the soil, the proportion of micro pores are relatively high and at 15 bar tension these soils still retain about 15 to 20 percent of moisture.

Calcisols

The moisture retention properties of the Calcisols are intermediate between that of the Ferric Luvisols and the heavy textured Luvisols. Although the total porosities and the clay contents in these soils are somewhat comparable to that of the heavy textured Luvisols, there is an overall increase in the pore sizes due to the calcium carbonate in the profile. Consequently, there is an increase in the proportion of freely draining macro-pores and a decrease in the micro-pores which retain the adsorbed moisture. At saturation, the volumetric moisture content is about 45-50 percent and of these 15-20 percent drain freely under gravity. At 15 bar tention these soils retain about 10-12 percent of moisture by volume.

Saline and Alkali soils

Moisture retention properties of saline and alkali soils are not fully dependent on pore size distribution alone. Part of the soil moisture is retained due to osmotic potential. The moisture con-

tent at any particular tension is never constant and usually
moisture retention properties are never used in any interpreta-
tions.

Vertisols

The swelling and shrinking properties of Vertisols cause con-
siderable variations in the pore size distribution during the
wetting and drying process respectively. Due to the high clay
content, the proportion of micro pores are high resulting in high
moisture contents at all tensions. The moisture release and free
drainage depends largely on the macro pores that develop when the
moisture content changes. At saturation, the Vertisols hold more
than 60% moisture by volume, and only 10% may drain under gravity
resulting in field capacity value of 50%. Even at 15 bar tension,
about 30% moisture is retained. Thus in Vertisols, moisture
retention is high but the moisture release is moderate to low.

Gleysols

The high clay content in the Gleysols increase the microporosity
and the moisture retained at 15 bar tensions is generally in the
range of 20-25 percent by volume. The high organic matter on the
other hand seems to cause only an increase in the capillary
porosity and the freely draining pores are relatively low, being
in the range of only 10 percent by volume. Thus, these soils can
develop anaerobic conditions even with slight excess of water and
remain water logged for prolonged periods after saturation, due
to their low infiltration rates. The saturated moisture content
of the Gleysols are of the order of 50-55 percent by volume and
can retain about 40-45 percent moisture after free drainage.

2.2.5. Moisture availability

Soil moisture availability for plant growth is perhaps the most
important physical property which is derived from soil moisture
retention measurements and bulk density. Available moisture for
plant growth is defined as the water that is retained in the soil
between field capacity and wilting point. The values for field
capacity and wilting point of soil are required for planning both
rainfed and irrigated agriculture. In order to obtain this infor-
mation quickly, agriculture scientists often resort to developing
functional relationships between moisture availability and tex-
ture and/or other related soil properties. This approach is
generally valid for use within the region where the functional
relationship was developed with actual measured data. However,
the results can be very misleading if such relationships are ex-
trapolated to other regions where the soils are different. In
Botswana, the soil physical properties were measured extensively

on many soil units covering the whole country. Therefore, any possible correlation between available moisture and relevant physical properties will probably be valid.

Initially, a multiple regression analysis and test of significance were made on all the results using clay, total coarse sand, total fine sand, total silt and organic carbon content as independent variables with either field capacity, or wilting point or available moisture as dependent variable. Results indicated that sand, clay and organic matter correlated significantly with field capacity and wilting point having correlation coefficients (R) of .76 and .86 respectively. However, the correlation was very poor for available moisture and the correlation coefficient was only .44. Results from step-wise regression with backward elimination indicated that the different sand fractions did not independently influence the moisture retention properties. It should be noted that the different particle size fractions are not strictly independent variables as their sum is equal to 100%. Since silt content is very low, clay and sand contents are inter dependent and are inversely related. Therefore either total sand or clay can be used as independent variable together with organic matter to correlate with field capacity or wilting point as dependent variable. As seen earlier, field capacity is measured as the gravimetric moisture content of an undisturbed soil core sample subjected to either 0.1 bar or 0.3 bar tension. Soil core samples of the same texture can retain different amount of moisture at the same tension depending on their bulk densities. Consequently, field capacity expressed in gravimetric moisture content should be better correlated with texture and bulk density together than in volumetric moisture content with texture alone. Since wilting point is measured in gravimetric moisture content of crushed and seived soil samples, wilting point expressed in gravimetric moisture content will be correlated with texture only. In addition, organic matter is known to influence both field capacity and wilting point. Therefore it can be assumed that field capacity expressed in gravimetric moisture content will be correlated with total sand or clay, bulk density and organic matter, and wilting point expressed in gravimetric terms will be correlated with total sand or clay and organic matter.

In order to obtain the best possible estimate of field capacity and wilting point, multiple regression analysis was carried out by grouping soil horizons into categories as given in the section on "Methods and materials". Table 4 shows the correlation coefficient, R , in the regression analysis of field capacity with the selected set of soil physical properties. It is clear from the results, that grouping horizons into different categories based on the amount of organic matter or clay content did not improve on the correlation that was obtained when all the horizons were taken together. However clay consistently improved the correlation as compared with total sand. When considering the magnitude

of the correlation coefficient, field capacity expressed as gravimetric moisture content correlates best with clay, bulk density and organic matter.

Table 4. Multiple regression Analysis for Field Capacity (g) with sand/clay, Bulk density and organic carbon as independent variables

Soil Category	Independent variable				Corr. Coef R
	Tot.sand	bul dens	Org.C	Clay	
All Soils	x	x	x		0.88
- do -		x	x	x	0.90
Org. C.> 0.5%	x	x	x		0.89
- do -		x	x	x	0.90
Org. C.< 0.5%	x	x	x		0.57
- do -		x	x	x	0.67
Clay > 40%	x	x	x		0.86
- do -		x	x	x	0.86
Clay < 40%	x	x	x		0.47
- do -		x	x	x	0.66

Table 5 shows the results of regression analysis of wilting point with the selected soil physical properties similar to the analysis on field capacity. Here again the results lead to the same conclusion as for field capacity in that, grouping horizons into different categories did not improve the correlation significantly. The best and the most convenient correlation of wilting point expressed in gravimetric moisture content was with clay and organic matter when all the horizons were considered together. Thus, it is seen from the above analysis that a single equation can be established for each, field capacity and wilting point separately, to cover most of the soils of Botswana. The necessary inputs are percentage clay, percentage organic carbon and bulk density. The bulk density values are not required for the wilting point. The equations are :

$$FC \text{ (g)} = 51.04 + 0.31CL - 28.9BD + 3.54OC$$

Standard error = 5.24, correlation coef = 0.90

$$WP(g) = -0.64 + 0.32CL + 2.06OC$$

Standard error = 2.77, correlation coef = 0.90

Table 5. Multiple regression Analysis for wilting point (g) with sand/clay, and organic carbon as independent variables

| Soil Category | Independent Variables | | | Corr.Coef R |
	Tot.sand	Org. C.	Clay	
All Soils	x	x		0.87
- do -		x	x	0.90
Org. C.> 0.5%	x	x		0.92
- do -		x	x	0.94
Org. C < 0.5%	x	x		0.76
- do -		x	x	0.72
Clay > 40%	x	x		0.81
- do -		x	x	0.72
Clay < 40%	x	x		0.54
- do -		x	x	0.70

Where

FC(g) = gravimetric moisture percent of soil at field capacity

WP(g) = gravimetric moisture percent of soil at wilting point

CL = weight percent of clay fraction

OC = percentage of organic carbon
BD = bulk density in gm/cc

Using the above relationships for field capacity and wilting point, the available moisture can be calculated from the following equation.

Available moisture = [FC(g) - WP(g)] x BD

Where the available moisture is in volumetric moisture percent.

Very often quantitative data on organic carbon and bulk density are not available in respect of soils for which available mois ture is to be estimated. The information on soil that is commonly available is either the quantitative data on particle size fractions or the textural class to which the soil belongs. In the latter case, the clay content can be approximated. Under such circumstances, the only possible way to estimate available moisture very approximately, is through a functional relationship of field capacity and wilting point with either the clay or the total sand content. In order to derive such a relationship, linear regression analysis was carried out on the available data using clay content as independent variable with field capacity and wilting point as dependent variable separately. The following results were obtained.

$FC(v) = 9.64 + 0.57\ CL$

standared error = 6.8, correlation coefficient = 0.80

$WP(v) = 1.68 + 0.40\ CL$

standared error = 3.3, correlation Coefficient = 0.89

where

$FC(v)$ = Volumetric moisture percent of soil at field capacity
$WP(v)$ = Volumetric moisture percent of soil at wilting point
CL = Weight percent of clay fraction

The available moisture in volumetric percent is given by

available moisture = $FC(v) - WP(v)$

In general, the available moisture of similar soil units fall within a characteristic range of moisture contents. The general trends in the values of available moisture of the different categories of soils that were grouped together are discussed below. Table 6 gives the mean values and the range of the measured field capacity, wilting point and available moisture in volumetric moisture percent for the different groups of soil units.

Table 6. Average and range of field capacity,
          Wilting point and available moisture
          for the different soil groups.

Soil group	Field Capacity % V	Wilting point % V	Av. Moisture % V
Arenosol	9.74	3.23	6.51
	(5.1 - 12.1)	(1.6 - 5.0)	(3.2 - 8.4)
Luvisol - ferric	18.96	8.96	10.06
	(10.21 - 27.18)	(4.00 - 16.90)	(5.43 - 16.92)
Luvisol - light	18.09	8.08	10.01
	(12.84 - 25.52)	(4.78 - 17.12)	(6.79 - 18.02)
Luvisol - heavy	34.16	17.67	16.79
	(12.46 - 50.47)	(6.82 - 32.59)	(6.56 - 31 60)
Calcisol	26.36	11.12	15.55
	(12.46 - 53.92)	(5.78 - 17.50)	(5.39 - 39.76)
Vertisol	46.32	32.79	13.53
	(39.34 - 55.84)	(28.38 - 38.45)	(10.8 - 16.6)
Gleysol	43.18	22.71	19.59
	(29.81 - 53.99)	(15.36 - 30.80)	(10.04 - 35.42)

Number in parentheses gives the range of values

Arenosols

The Arenosols have very low amount of available moisture due to
their predominantly sandy texture. The available moisture con-
tents vary between 5 and 10 percent by volume and seldom exceed
10%. The surface horizons have slightly higher available moisture
of about 8% compared to that of sub-surface horizons which is
usually in the range of 3 -6 percent.

Crop production will be very limited in these soils due to mois-
ture stress. Plants can survive only with very frequent rains,
even if it is in small amounts.

Luvisols - ferric

The modal value of the available moisture for ferric Luvisol was
about 10% by volume. More than 80% of the soil samples of ferric
Luvisol analyzed had available moisture between 7.5 and 12.5 per-

cent. The low available moisture facilitates soil reaching field capacity with rains of relatively small amounts. But plants tend to suffer from moisture stress quickly unless rains are frequent enough to replenish soil moisture.

