DETERMINATION OF THE CAUSES OF SECONDARY SALINIZATION IN KIBWEZI

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A Thesis submitted to the Faculty of Agriculture in Partial Fulfilment of the Requirements for the Degree of Master of Science in Soil Science

UNIVERSITY OF NAIROBI

1996

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

This thesis is dedicated to my loving parents, husband and children.

ACKNOWLEDGEMENTS

I am grately indebted to my supervisor Mr S. M. Kinyali who has readily provided me with guidance and encouragement throughout the research and writing of this thesis.

My sincere thanks go to all the laboratory staff of the Soil Science Department especially Messrs I. Ndari, D. Ndambuki, S. K. Tirop and A. Gichobi, for their assistance in the field and/or in the laboratory.

My deepest gratitude goes to the University of Nairobi through the chairman of the Department of Soil Science, Professor J. P. Mbuvi, through whom I obtained my sponsorship from the Swedish Agency for Research with Developing Countries (SAREC). You always gave me financial support at my time of need.

Special thanks go to my husband, Eliazer, and children, for bearing with my busy schedules especially at times when they needed me most.

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ABBREVIATIONS

cm	Centimetre
C	Clay
cm^3	Cubic centimetre
Ed(s)	Editor(s)
exp.	Exponential function
FAO	Food Agricultural Organisation
g	Grams
Hor	Horizon
hr	Hour
km	Kilometre
kPa	KiloPascals
LS	Loamy sand
M	Molar
me/l	Milliequivalents per litre
mg/l	Milligrams per litre
ml	Millilitre
mm	Millimetre
mS/m	Millisiemens per centimetre
No.	Number
ppm	Parts per million
Prof.	Profile
r	Simple linear regression coefficient
SC	Sandy clay
SCL	Sandy clay loam
SL	Sandy loam
SOC	Soil Organic Carbon
TARDA	Tana and Athi Rivers Development Authority
Tr	Trace
Trt	Treatment
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational Scientific and Cultural Organisation

USDA	United States Department of Agriculture
wt	Weight
Δ	Change in
ρ (rho)	Density
μm	Micrometres
* (in equations)	Multiplication sign

ABSTRACT

Following increased rates of population growth, more and more marginal land has been opened up to meet the ever increasing food demand. Crop production in the arid and semi arid lands suffers from inssuficient rainfall. Irrigation is practised where possible to suppliment rainfall in meeting crop water requirement. Irrigation has however been known to responsible for the degradation of some marginal lands. A piece of land owned by the Tana and Athi Rivers Development Authority (TARDA) has been abandoned due to secondary salinization. In a bid to find out the causes of this secondary salinization, four existing land uses were randomly selected to represent treatments on Kibwezi Lixisols. The treatments were i) abandoned salinized field (Trt 1), ii) irrigated cropland (Trt 2), iii) virgin natural savanna (Trt 3) and iv) non-irrigated cropland (Trt 4). The first objective of the study was to find out if irrigation water or groundwater qualities resulted in secondary salinization while the second aimed at determining the influence of secondary salinization on physical and chemical characteristics of the soil. Costat was used for the analyses of variance and Duncan's Multiple Range Test for the separation of means.

It has been observed in the past that some physical and/or chemical properties of the soil increase with depth on irrigated lands but not so on non-irrigated ones. Based on these observations analyses of results obtained from the first and the third horizons were performed. The second horizons had intermediate values between the two.

The irrigation water had moderate to medium salinity having an electrical conductivity, EC, of 0.94 mS/cm. Its sodium level was low with an adjusted sodium adsorption ratio, SARadj, of 6.72. The soluble sodium percentage, SSP, was as high as 57. The pH was moderately alkaline with bicarbonates and chloride levels at 5.0 and 9.0 me/l respectively. The ratio of Mg:Ca was 4:1.