Luvisols - light

The estimation of available moisture made on the light textured Luvisol showed that they were almost identical to those of ferric Luvisols. These soils too have an average value of 10% by volume of available moisture.

Luvisol - heavy

The heavy textured Luvisols are by far the best soils in Botswana for their moisture retention properties and moisture availability. On an average they have about 18% by volume of available moisture and the modal value is about 15%. Unlike the Arenosols and ferric Luvisols which can reach field capacity with less amount of rain, the heavy textured Luvisols would require more rain to bring the moisture content from air-dry to within available range. Thus, these soils would have fewer planting opportunities during the growing season. But once the soil moisture storage becomes adequate for planting, plant growth can be sustained for longer period without rain, thereby reducing the chances of crop failure compared to other soils.

Calcisols

The available moisture holding capacity of the Calcisols are comparable to that of the heavy textured Luvisols. Although, both the field capacity and the wilting point are lower in the Calcisols, the relative increase in the pores sizes in the available range is such that the available moisture in both these soils are similar. The field capacity and the wilting point are of the order of 26 percent and 11 percent by volume respectively. The available moisture is about 16 percent by volume.

Vertisols

Moisture retention in Vertisols is very high but much of the water is in the unavailable form. The available moisture of the Vertisols is about 10 to 13 percent by volume. Due to the high field capacity of these soils, the soil moisture can reach the available range only after large amount of rain if the soil is initially at air dry moisture content. The cracking nature of the dry Vertisols aggravate the problem as all the initial rains flow

through the cracks to the lower soil layers below the surface. Once the cracks close up and the moisture builds up to the available range, successful crop production is possible.

Gleysols

The average available moisture of 19-20 percent by volume for the Gleysols is the highest as compared to other soils. However, the high moisture contents of 40-45 percent by volume at field capacity in relation to a total porosity of 50-55 percent can cause poor aeration to inhibit plant growth. Thus, the Gleysols have to dry sufficiently below field capacity for any crop production to be successful. In reality therefore, the available moisture for plant growth will be lower than the value that is obtained by moisture retention procedures.

2.2.6. Structural Stability

The degree to which the soil aggregates withstand the disintergrating effect of water and mechanical agitation is referred as structural stability. The relative stability of soil aggregates to wetting is assessed by comparing the degree of collapse of air-dried soil aggregates when rapidly wetted as opposed to slow wetting under a tension. When wetted slowly, soil aggregates do not collapse while under fast wetting they collapse and slake according to their degree of stability. The degree of collapse of the fast wetted aggregates is estimated by a measure of the ratio of pore size distribution of the large pores in the two samples which had undergone the two types of wetting. The pore size distribution in turn is measured by the moisture release characteristics of the two samples at low tensions. If the soil aggregates are fully stable and do not collapse on fast wetting, the pore size distribution in the fast and the slow wetted samples will be nearly equal and their ratio will be close to unity. If the soil aggregates are completely unstable, then they will fully collapse on fast wetting and the ratio will be almost zero. Any intermediate value in the ratio indicates an intermediate level in the aggregate stability between the two extremes. Thus, the ratio of the pores size distribution of the fast wetted to the slow wetted aggregates is a measure of stability and is referred to as the structural stability index of the soil. Structural stability indices are measured on soil samples in the size range between 1 and 2mm.

The structural stability index measured by the above method has to be interpreted in relation to the proportion of single grains of sizes between 1 and 2mm that are present in the soil sample. In soil samples having both soil aggregates and single grains, only the soil aggregates undergo disintegration on fast wetting

and the single grains remain unaffected. Therefore, soil sample
with significant proportion of single grains tend to show a
higher structural stability index than what it would have been if
the sample consisted of soil aggregates only.

Only with few exceptions, all the soil units, for which struc-
tural stability was measured, had structural indices less than
0.5. Surface soils on only three profiles showed good aggregate
stability with indices between 0.60 and 0.65. These soils were
high in organic matter content without any single grains in the
1-2mm size range. All the soils which showed high aggregate
stability indices above 0.70 were, without exception, sandy soils
with high percentage of single grains in the 1 -2mm size range.
All the results of structural stability index measurements are
stored in the soil data base with other soil physical properties.
The structural stability of most of the soils of Botswana can be
considered poor with the attendant erosion and surface sealing
under rainfall. However the soils with very sandy surface soils,
although do not have any aggregation, can be considered somewhat
like a structurally stable soil. They do not develop surface soil
crusts because of the loose sands and also do not produce much
run-off due to their high infiltration rates. Thus, the soils
showing very high apparent structural stability index due to the
presence of high proportion of 1 - 2mm single grains, in fact,
behave like structurally stable soils under rainfall. Arenosols,
some ferric Luvisols and light textured Luvisols belong to class
of soils where the surface soils are sandy and show apparently
high structural stability index.

REFERENCES

FAO/1988   Revised Legend of the FAO/Unesco Soil Map of the world. FAO,Rome.

Joshua, W.D. Methods for the measurements of physical properties of soils. Project AG/BOT/85/011. Field Document 19.

Properties of Arenosols

Profile Number	Sample Number	pH	Elec. Cond. (mS/cm)	Bulk Density (g/cc)	Clay %	Field Capacity (cc/cc)	Wilting Point (cc/cc)	Available Moisture %(v)
DI0901	A	5.20	0.0	1.57	3.0	0.0644	0.0188	4.55
DI0901	B	4.90	0.0	1.63	4.0	0.0880	0.0196	6.85
DI0901	C	5.00	0.0	1.77	5.0	0.0920	0.0212	7.08
GO0902	A	7.10	0.1	1.27	18.0	0.2959	0.0968	19.91
GO0902	B	7.10	0.0	1.48	0.0	0.0478	0.0124	3.54
MW0902	A	4.80	0.0	1.46	3.8	0.0565	0.0168	3.97
MW0902	B	4.90	0.0	1.49	3.8	0.0569	0.0158	4.11
MW0902	C	5.00	0.0	1.51	3.8	0.0518	0.0175	3.43
PA0901	A	5.20	0.0	1.73	5.0	0.1315	0.0329	9.86
PA0901	B	5.00	0.0	1.73	9.0	0.1142	0.0363	7.79
PA0901	C	4.60	0.0	1.72	9.0	0.1256	0.0361	8.94
PA0901	D	5.70	0.0	1.59	11.0	0.1018	0.0572	4.45
PA0901	E	5.30	0.0	1.62	11.0	0.1199	0.0583	6.16
PA0901	F	5.30	0.0	1.66	13.0	0.1428	0.0598	8.30
SP0904	A	6.70	0.0	1.51	7.4	0.0815	0.0498	3.17
SP0904	B	6.70	0.0	1.52	9.1	0.0836	0.0304	5.32
SP0904	C	6.80	0.0	1.53	7.5	0.0887	0.0337	5.51
TO0903	A	6.40	0.0	1.63	0.0	0.1203	0.0363	8.39
TO0903	B	6.50	0.0	1.51	3.9	0.1149	0.0368	7.81
TO0903	C	6.80	0.0	1.54	3.9	0.1215	0.0459	7.56

Properties of Luvisols-light textured

Profile Number	Sample Number	pH	Elec. Cond. (mS/cm)	Bulk Density (g/cc)	Clay %	Field Capacity (cc/cc)	Wilting Point (cc/cc)	Available Moisture %(v)
MA0904	A	6.30	0.0	1.10	14.0	0.2552	0.1425	11.28
MA0904	B	7.50	0.0	1.68	9.0	0.2103	0.1712	3.91
MA0904	C	7.30	0.0	1.63	18.0	0.2448	0.1059	13.89
MC0901	A	6.90	0.5	1.70	12.0	0.2397	0.0595	18.02
MC0901	B	6.70	0.2	1.70	14.0	0.2108	0.0595	15.13
MC0901	C	6.50	0.2	1.63	15.0	0.1907	0.0880	10.27
MC0901	D	6.70	0.7	1.59	22.0	0.2115	0.0875	12.40
PN0902	A	5.70	0.0	1.44	18.9	0.1348	0.0727	6.21
PN0902	B	6.00	0.0	1.51	19.2	0.1666	0.0933	7.32
SP0902	A	6.10	0.0	1.52	10.1	0.1338	0.0593	7.45
SP0902	B	6.30	0.0	1.51	15.9	0.1284	0.0604	6.79
SP0902	C	6.30	0.0	1.58	15.4	0.1485	0.0679	8.06
TO0906	A	6.90	0.0	1.48	7.7	0.1385	0.0478	9.07
TO0906	B	7.60	0.0	1.46	9.2	0.1676	0.0876	8.00
TO0906	C	8.00	0.0	1.54	15.2	0.1953	0.0953	9.99

The results show that although there is no difference in the maximum rooting depth, there is a slight increase in root proliferation in the rip line. However this difference may be either due to lower bulk densities and soil strength in the rip lines or simply due to crop differences. In any case, the differences are not very large. Definite conclusions on rooting differences between treatments can be obtained only if the control is located in the same field as the other treatments and with the same crop.

Soil Moisture

One of the important objectives of the investigations was to measure the changes in moisture contents in the rip line, traffic line and control and compare with the amount of rainfall. This data was necessary to check whether the increase in moisture content in the rip line is greater than the other two treatments as well as the amount of rainfall, as expected. Unfortunately, the rainfall during the season was far too excessive and masked the difference between treatment by wetting the soil profile equally. However, one set of moisute content measurements by neutron probe was possible at the beginning of the season after a heavy rainfall of 84mm (Table 4b). At the end of the season gravimetric sampling was done at 15cms intervals to a depth of 60cms in the rip line and traffic line (Table 4a).

Table 4a

MOISTURE CONTENT AT END OF SEASONS

Depth cms	Moisture Content g/g	
	Rip-line	Traffic line
0-15	0.067	0,063
15-30	0.073	0.074
30-45	0.12	0.11
45-60		0.14

Table 4b

MOISTURE INCREMENT IN 45CMS OF SOIL DEPTH AFTER 84 MM R/FALL

Treatment	Moisture Increment cms
Rip line	3.5
Traffic line	1.9
Control	2.3

From Table 4b, it is seen that there has been an increase in moisture content in the rip line as compared to the traffic line and control. Apparently there is some run-off from the traffic line on to the rip line because the increase is more than the control. The result from one set of data cannot be taken as conclusive. Further, the increase in moisture is far less than the total rainfall which would also suggest that the moisture increment can be due to the incident rainfall alone without the effect of run-off. At the end of the season, the moisture contents of soil in rip line and traffic line are almost identical (Table 4a) showing that the rains wetted both the soil profiles equally thereby masking the effect of the two treatments. Therefore in order to evaluate the beneficial effect of rip line - traffic line treatment, it is necessary to repeat the experiment for another season with adequate measurement in the control plot for better comparison.

Summary and Conclusion

The physical properties of soils that were either ripped or compacted consecutively for three years of the growing season were measured.

The infiltration in the ripped lines was higher than the normal soil in the beginning of the season but became similar to that of normal soil at the end of the season. The infiltration rates of the normal soil itself are high. Compaction in the traffic lines reduced infiltration and increased bulk density and induced run-off during rainfall. The reduction in bulk density and soil strength caused by ripping persisted even after the rainy season and also increased rooting density of plants. The moisture contents in the rip lines were higher than those of traffic lines and control plots after rainfall. But the data are insufficient to conclude that there is definite rainfall run-off from the traffic line into the rip line.
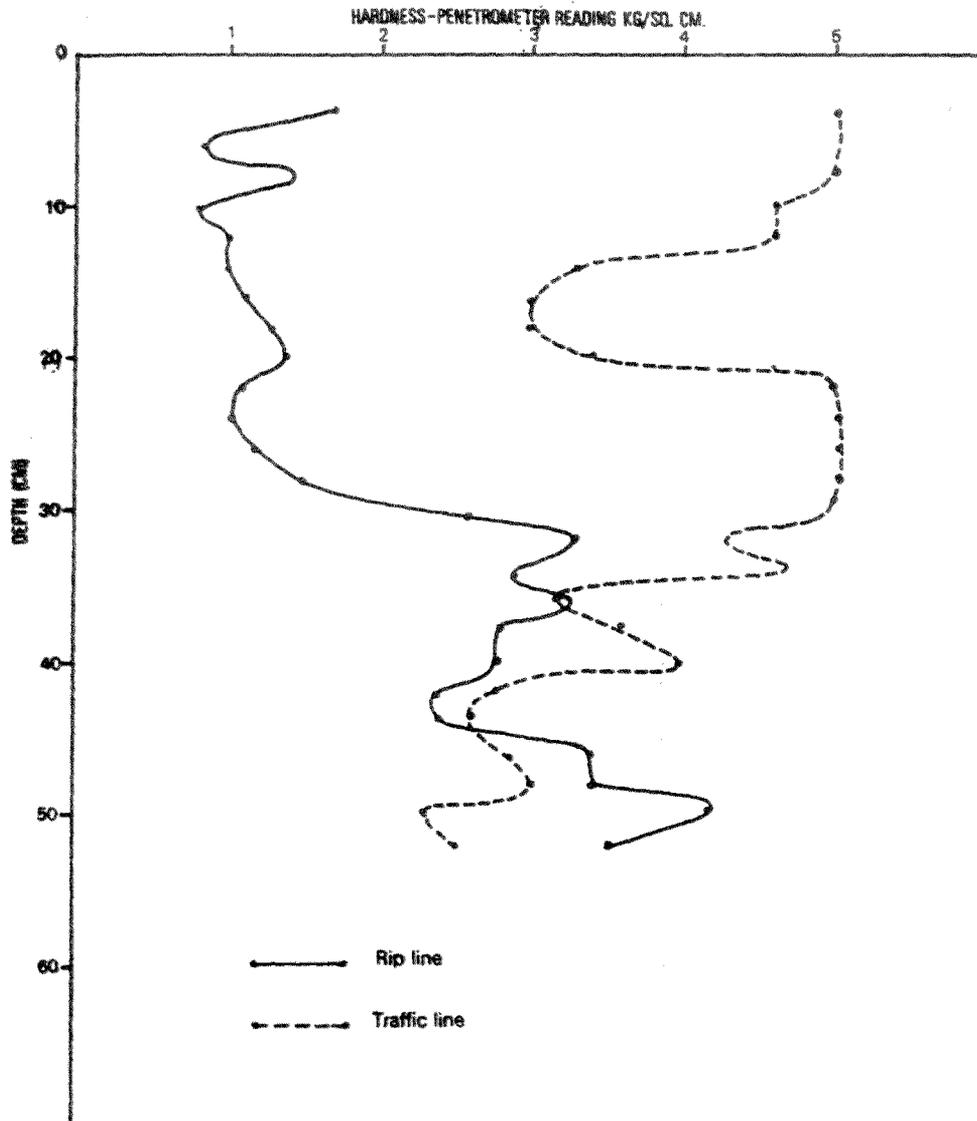
Figure.1 - VARIATION OF SOIL STRENGTH WITH DEPTH

AG: BOT/85/011

Technical Paper 2

Soil Mapping And Advisory Services

Botswana

PHYSICAL PROPERTIES OF VERTISOLS
AND ARENOSOLS OF PANDAMATENGA

Food and Agricultural Organization Of The United Nations
United Nations Development Programme

Gaborone, November 1988

Introduction

The physical properties of a typical Vertisol profile of Pandamatenga were determined for the purpose of characterizing these soils. The major part of the Pandamatenga Plains consist of Vertisols. The data can be used as a guide for planning agricultural practices. Some physical property measurements were also carried out on the Arenosols which occur adjacent to the Vertisols on topographically higher position in the landscape. The Vertisols profile has a high clay content (>76%) and is classified as Pellic Vertisol (FAO) while the Arenosol which is very sandy (>90%) is classified as Ferralic Arenosol.

Bulk density

(a) Vertisols:- Due to the shrink-swell and cracking nature of these soils, bulk density measurements by the core-sampling technique was not possible. Instead, bulk densities were estimated by using saturated moisture content of large natural clods and assuming particle density of 2.65 gms per cc. Since these soils expand continuously from air-dryness to saturation, the bulk densities thus obtained are that of nearly saturated soils without the effect of overburden pressure. Bulk densities were also estimated by the equation given for Vertisols by Australian workers (Shaw and Yule, 1978) using 15 bar moisture content with allowance for overburden pressure. The latter method is considered by these workers as most suitable for agricultural planning purposes. Table 1 gives the bulk density values for the different horizon estimated by both methods.

Table 1

BULK DENSITIES OF VERTISOLS

Soil Horizon depths (cms)	Bulk density (gm/cc)	
	water saturation	Australian method
5 - 23	1.30	1.30
23 - 50	1.33	1.35
50 - 85 +	1.32	1.37

(b)   Arenosols:- Bulk density measurements were made by the core-sampling techniques at two sites on the Arenosols. Although texturally these soils were very similar at both sites, the soils on the higher topographical positions were redder and the soils at slightly lower positions were yellowish. The average of five replicate measurements for 0 - 18cms soil depth at the upper and lower positions of the slope were 1.53gm per cc and 1.58gm per cc respectively.

Infiltration

(a) Vertisols:- As extensive wide cracks develop in dry Vertisols, infiltration rates are not generally measured in these soils. The infiltration rates are assumed to be very high due to the cracks when the soils are dry and very low (as per clays) when the cracks close up in wet soils.

(b) Arenosols:- The double ring infiltration method was used to measure the intake characteristics of the Arenosols in replicates. The cumulative in- filtration was plotted against elapsed time on a log-log graph and a best-fit straight line was drawn through the data points to estimate the infiltration characteristics. Figure 1 and Table 2 show the relevant characteristics.

Table 2

INFILTRATION RATE OF ARENOSOLS

Site No	Basic Infiltration Rate (cm/hr)	Time taken to reach basic rate (mins)
1	14.7	90
2	41.3	48
3	44.8	60
4	44.4	54
5	41.2	6
6	22.5	96

The results clearly show that the infiltration rates are excessive in the sandy soils. Somewhat lower values of sites 1 and 6 are probably due to spa- tial variability of the soils.

Soil Moisture Retention

(a) Vertisol:- Soil moisture characteristics (moisture retention curves) were determined on large natural soil clods for tensions at 0, .03, .05, 0.1, 0.3, and 1 bars. For 3, 5, and 15 bars, 2mm sieved samples were used. Sand table and pressure plate methods were used to impose the required tension on the soil samples. Separate samples from each horizon were used in quadruplicate at each imposed tension. Figure 2 shows the moisture retention curves for 3 horizons and Appendix Table A1 gives the mean gravimetric moisture content at each respective tension.

(b) Arenosols:- Soil moisture characteristics were not measured on the Arenosols.

Moisture Availability

(a) Vertisols:- Recent work on Vertisols has shown that the available mois- ture estimated by the conventional method as the difference between .3 bar and 15 bar moisture contents can be misleading due to the swell-shrink nature of the soil. Although the wilting percentage is approximately equal to the 15 bar moisture content, the tension at which the moisture content approximates the field capacity is very variable. Consequently, through extensive field measurement, Australian workers (Shaw and Yule, 1978) have developed an equa- tion using 15 bar moisture content to estimate the upper storage limit in field soils. Table 3 gives the moisture availability estimated by this method.

Table 3

MOISTURE AVAILABILITY OF VERTISOLS

Horizon depth (cms)	Upper storage Limit (g/g)	Lower storage Limit -15bar g/g	Available moisture cc/cc	cms/m
5 - 23	0.3641	0.2211	0.1859	18.59
23 - 50	0.3212	0.2268	0.1274	12.74
50 - 85+	0.3135	0.2271	0.1201	12.01

On an average, the available moisture for the Vertisols can be approximated to 128mm per metre of soil.

(b) Arenosols:- No moisture retention measurements were done on Arenosols. However, based on results obtained from similar soil in the area (ATIP-USAID July 1987), available moisture is estimated to be 0.0718 cc per cc or 72mm per metre of soil.

Structural Stability

The relative structural stability of soils to wetting was assessed by comparing the degree of collapse of aggregrate of air dried soil when rapidly wetted as opposed to slow wetting under a tension. The degree of collapse is estimated by the relative change in pore-size distribution which in turn is determined from the moisture release characteristics of the samples which had undergone the two kinds of wetting. It is assumed that there will be little or no collapse of any sample that is wetted under a tension. Completely stable soil will have a stability index of 1, whereas a totally unstable soil will have a stability index of 0.

(a) Vertisols:- The structural stability index of the surface horizon of the Vertisol was determined by the above method in duplicate. The average structural stability index was 0.42, indicating that the soil is structurally unstable and would easily slake under rainfall.

(b) Arenosol:- No structural stability measurements were done on Arenosols as the soils were almost structureless (loose).