This water caused sodicity rather than salinity conditions to the soil. The EC of the soil extract was found to be <4 mS/cm and the ESP <15 in the first horizons for all treatments. However the ESP was as high as 59 for Trt 1 in the third horizons although the EC remained <4 mS/cm. There was no significant difference at P=<0.05 in EC for all treatments and horizons but the ESP was significantly different in the third horizons. The cation exchange capacity, CEC, was <24 Cmol/kg and the base saturation percentage >50 for all horizons and treatments. Soil organic carbon, SOC, was very low (<1%) for all horizons and treatments. The texture was insignificantly different at P=<0.05 for all horizons and treatments. It was mainly sandy with percentage sand >60.

The basic infiltration rate was significantly different at P=<0.05 for all treatments in the third horizons. It was highest in Trt 3 and lowest in Trt 1. The saturated hydraulic conductivity, Ksat, was insignificantly different for all treatments in the first horizons and insignificantly different for all treatments in the third horizons except Trt 1 which exhibited the lowest Ksat at the same level of significance. Water content values were very low all being <30%. Soil water retention was higher in irrigated fields than on non-irrigated ones for all treatments and horizons.

The cause of the secondary salinization in lixisols of Kibwezi area was attributed to the high Mg:Ca ratio of the irrigation water which led to greater adsorption of sodium on the soil exchange sites.

CHAPTER ONE

1.0. INTRODUCTION

It has been documented that the world population continues to increase and this is mainly contributed by the third world countries of which Kenya is a part. FAO (1981) has reported that the population increase in the third world countries will account for about 95% of the estimated total world population increase in the year 2110 when the population is estimated to stabilize. This population increase will be accompanied by a similar increase in food demand resulting in high pressures on agricultural and marginal lands. Unless radical changes in food production are employed, the prospects for meeting the food demand are bleak.

Soil degradation is a major problem affecting world food production . Soil degradation can be caused by salinization, erosion, waterlogging, depletion of plant nutrients and deterioration in structure. It is estimated that 5-7 million hectares corresponding to 0.3 - 0.5% of the total global cultivated land is lost through degradation every year (FAO/UNEP, 1983)

Much of Kenya's land is too dry to support rainfed agriculture. In the Central Bureau of Statistics of 1984, it is documented that only 12% of the Kenya's 57 million hectares of land is classified as being high potential.

The rate of population growth per annum in Kenya is one of the highest in the world. It increased from 3.1% (1962-1969) to 3.8% (1969-1979) and is estimated to increase to a rate of 4.1% in the year 2000 (Government of Kenya, 1986). This population growth has resulted in increased population pressure on the land. To counter the resultant high food demand, intensification of the land already in use can account for up to 66% while the remaining portion will have to come from expanding to new land areas. This expanding in agricultural land will have to come from marginal land as most of the high potential areas have been occupied (Were, 1980). The irrigation of the marginal areas of Kibwezi such as the TARDA Pilot Irrigation Project are practical examples of the expansion of agricultural land in Kenya.

Extensive areas of marginal land under irrigation have, however, gone out of cultivation due to secondary salinization. Secondary salinization is the gradual accumulation of salt in the soil profile over a period of time to such an extent that its levels become harmful to the normal growth of crops. An accumulation of salts in the soil leads to unfavourable salt-water-air relationships and decreases crop production (Michael, 1978). Salinity conditions reduce the value and productivity of considerable areas of land in the world. The problem is an old one dating back to the River Nile civilization (Richards, 1954). Land then was not limiting and a problem-soil was abandoned and new areas opened up. Today, however, land is a limiting factor to agricultural production and care must be taken in its usage.

The problems of soil salinity are not restricted to any specific region of the world. However, in the arid and semi-arid regions the problem is much more acute and widespread. This is because the rainfall received is not sufficient to transport salts from the root zone (Thorne and Peterson, 1954). More interest has therefore been centred around it here and more effort directed to its solution. More than 80% of Kenya's land area is semi arid to very arid (Government of Kenya, 1986). Yet about 10,031,200 hactares of the total land area are salt affected. These are in the districts of Marsabit (Chalbi Desert), Tana River, Garissa, Wajir, Mandera, Turkana, Taita-Taveta, Kajiado (Amboseli area) and Baringo (Muchena, 1985). It will be noted from any map of Kenya that all these districts are in the arid regions of the country.