Reference

Shaw, R. J. and Yule, D. F. 1978. The assesment of soil for irrigation Emeral Qld. Technical Report No 13. Department of Primary Industries Brisbane Australia

Appendix 1

Table A1

MOISTURE CONTENTS AT IMPOSED TENSIONS - VERTISOLS

Tension (bars)	Moisture Content (gm/gm)		
	5 - 23cms	23 - 50cms	50 - 85+ cms
0.03	0.3790	0.3749	0.3682
0.05	0.3511	0.3540	0.3567
0.1	0.3161	0.3160	0.3506
0.3	0.3060	0.3068	0.3044
1.0	0.2735	0.2755	0.2778
3.0	0.2425	0.2447	0.2425
5.0	0.2308	0.2365	0.2366
15.0	0.2211	0.2268	0.2271
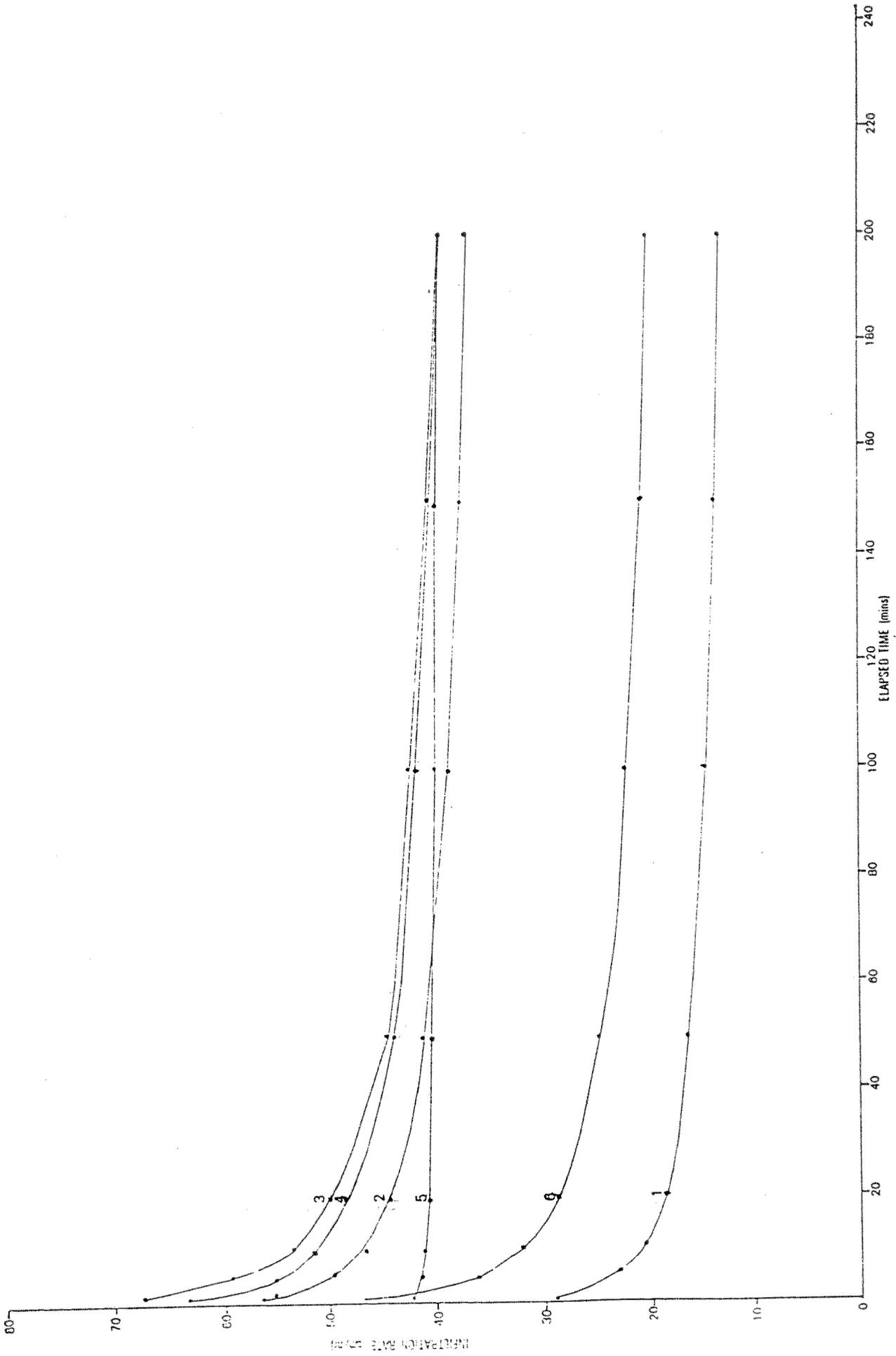
Figure 1 - INFILTRATION RATE vs TIME - ARENOSOLS - MPANDAMATENGA

Figure 2 - MOISTURE RETENTION   VERTISOLS - MPANDAMATENGA

1   5 - 23 cms.
2   23 - 50 cms.
3   50 - 85+ cms.

LOG TENSION (cm H₂O) or pF

MOISTURE CONTENT (cc/cc)

Figure 2 - MOISTURE RETENTION   VERTISOLS - MPANDAMATENGA

ANNEX 3

Soil Mapping And Advisory Services

Botswana

PHYSICAL PROPERTIES OF SOILS OCCURRING ADJACENT TO THE MOTLOUTSE RIVER
IN THE SELEBI-PHIKWE AREA AND THEIR SUITABILITY FOR IRRIGATION DEVELOPMENT

Introduction

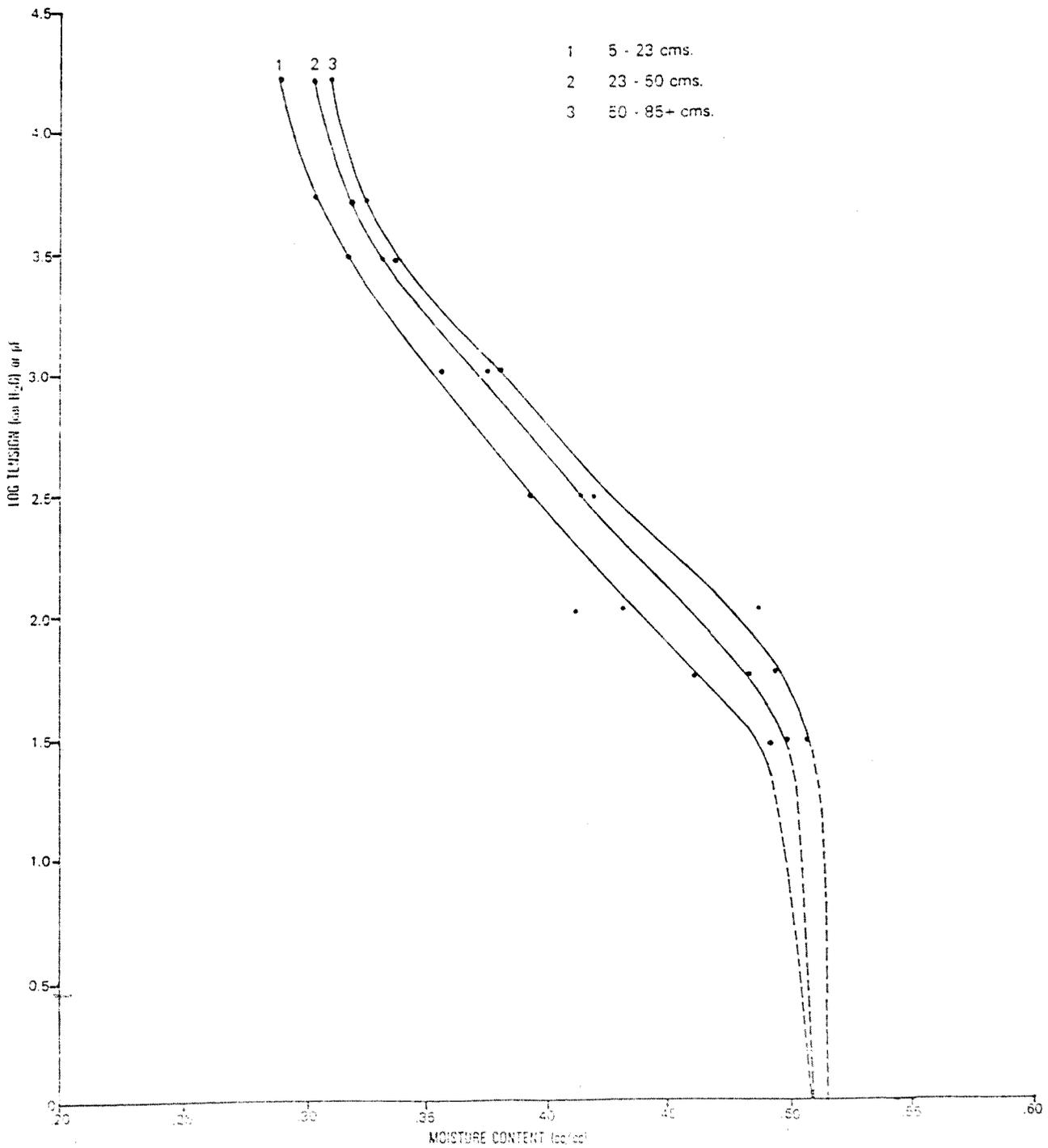The physical characteristics of some soils along the Motloutse River were determined with the view to asses their suitability for irrigation development. The soil survey of the area had been carried out at a reconnaissance level and a soil map was produced at a scale of 1:50,000, showing associations of soils as mapping units. Representative soils whose morphological characteristics indicated their suitability for irrigation development were selected for measurement of soil physical properties. In addition, a profile with high sodium content was also included for the purpose of characterisation. The selected soil units are: (1) Calcic Luvic Xerosol, Soil Unit A37, Profile No SP141 (2) Luvic Xerosol, soil unit G14a, Profile No SP142 (3) Orthic Solonetz, soil unit A5b, Profile No SP143 (4) Cambic Arenosol, soil unit A22a, Profile No SP144.

Method

(a) **Infiltration:** Double ring infiltrometer method was used in 3 replicates. At sites where surface sealing/compaction was evident, two additional measurements were made after removing the surface soil to a depth of 20cms.

(b) **Bulk Density:** Core sampling method was used with core samples of 100cc capacity. Five replicate measurements were made for each horizon.

(c) **Moisture Retention:** Moisture content at 0.1 bar and 0.3 bar were determined on undisturbed core samples in duplicate. Moisture content at 15bar was determined using 2mm sieved samples. Pressure plate apparatus was used in all measurements.

(d) **Structural Stability:** Structural stability index was determined by measuring the degree of collapse of aggregates of sizes between 1 and 2mm seived samples on slow and fast wetting. A Structural stability index of 1 represents complete stability and a structural stability index of 0 represents total instability. The values in-between represent intermediate structual stability.

Results

(a) **Bulk Density:** Table 1 shows the average bulk density of the major horizons of the four soil units. With the exception of Orthic Solonetz (Unit A5b) bulk density varies from 1.51 gms/cc to 1.63 gm/cc for all soils. The higher values are associated with the lower horizons of Luvic Xerosols. The bulk densities of the sub-surface horizons of Orthic Solonetz are 1.35 and 1.33 gm/cc which are in line with the high clay contents of these horizons.

(b) **Infiltration:** Table 2 and figures 1, 2, 3 and 4, give the infiltration characteristics of the four soil units. In all the sites, the initial moisture conditions were air dry. The basic infiltration rates of all soils except the Orthic Solonetz (Unit A5b) were high to excessive. Although the Calcic Luvic Xerosol (Unit A37) had heavier and alkaline sub-surface horizons, the lighter textured surface horizons contributed much to the higher infiltration rates.

However, all other soil profiles of this unit which were described and sampled during soil surveys do not have the alkaline horizon and this site probably is an exception in this respect. Surface sealing and compaction was quite evident in Luvic Xerosols (Unit G14a), but the infiltration rates were high even under these conditions because the soils were sandy throughout the profile. After the removal of compact surface layer, the infiltration rates increased significantly in these soils (Figure 2). Infiltration rates in the Orthic Solonetz (Unit A5b) is very low as could be expected for an alkaline soil. However on slightly elevated mounds with grass cover, the infiltration rates were slightly increased (Table 2, Replicate No I_3 for SP143), probably due to the sandy non-alkaline surface soil.

(c) **Moisture retention:** Table 1 gives the moisture retention values for the major horizons of the four soil units at 0.1, 0.3, and 15 bars tensions. The values for the alkaline horizons were inconsistent and hence not reliable. The moisture contents at the different tensions are in keeping with the textural variations of the horizons. Therefore, these values may be extrapolated to soil horizon of similar textural class in the survey area.

(d) **Moisture availability:** As most of the soils of the survey area are light to medium textured, moisture contents at 0.1 bar can be assumed to approximate the field capacity. Based on this assumption, the sandy clay loam soils have available moisture of about 150mm/m, sandy loams have about 70-80 mm/m, and loamy sand have about 50mm/m

(e) **Structural stability:** As the surface soils of all the profiles are sandy with little or no structural development, the particles of size between 1mm and 2mm sieved samples consisted mostly of primary particles rather than aggregrates. Consequently the structural stability indices shown in Table 3 should be interpreted with caution. In the first replicate measurements, adequate amount of aggregrated particles in the range of 1mm - 2mm would have been present as aggregrates larger than 2mm were carefully crushed and passed through 2mm sieve. In the subsequent replicates, due to the lack of larger aggregrates, bulk samples containing largely of loose small particles were passed through 2mm sieve and collected on 1mm sive for the measurements. Consequently these samples contained mostly single grain sand particles as was later confirmed by observation after the experiment. Under such conditions, the pores formed due to arrangement of single grains do not collapse on fast wetting, thus resulting in higher structural stability indices. Therefore the first replicate values are most likely to be the true structural stability indices of these soils. In the case of Cambic Arenosols (Unit A22a) there were little or no aggregate and the first replicate itself had higher structural stability index for the same reason mentioned above.

The results indicate that the small degree of aggregation developed in the surface soils are very unstable. The surface soils can therefore be considered to behave like structureless loose (single grain) under irrigation. However, under rainfall, run-off and soil erosion will occur on soils which have developed some soil aggregration due to the formation of thin surface crusts.

FEASIBILITY OF IRRIGATION DEVELOPMENT ON SELEBI-PHIKWE SOILS

The proposal is for the Motloutse river to be dammed and the water utilised downstream for irrigation under sprinkler system. As the soils are generally sandy and have high inlfiltration rates, sprinkler or drip irrigation would be the obvious choice for the method of irrigation. The whole project involves large capital investment and therefore it is imperative that the irrigated agriculture has also to be intensive with high returns for the investment. Consequently, it is assumed that maize or high valued vegetables will be cultivated with optimum inputs of fertiliser and high management under sprinkler system. Feasibility for irrigation was evaluated under the above production system using the measured land (soil) characteristics. No quantitative economic critirea were used and hence feasibility for irrigation may change with economic considerations.

The procedure adopted was based on the FAO system for land evaluation. Firstly land utilisation type (LUT) was defined (Table 4). Then land suitability class specifications were developed for this LUT by identifying class determining factors and quantifying critical limits for rating the relevant land characteristics (Table 5). This step was subjective and based on experience and practices adopted commonly. Thirdly 'modal' values of all land characteristics of the selected soil units were determined by collating all data on soils obtained during soil surveys (Table 6). Fourthly, each land characteristics was assigned the appropriate suitabiliy class rating by matching the land characteristic values with the critical limits for the different suitability classes (Table 7). The next step was to assign a suitability class rating for the individual class determining factor as whole, based on the preceding suitability rating of the land characteristics, by considering interactions and their significance (Table 7). Finally overall suitability class was assigned to each soil by considering the suitability rating of each class determining factor and their interactions and significance in affecting the suitability of the land (soil) for the particular land utilisation type. The last two steps are again subjective and depends on experience. Therefore the evaluation is essentially qualititative based on physical factors only. Moreover, suitability is assigned to soil unit, whereas strictly, suitability is meant for land unit. In this instance the suitability may be considered for the land unit containing the particular soil unit. The suitability rating of S1 is highly suitable S2 is moderately suitable and N is not suitable.

Land (soil) suitability for sprinkler irrigation.

1	Eutric/Cambic Arenosol	A22	N
2	Luvic Xerosol	A36	S1
3	Calcic Luvic Xerosol	A37	S1
4	Calcic Luvic Xerosol (Imperfectly drained)	A37a	S2

Remarks on class determining factors and their significance

1   Rooting – Rooting is considered as a land quality for anchorage, soil volume for nutrient supply and root proliferation only. The same land characteristics have to be considered for interaction with water quantity and water management when assessing overall suitability rating.

2   Aeration – Specification for aeration is based on criterea for oxygen supply only.

3 Water quantity – Available water capacity is chosen to reflect suitability with respect to quantity and frequency of irrigation. May not be significant if modified by deeper rooting and easier method of irrigation.

4   Water management – Limits for infiltration rates are chosen to reflect suitability in respect of surface ponding under common sprinkler application rates. Frequency of irrigation is a combined land characteristic of rooting depth (1 meter), available water capacity and evapotranspiration rate to reflect suitability in respect of the amount of laterals (pipes) required and movement of laterals. This is a very important factor in sprinkler irrigation systems to determine the suitability rating. The rating of this factor can overide higher rating in other factors.

5   Drainage – The criterea for ground water depths is based on the requirements for providing drainage measures to prevent build up of water table.

6 Erosion hazard – The structural stability assesses the break down of soil aggregates for forming surface crusts while slope assesses the run-off. Erosion hazard is estimated by the combined effect of these two characteristics and their significance. This factor may not be important if land surface configuration is modified by contour ploughing.

7 Nutrient retention – The texture or CEC determines the degree of leaching of nutrients and consequently the amount of fertilizer required to maintain yield. This is an important factor in determining overall suitability rating as irrigation in reality is never one hundred percent efficient.

Table 1
PHYSICAL CHARACTERISTICS OF SELECTED SELEBI-PHIKWE SOILS

(a) Profile No Sp141, Luvic Xerosols - A37

Horizon	Moisture retention g/g			Moisture availability		Bulk density
Depth	1/10 bar	1/3bar	15bar	cc/cc	mm/m	gms/cc
6-45	0.1571	0.1300	0.0558	0.1550	155	1.53
45-75	0.2181*	0.1724*	0.1012*	0.1847*	185*	1.58
75-110	0.1967*	0.1706*	0.1238*	0.0763	76*	1.63

* Due to high pH and electrical conductivity of the soil, the replicate values are inconsistent and therefore not reliable.

(b) Profile No SP142, Luvic Xerosols - G14a

Horizon	Moisture Content g/g			Moisture Availability		Bulk density
	1/10bar	1/3bar	15bar	c/cc	mm/m	g m / c c
0-20	0.0880	0.0524	0.0394	0.0739	74	1.52
20-50	0.0848	0.0718	0.0398	0.0681	68	1.51
50-85+	0.0942	0.0753	0.0433	0.0804	80	1.58

(c) Profile No SP143, Solonetz - A5b

Horizon	Moisture Content g/g			Moisture Availability		Bulk density
	1/10bar	1/3bar	15bar	c/cc	mm/m	g m / c c
10-25	0.2167*	0.1764*	0.0995*	0.1192*	119*	1.55
30-50	0.2557*	0.2308*	0.1935*	0.0503*	50*	1.35
65-85*	0.2592*	0.2403	0.1962	0.0586*	58*	1.33

* Due to high pH and electrical conductivity of the soil the replicate values are inconsistent and therefore not reliable.

(d) Profile No SP144
CAMBIC ARENOSOL

Horizon	Moisture Content g/g				Moisture Availability	Bulk density				
	1/10bar	1/3bar	15bar	c/cc	mm/m	g	m	/	c	c
25-45	0.0540	0.0408	0.0332	0.0314	31	1.51				
55-75	0.0548	0.0435	0.0201	0.0527	53	1.52				
90-110	0.0576	0.0454	0.0215	0.0552	55	1.53				

Table 2
INFILTRATION CHARACTERISTICS OF SELEBI-PHIKWE SOILS

Profile	Replicate No	Basic Infiltration Rate (cm/h)	Time Taken To Reach Basic Rate (Hrs)
Luvic Xerosols Unit A37 SP 141	I_1 I_2 I_3	13.6 10.1 13.5	2.5 2.9 2.1
Luvic Xerosol Unit G14a SP 142	I_1 I_2 I_3 I_4 I_5	10.7 46.8 12.9 19.4 12.8	0 1.3 0.86 1.5 0.84
Orthic Solonetz Unit A5b SP 143	I_1 I_2 I_3	0.1 0.4 2.6	8.32 6.48 3.0
Cambic Arenosol Unit A22a SP 144	I_1 I_2 I_3	54.3 46.1 40.8	0.1 0.1 0.1

<u>Table 3</u>
STRUCTURAL STABILITY INDICES OF SELECTED SURFACE SOILS OF SELEBI-PHIKWE

Profile No & Soil	Replicate Value of Structural Stability Index
SP141, Luvic Xerosol A37	0.39, 0.65, 0.95
SP142, Luvic Xerosol G14a	0.38, 0.55, 0.77, 0.84
SP143, Orthic Solonetz A5b	0.23, 0.68, 0.80
SP144, Cambic Arenosol A22a	0.64, 0.94

<u>Table 4</u>
LAND UTILIZATION TYPE SPECIFICATION FOR SPRINKLER
IRRIGATION OF MAIZE/VEGETATBLE

ITEMS	DESCRIPTIONS
1 Cropping system	Maize and high cash vegetable crops as Multiple or simple land utilisation type
2 Market	Commercial domestic
3 Water supply	Adequate
4 Irrigation method	Sprinklers with mains and laterals
5 Capital	Capital intensive
6 Labour	Hired labour without any constraints
7 Technical skills	Commercial farmers with all modern technical resources available
8 Power	Human and tractor power available
9 Land tenure	Freehold -individually owned or corporately owned.
10 Water rights	State owned but readily available
11 Infrastructure	To be developed by state
12 Material inputs	Optimum inputs - planting materials, fertilizers etc...
13 Cultivation practices	Commercial enterprise with adequate inputs
14 Yields	Maximum potential under the practical production system on S1 land

Table 5

CLASS DETERMINING FACTOR, RELEVANT LAND CHARACTERISTICS AND THEIR CRITICAL LIMITS FOR SUITABILITY CLASSES - SPRINKLER IRRIGATION OF MAIZE/VEGETABLE