It is estimated that one third of 12 million hectares of irrigated land in the arid and semi-arid parts of the world is affected by secondary salinization (Reeve and Fireman, 1967). The salt problem has recently encroached to a majority of irrigation schemes in Kenya and Tanzania causing their abandonment. Notable examples as given by Kinyali (1976) are the Naivasha vegetable farm, Mwea rice station and TPC farm in Tanzania. Every soil contains a certain amount of soluble salts. However, not every soil is considered saline. It is only when soluble salt accumulation in the soil reaches a level harmful to plant growth that a salinity condition is said to have developed (Yaron *et al*, 1973). However, a soil saline to one type of crop might be quite suitable to another.

Control of the salinity regime in the root zone is one of the main problems of irrigation in arid and semi-arid areas. Development of irrigation in arid and semi-arid lands requires permanent control of salinity in soils and in irrigation water since the development of soil salinity is a challenge to the permanence of irrigated agriculture. (Yaron *et al*, 1973) gives the principle difference between irrigated and non-irrigated agriculture, when considered in relation to persistence and permanence, as arising from soil salinization.

Water requirement in an irrigation system must take into consideration not only the water consumption of the irrigated crops but also the quantity of water necessary to remove the salts from the root zone. The quantity is known as the leaching requirement.

All irrigation waters contain certain amounts of soluble salts. It is therefore a matter of time until a salinity problem arises from an otherwise good quality irrigation water unless measures are taken in good time to prevent it. Irrigation is a very expensive enterprise and care must be taken in its planning and implementation. Such planning and implementation must take into consideration the chemical and physical properties of the irrigated soils so that the soils may be productive both in the present and in the future.

The aim of the study, though geared towards the causes of secondary salinization will serve as a basis upon which recommendations on the possible solutions to secondary salinization can be made.

1.1 Hypotheses

1. Secondary salinization results from irrigation and its related management practices.
2. Secondary salinization has an effect on physical and chemical properties of the soil.

1.2 Objectives

1. To find out the effects of irrigation water and groundwater qualities on secondary salinization.
2. To determine the influence of secondary salinization on physical and chemical properties of the soil.

1.3 Justification of the study

Irrigation is a very expensive enterprise and once implemented should be maintained lest it comes to an abrupt halt, causing a lot of loss not only to the community in terms of soil degradation, but also to the nation due to loss of large sums of money including foreign exchange. Secondary salinization is one unforeseen reason that could bring an otherwise flourishing irrigated agriculture into such an abrupt halt within a few years.

Some irrigation farms in Makindu and Kiboko areas of Makueni District have already been abandoned due to secondary salinization (Tonui, 1992). The problem is now seen to occur in Kibwezi area of the same district particularly in TARDA Pilot Irrigation Project and Kibwezi University Dryland Field Station. The adjacent non-irrigated lands are fully operational with no signs of salinization although they have been under cultivation for a longer period. These large irrigarion farms have acted as demonstration fields for the local farmers and some farmers have adopted the irrifation technology while others are aspiring to do so in future. These farmers are going to benefit from the results and recommendations given from this study.

The two main factors that contribute to the accumulation of salts are the quality and quantity of irrigation water and soil properties. The TARDA Pilot Irrigation Project uses the Kibwezi River water for irrigation. The quantity used is in excess of the amount required to meet the crop water requirement. The quality of the irrigation water was found to be suitable for irrigation as is documented in the proposal report for the establishment of the University Irrigation Project. The electrical conductivity of irrigation water, ECiw, is given as 0.65 mS/cm. The soils are mainly chromic Luvisols which are well drained. The rate of infiltration is documented as being moderate to moderately rapid (20-40 mm/hr). The electrical conductivity of the soil extract, ECe, is given as 0.3-0.5 mS/cm (Faculty of Agriculture, 1990). This suggests no primary salinity.