Class determining Factor	Land Characteristics	S1	S2	S3	N
1 Rooting	- effective soil depth (cms)	>75	75-50	50-30	<30
	- stones and gravel surface (%)	<10	10-20	20-30	>30
	sub-surface(%)	<15	15-35	35-50	>50
	- bulk density (gms/cc)	<1.6	1.6-1.7	1.7-1.75	>1.75
2 Aeration	- Drainage (colour & motling)	Well	Imperfect	Imp./gley	poor
	Aeration at field capacity(%)	>10	10-6	6-3	<6
	Duration of floods (days)	<2	2-4	4-5	>5
3 Water Quantity	- Available water capacity (mm/m)	>100	75-100	50-75	<50
	- Agro-climatic zone				
4 Water Management	- Infiltration basic rate (cm/h)	>1	1-0.5	0.5-0.2	<0.2
	- Frequency of irrigation (days)	>15	15-10	10-5	<5
5 Drainage	Groundwater depth (cms)	>120	120-90	90-75	<75
6 Erosion Hazard	- structural stability index	70.75	0.75-0.5	0.5-0.25	<.25
	- slope (%)	<1	1-2	2-4	>4
7 Nutrient Retention	- Texture or CEC of sub-surface horizon	SCL-C	SL	-	LS,S
8 Alaklinity Salinity	Exch. Sod Perc. (ESP)	<5	5-15	-	>15
	Electrical conductivity (ms/m)	<2	2-4	4-8	>8

<u>Table 6</u>

LAND CHARACTERISTIC VALUES OF THREE SELECTED SOIL UNITS OF SELEBI-PHIKER AREA

Land charcterisitic	Eutric/Cambic Arenosol A22	Luvic Xerosol A36	Calcic Luvic Xerosol A37
1 Average soil depth	>150	>100	>75
2 Stones and gravel% surface 0-25cms sub-surface 25-100cms	None None	None None	None None
3 Average bulk density gm/cc	1.5-1.55	1.55-1.65	1.55-1.65
4 Drainage	Excessive	Well drained	Mod well-Imp.
5 Aeration at field capacity	33%	14.5%	14.5%
6 Flooding Risk or less	Nil	Nil	Slight
7 Available water mm/m	55	155	155
8 Infiltration (basic) cm/h	40-50	5-10	5-10
9 Frequency of irrigation at ET = 6mm/day-days	4.5	13	13
10 Ground water depth (cms)	>150	>150	>150
11 Structural stability Index	0.64	0.39	0.39
12 Slope of land %	0-1	0-1	0-1
13 Texture Surface 0-25cms sub-surface 0-100cms or heavier	S-LS S-LS	S,LS/SCL SCL or heavier	S,LS/SCL SCL
14 Alkalinity pH ESP	<8.5 <5	<8.5 <5	<8.5 <5
15 Salinity EC ms/m	<2	<2	<2

Table 7

SUITABILITY RATING FOR INDIVIDUAL LAND CHARACTERISTICS AND CUMULATIVE RATING FOR CLASS DETERMINING FACTORS – SPRINKLER IRRIGATION MAIZE/VEGETABLE SELEBI-PHIKWE

Class determining factor and relevant land characteristics	Suitability Class rating					
	Eutric/Cambic Arenosol A22		Luvic Xerosols A36		Calcic Luvic A37	
	Ind	Cum	Ind	Cum	Ind	Cum
Rooting						
– effective soil depth	S1		S1			S1
– stones & gravel surface	S1	S1	S1			
stones & gravel sub surface	S1		S1		S1	
– Bulk density	S1		S1		S1	
Aeration						
– Drainage	S1		S1		S1	
– Aeration at field capacity	S1	S1	S1	S1	S1	S1
– Flood Risk	S1		S1		S1	
Water quantity						
– Available water capacity	S3	S3	S1	S1	S1	S1
Water management						
– Infiltration	S1	N	S1		S1	
– Frequency of irrigation	N		S2	S1	S2	S1
Drainage						
– groundwater depth	S1	S1	S1	S1	S1	S1
Erosion hazard						
– structural stability	S2	S1	S2	S1	S2	
– slope	S1		S1		S1	S1
Nutrient retention						
– Texture	N	N	S1	S1	S1	S1
Salinity & Alkalinity						
– pH / ESP	S1	S1	S1	S1	S1	S1
– electrical conductivity	S1		S1		S1	

Figure 1 - INFILTRATION HUMIC XEROSOLS - A37 (SP 141)

KEY

I_1
I_3 Replicate measurements
I_6

I_2 Same as I_1, but surface 20 cms of soil removed

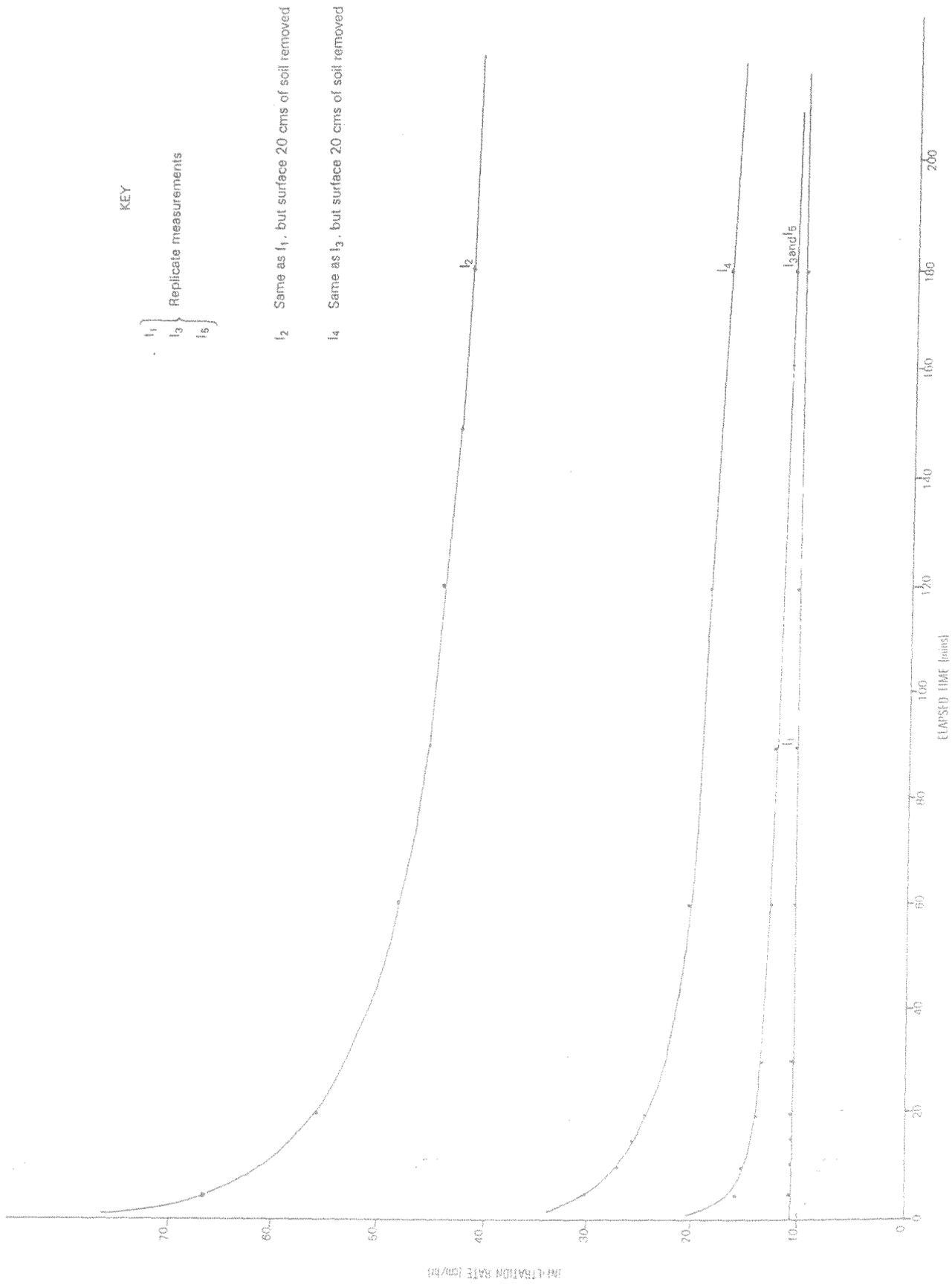I_4 Same as I_3, but surface 20 cms of soil removed
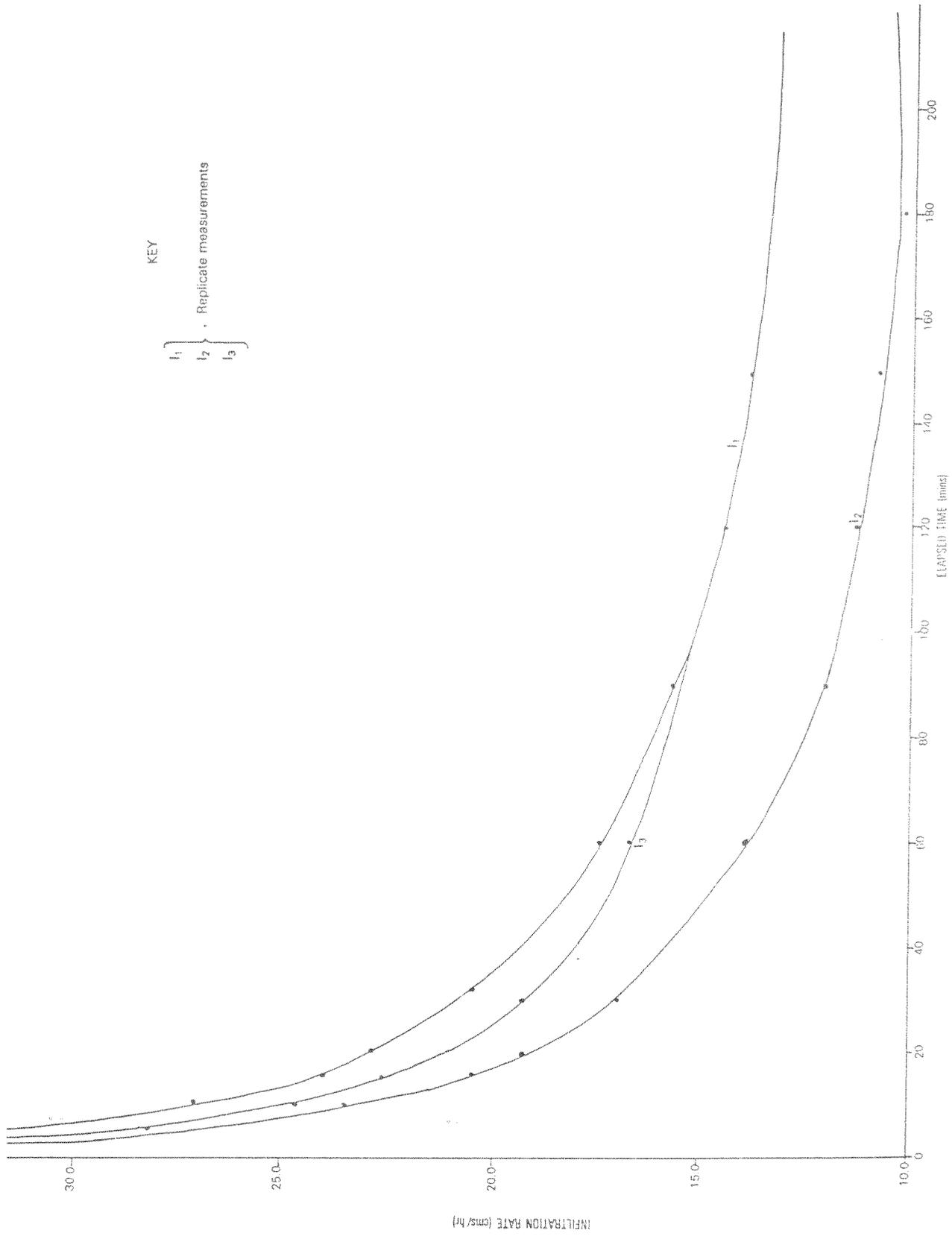
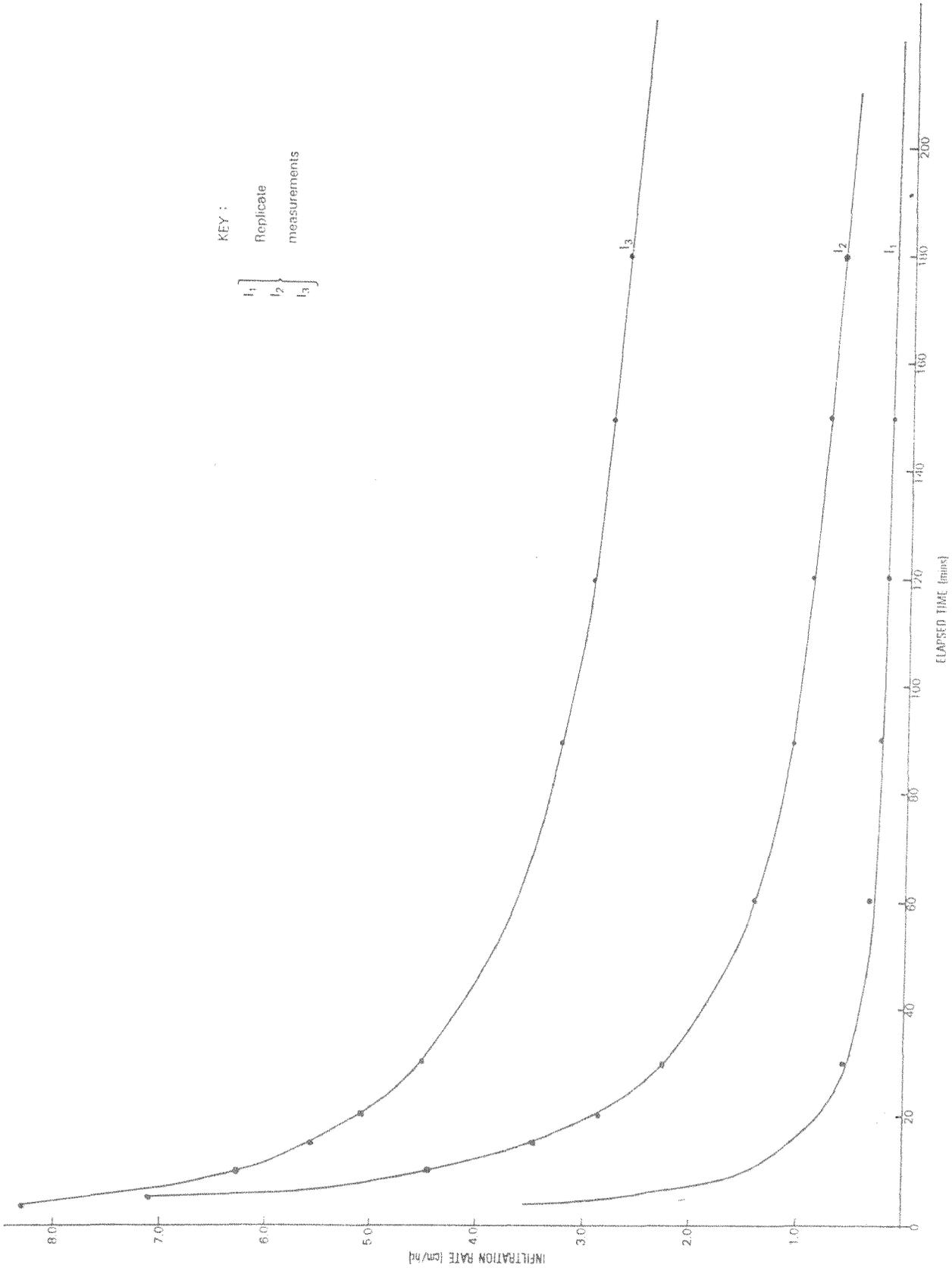Figure 2 – INFILTRATION : LUVIC XEROSOLS – G1/a SP 1/2)
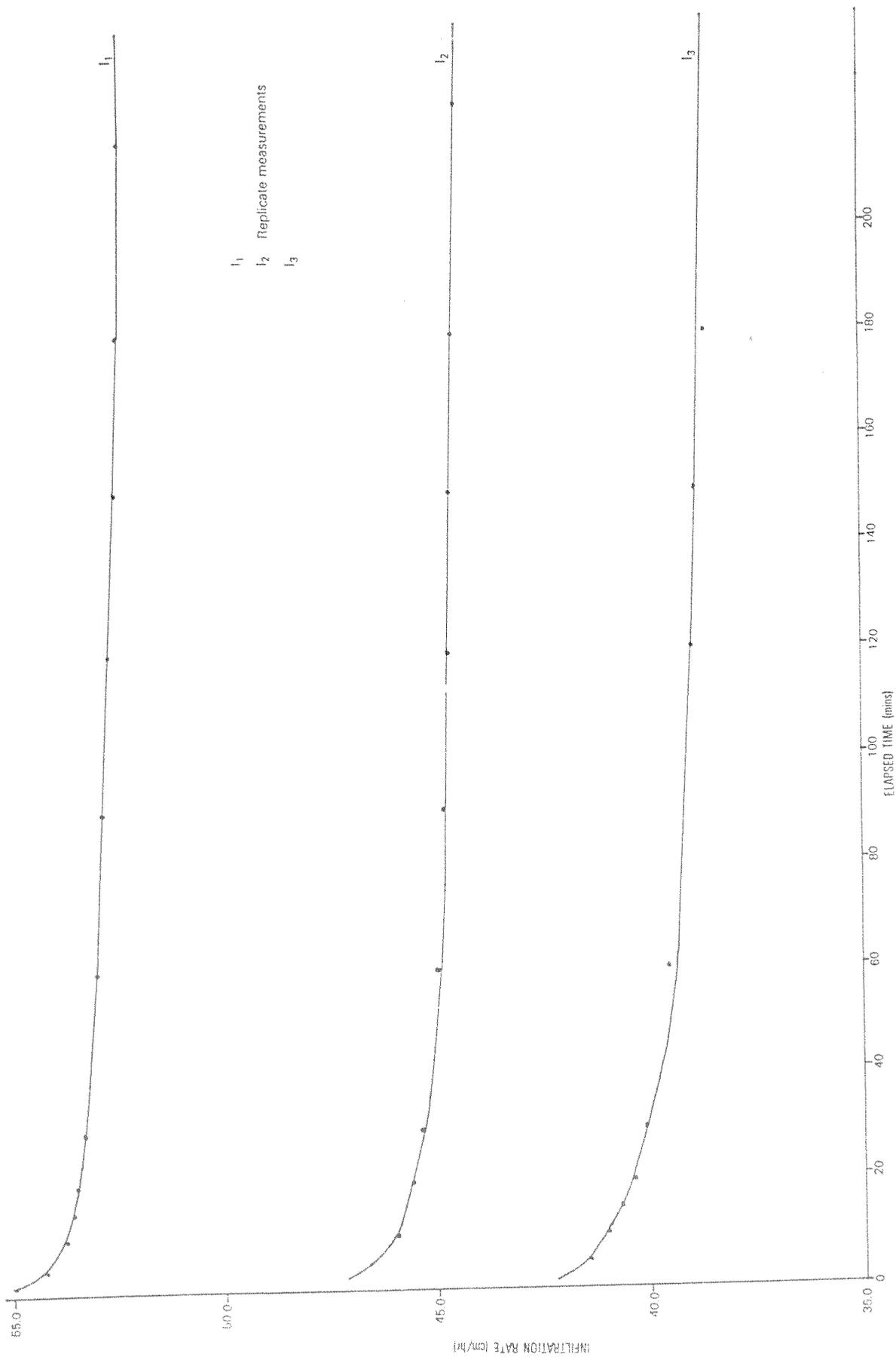
ANNEX 3

Figure 3 - INFILTRATION ORTHIC SOLONETZ - A5b (SP 143)

Figure 4 - INFILTRATION CAMBIC ARENOSOLS - A22a (SP 144)

ANNEX 4

Soil Mapping And Advisory Services

Botswana

PHYSICAL PROPERTIES OF FERRIC LUVISOLS - OTSE

Food and Agricultural Organization Of The United Nations
United Nations Development Programme

Gaborone, November 1988

Introduction

The physical properties of Ferric Luvisol of Otse was determined under the regular programme of the Soil Mapping and Advisory Services Project of the FAO. The soil profile had been earlier described, analysed for chemical properties and classified. The physical properties measured were infiltration, bulk density, complete moisture characteristic curve and the structural stability of the surface soil.

Methods

(a) Infiltration : Double ring infiltration method were used in six replicates. At sites where surface sealing was evident, two of the replicate measurements were made after removing the surface crusts.

(b) Bulk density: Core sampling method was used with core samples of 100 cc capacity. Five replicate measurements were made for each horizon.

(c) Moisture retention: Moisture content at 0.03, 0.05, 0.1, 0.3, 1.0 bar suctions were determined on undisturbed core samples in duplicates. Moisture contents at 3.0, 5.0 and 15 bar suctions were determined on soil samples passing through 2mm sieve. Sand table was used for 0.03 and 0.05 bar suction and pressure plate apparatus was used for the higher suctions. When duplicate values differed by more than 2 percent moisture, measurements were repeated till consistent values were obtained.

(d) Structural stability: Structural stability index was determined by measuring the relative degree of collapse of aggregates of sizes between 1 and 2mm on slow and fast wetting. Structural stability index of 1 represents completely stable soil and index of 0 represent total instability and collapse of structural units. Intermediate values represent the relative stability between these two extremes.

Results and discussions

Table 1 gives all the measured physical properties of the soil. Moisture retention values are mean of duplicates, the bulk density is the mean of 5 replicates and the structural stabiliy index is the mean of two measurements.