From a soil survey and water quality assessment done prior to the irrigation, the soils and the water used for irrigation did not suggest any possibility of the occurrence of secondary salinization. It is of extreme importance therefore that its causes and possible preventive measures be identified in order to save these vast irrigated lands from turning saline and subsequently unproductive in the near future. It should be remembered that a stitch in time saves nine and that it is better late than never.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Causes of Salinity

FAO (1970) reports that the most important factors causing salinity are the aridity of the climate, geomorphology, hydrology of the terrain, physicochemical properties of the soil and soil and water management practices. Arid climate causes a high evapotranspiration that exceeds effective precipitation. Water evaporates in pure state leaving salts and other substances behind. The salts are mainly chlorides, sulphates, bicarbonates and carbonate (and sometimes nitrates) of sodium, calcium and magnesium. Potassium is the rarest of all. Heavily salinized soils may show efflorescence or complete salt crusts.

Irrigation water quality is of utmost importance in any irrigation project. Saline water used for irrigation will cause saline soils. Although irrigation has been practised in the world for several millennia it is only in this century that the importance of the quality has been recognized. River water dissolves soluble salts contained in parent materials or sediments. The salt content of the surface water is a function of the weathering of rocks prevalent at the source, of the climatic zone and of the nature of the soil over which the water must flow (Yaron *et al.*, 1973). Paliwal (1972) has outlined factors governing weatherability of rocks while Rao (1967) observed that granites, gneisse and porphyry rocks are least affected by weathering. Although salts dissolve slowly from most soil minerals, several tonnes per hectare can be dissolved in a year.

As the river water used for irrigation evaporates, the salt concentration in the remaining soil solution may be 4-10 times that in the irrigation water within 3-7 days after irrigation. This salt remains in the soil and accumulates unless it is leached away by water applied in excess of crop requirements.

Each irrigation adds some salt to the soil. How much is added depends upon the amount of water entering the soil and the salt concentration in the water. Ayers and Westcot (1976) and Rhodes (1977) have suggested electrical conductivity values for irrigation water which are needed to prevent the deleterious effect of sodium. From these publications, waters with salinity below 0.2 mS/cm cause severe permeability problems.

As the demand for irrigation water increases, the tendency to develop groundwater increases. This results in using more medium and highly saline groundwaters, and thus intensifying the salinity problem (Carter, 1975). A considerable capillary transport of groundwater to the surface only occurs when water tables are high for prolonged periods of time. Verhoeven (1979) showed that the rate of water transport to the soil surface depends on the depth of the groundwater table.

Irrigating one area may cause salt problems in another. Salts may be transported from one cropped area with adequate drainage to another with inadequate drainage where it accumulates.

The importance of a good combination of irrigation and drainage cannot be overstressed. Irrigated lands, even in arid regions, frequently require drainage (Hillel, 1980b). In the past, many irrigated areas have suffered from soil salinity due to improper management of irrigation and drainage (Fukuda, 1976).

Drainage water that has passed through the soil has a higher salt concentration than the irrigation water (Wilcox and Resch, 1963; Carter *et al.*, 1971). Most of this drainage water returns to the natural stream or river channel, downstream from the point where the irrigation water is diverted. As a result, the salt concentration in rivers and streams in arid and semi-arid regions generally increases from the headwaters to the mouth. This in itself, creates a salinity problem for agriculture because the salt concentration in the stream can become so high that the water may be unsuitable for irrigation. In summary, salinity problems in agriculture arise from many sources, both natural and man-made.

2.2 Salt Affected Soils and their Management

Richards (1954) has defined salt affected soils as those which contain excessive concentrations of soluble salts and/or exchangeable sodium. Soluble salts produce harmful effects on plants by increasing both the salt content of the soil solution (thereby causing toxicity and reducing the water availability through the action of osmotic pressure) and the degree of saturation of the exchange complex of the soil with exchangeable sodium. This causes the destruction of the soil structure.

Before any solution for a problem can be obtained it must first be correctly identified. Richards (1954) classified salt affected soils into three categories.