(a) Infiltration : It is assumed that the equation $F = at^n$ adequately represents the infiltration characteristics of the soil. In this equation, F is the cumulative infiltration in cms, t is the elapsed time in mins., and a, n are constants which are characteristics of the soil. Log F was plotted against Log t and a straight line was fitted through the points (Figure 1). The intercept and slope gives the 'a' and 'n' values respectively (Table 1).

The infiltration rates are excessive to high. There is no apparent difference in the infiltration characteristics between the normal sites and the ones from which surface crusts have been removed. This may be due to the fact that the surface crusts disintergrated when the infiltration cylinders were driven into the soil. Although the soil is of medium texture, the infiltration rates are high due to the predominance of freely draining macro pores as indicated in the moisture retention curves.

(b)   Bulk denisty: The bulk densities are moderate, varying from 1.5gms/cc in the surface horizon to 1.64gms/cc in subsurface horizons. Total porosity of these soils are in the order of 38 - 43 percent of which nearly half are freely draining macropores.

(c)   Moisture retention: Figure 2 shows the moisture retention curves (pF curves) of the three horizons. It is seen that for all three horizons, there is a sharp decrease in moisture content from saturation to 0.1 bar indicating the presence of substantial amount of freely draining large pores.   These pores contribute to high infiltration rates.   Above 0.1 bar the moisture retention curves are parallel and steep indicating that all three horizons have relatively low available moisture and are of the same order of magnitude. The actual amount of available moisture for each horizon is given in Table 1.

(d)   Structural stability: The average structural stability index of the surface soil is 0.40. The soils therefore are structurally unstable and tend to slake on wetting. Surface soil crust formation was found to be common in the area thus confirming the poor structural stability of the soil.

Table 1. PHYSICAL CHARACTERISTICS OF FERRIC LIXISOL OF OTSE AREA

(a) Moisture retention and Bulk density

Horizon depth	Moisture content g/g								Bulk density	Available moisture
cms	0.03 bar	0.05 bar	0.1 bar	0.3 bar	1.0 bar	3.0 bar	5.0 bar	15.0 bar	g/cc	mm/m
0-24	0.1280	0.1040	0.0862	0.0797	0.0645	0.0531	0.0516	0.0420	1.50	66
24-80	0.1344	0.1301	0.1167	0.1113	0.0976	0.0841	0.0819	0.0685	1.64	79
80-107+	0.1685	0.1496	0.1453	0.1282	0.1250	0.1018	0.1019	0.0870	1.62	94

ANNEX 4

(b) Infiltration

Replicate No	Initial Infiltration cm/hr	Basic Infiltration cm/hr	'a' Value	'n' Value
1*	25.2	17.0	0.42	0.92
2	43.8	15.5	0.73	0.82
3	63.6	20.9	1.06	0.81
4*	39.0	24.8	0.65	0.91
5	34.2	15.8	0.57	0.86
6	31.2	13.5	0.52	0.85

'a' and 'n' are constants in the equation $F=at^n$ where F is the cumulative infiltration in cms and t is the time in minutes.

* Results of infiltration measurements done after removing surface soil crusts.

Structural stability
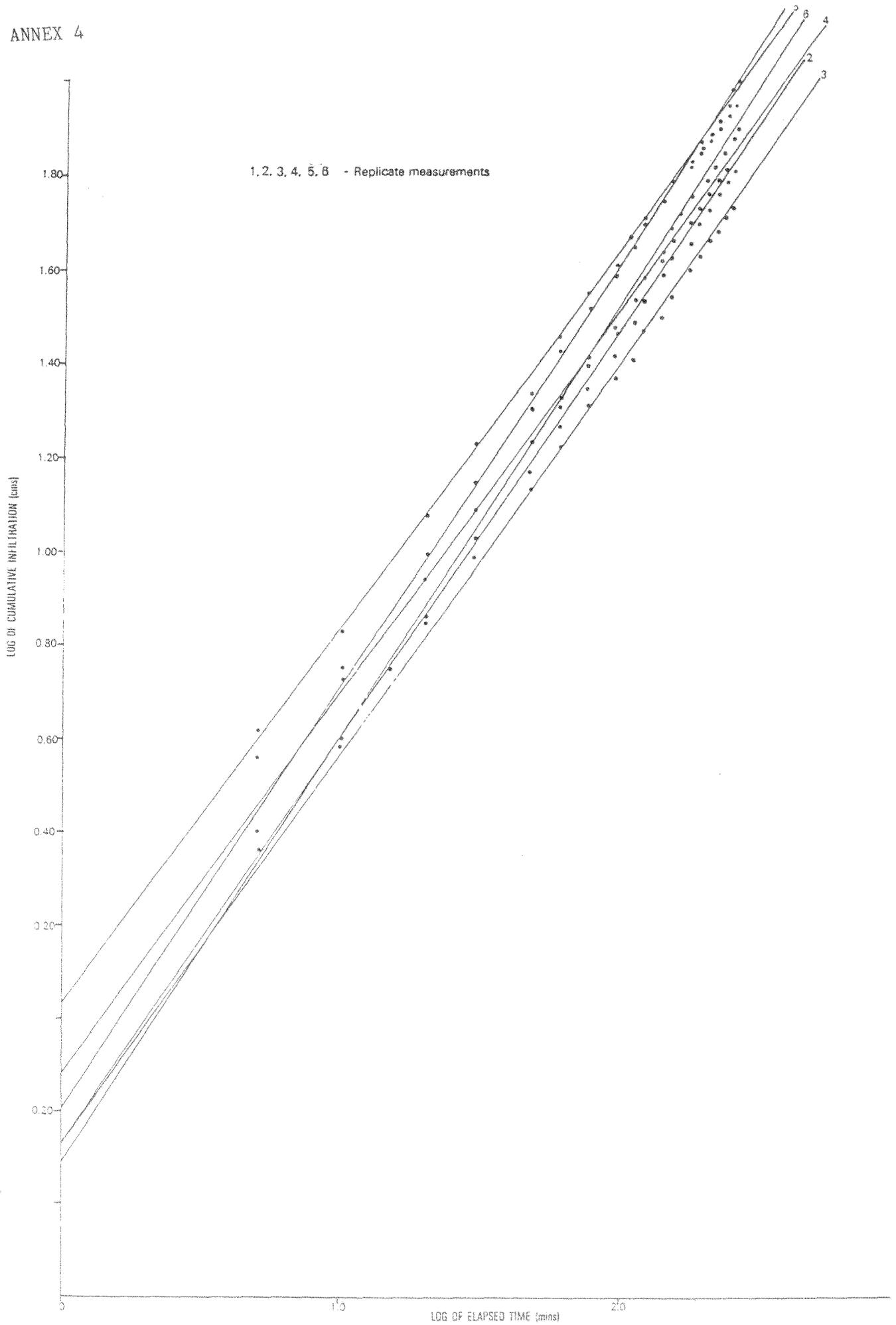
Structural stability index = 0.40
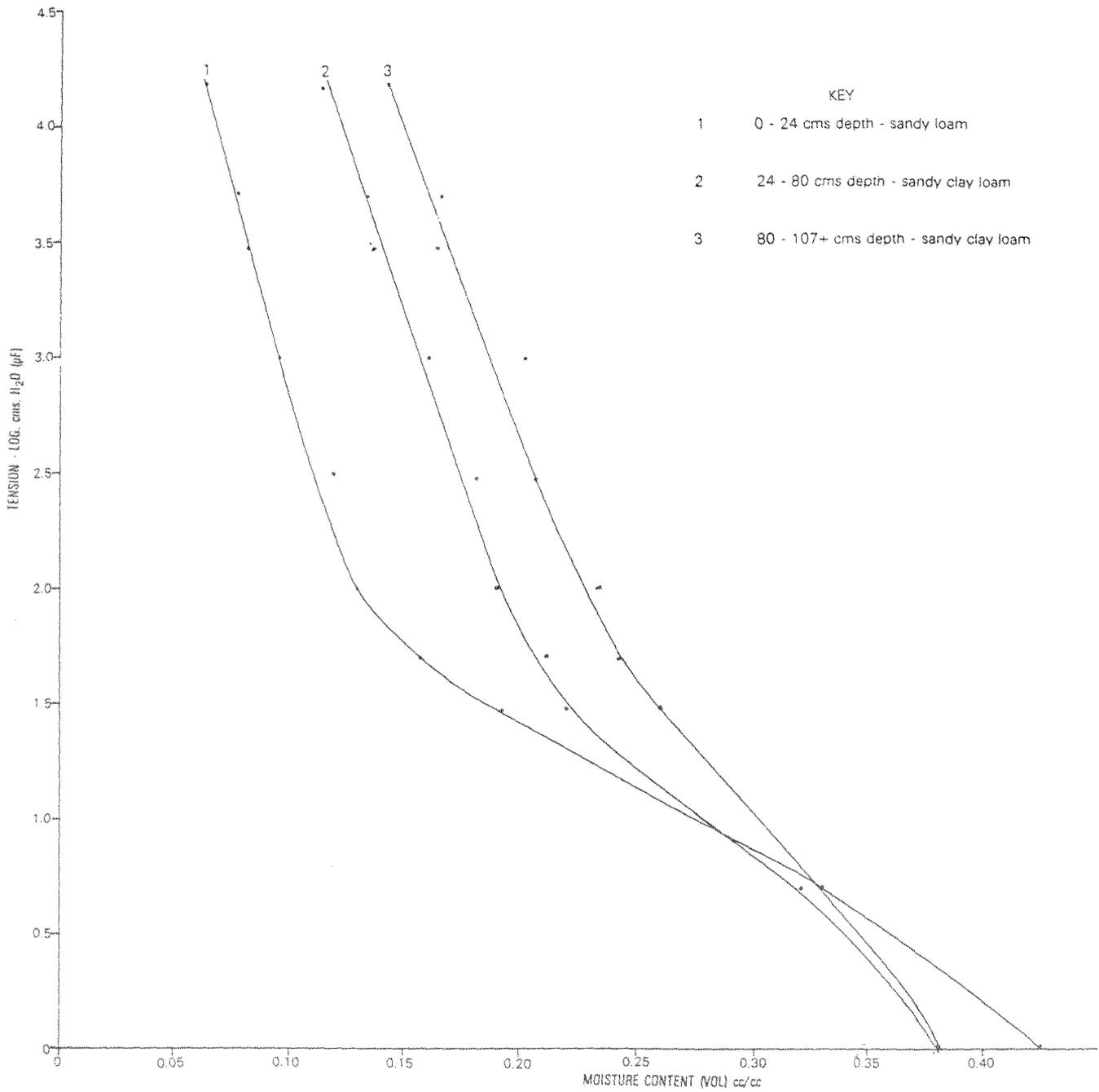
Figure 1 INFILTRATION - OTSE

Figure 2 - MOISTURE RETENTION CURVES (pF)   OTSE - FERRIC LIXISOLS