2.2.1 Saline Soils

These are soils which have an electrical conductivity (EC) of the saturation extract greater than 4 mS/cm and an exchangeable sodium percentage (ESP) less than 15 (Richards, 1954). Owing to the presence of excess salts and the absence of significant amounts of exchangeable sodium, saline soils generally are flocculated and consequently water infiltration and permeability are equal or higher than those of similar non-saline soils (Shainberg, 1975). The amount of salt in a soil above which plant growth is affected depends upon the species of the plant, the texture and water capacity of the soil and the composition of the salt. Thus, the critical concentration of the salt in the soil for distinguishing saline from non-saline soils is arbitrary. Upon leaching such a soil with excess water, the salts are removed and a non-saline soil is obtained without the need to add amendments. However, application of excess water in all types of soils may not necessarily remove excess salts. This very much depends on the permeability of the soil and the nature of the salts present.

2.2.2 Non-Saline Sodic Soils

These soils have an ESP that is greater than 15 and an electrical conductivity of the saturation extract less than 4 mS/cm (Richards, 1954). These soils contain exchangeable sodium in quantities sufficient to interfere with the growth of most crop plants. They also do not contain appreciable quantities of soluble salts. The exchangeable sodium present has a marked influence on the physical and chemical properties of the soil particularly in the dispersion of clay particles which block the pores through which the water flows. This diminishes the hydraulic conductivity of the soil and causes poor aeration. Lewis and Juve (1955) have pointed out that alkalinity is a secondary effect of the removal of excess soluble salts leaving the soil colloids saturated with respect to sodium ions. The pH of these soils usually ranges between 8.5 and 10.0 due to hydrolysis of adsorbed sodium in the absence of electrolytes in the soil solution. Such soils require amendments, in particular calcium salts such as gypsum.

2.2.3 Saline-Sodic Soils

These are soils for which the electrical conductivity of the saturation extract is greater than 4 mS/cm and the ESP greater than 15. As long as the concentration of salt in the solution is high, the properties of these soils are similar to those of saline soils. Kamil and Shainberg (1968) found out that in the presence of excess salt, adsorbed sodium does not hydrolyse and therefore the pH of these soils is usually less than 8.5. As the concentration of the salts in the soil solution is lowered, e.g. due to leaching, the properties of these soils may change markedly and become similar to those of sodic soils. Thus leaching of the excess salts from these soils of the excess salts, amendments such as gypsum must be added to the water.

From the description of salt affected soils, it is evident that the type of exchangeable ion and the concentration of the soil solution have very marked effects on the physical and chemical properties of the soils. These two factors affect the macroscopic properties of the soils through their effect on the electrical phenomena at the soil water interface.

The degree of soil salinization often exhibits strong spatial and temporal variation: the salt content is not a stable, permanent soil property (Driessen, 1970). Temporal variations are related to seasonal or annual variation in rainfall and to variations in solubility due to differences in temperature. Spatial variation can be caused by topographic, hydrologic and soil factors e.g. variations in groundwater depth, capillary rise, run-off or run-on.

2.3 Leaching Requirements

Michael (1978) defines leaching as the process of dissolving and transporting soluble salts by downward movement of water through the soil. Leaching is the most common method by which salt is removed out of the root zone with water.

The average salt concentration of the root zone does not change appreciably if the product of the volume of irrigation water, Di, and its salt concentration, ECi, is equal to the product of the volume of water draining out of the soil, Dd, and the salt concentration of this drainage water, ECd. An equation for this is given below:

$$DiECi - DdECd = 0 \ldots\ldots\ldots (2.1)$$

The above equation can be rewritten as:

$$DiECi = DdEcd \ldots\ldots (2.2)$$

The concept of leaching requirement (LR) is now naturally derived from equation (2.2) as given in equation (2.3).

$$LR = \frac{Dd}{Di} = \frac{ECi}{ECd} \ldots (2.3)$$

Where LR = leaching requirement
Dd = depth of drainage water
Di = depth of irrigation water
ECi = electrical conductivity of irrigation water
ECd = electrical conductivity of drainage water.

It is evident from equation (2.3) that as the salinity of the irrigation water increases, so does the leaching requirement, implying that a higher percentage of irrigation water must be drained in order to prevent salinization of the soil.

Leaching requirement is defined by Michael (1978) as the fraction of irrigation water that must be leached through the root zone to keep the salinity of the soil below a specific limit. Richards (1954); Wilcox and Resch (1963); and Thorne and Peterson (1954) have defined it as the excess water applied periodically to leach salts from the root zone. Leaching of soluble salts from the root zone is essential in irrigated soils since it counteracts the possibility of salt build up. Without leaching, salts accumulate in direct proportion to the salt content of the irrigation water and the depth of water applied. The depth of irrigation water per unit depth of soil required to produce any specific increase in soil salinity for any given conductivity of irrigation water can be calculated from the following equation.

$$\frac{Di}{Ds} = \frac{\rho b}{\rho w} * \frac{SP}{100} * \frac{\Delta ECe}{ECi} \;.....(2.4)$$

Where Di = depth of irrigation water

SP = saturation percentage of the soil

ρb = bulk density of soil

ρw = density of irrigation water

Ds = depth of soil

ECe = increase in EC of the soil extract

ECw = electrical conductivity of irrigation water.

Under high water table conditions, the increase in soil salinity by the evaporation of ground water can be determined by the following formula.

$$\Delta ECe = \frac{Dg}{Ds} * \frac{ECg}{Sp} * \frac{\rho w}{\rho b} * 100 \;....(2.5)$$

Where Dg = depth of groundwater evaporated

ECg = electrical conductivity of groundwater

All other terms are as defined before.

Good crop yields are dependent on the maintenance of the salt concentration of the soil solution in the root zone at or below certain levels. The levels required for many crops have been determined and published by Richards (1954) in terms of the electrical conductivity of saturation extracts (which is about twice that of a soil solution at field capacity) and by Bernstein (1964).

2.4 Salt Balance

In an irrigated area, a favourable salt balance must be maintained if irrigated agriculture is to be permanent. Salt balance is defined as a condition where the output of salts equals or exceeds the input. The salt balance for any given land area or soils unit can be expressed by the following equation as given by Hillel (1980a).

$$SP + Si + Sr + Sd + Sf = Sdw + Sc + Sppt \quad .....(2.6)$$

Where SP = salt in natural precipitation

Si = salt in irrigation water

Sr = residual salts in the soil

Sd = salt dissolved from soil minerals

Sf = salt in applied fertilizers

Sdw = salt in drainage water

Sc = salt taken up by crops

Sppt = salt chemically precipitated in the soil.

The salt balance is determined by accounting for all the processes that contribute to inflow and outflow changes of salt in the profile. By maintaining a salt balance in the root zone, one can ascertain, whether that salt concentration is increasing or decreasing.

The salt balance concept can be expressed mathematically in the simple conservation of mass equation given below.

$$DiECi + Sd - Dd\,ECd - SP - Sc = 0 \;......(2.7)$$

Where Dd and Di are the volume per unit of area of equivalent depths of drainage and irrigation waters respectively ECi and ECd are the electrical conductivity values for irrigation and drainage waters respectively. The other terms are as defined in the salt balance equation (2.6). Often Sd, Sp and Sc are considered negligible and equation (2.7) reduces to:

$$DiECi - Dd\,ECd = 0 \;...(2.8)$$

This equation can be written as follows.

$$\frac{Db}{Di} = \frac{ECi}{ECd} \;....(2.9)$$

All terms are as defined before.

Maintenance of a favourable salt balance in the soil requires water management practices. The salt balance in soil is influenced by the quantity and quality of irrigation water and the effectiveness of leaching and drainage. Maintaining a salt balance would maximize chemical precipitation of harmless salts; a minimum quantity of salt would be dissolved from soil minerals, and a minimum quantity of salt would be returned to river systems in drainage water (Carter and Bondurant, 1971). However two important factors must be considered before water management practices are changed to maintain a salt balance:

i) The salinity tolerance of the crops grown governs the salt concentration permissible in the soil solution, below which the salt balance must be established for successful cropping.

ii) The salt concentration in drainage water will be likely to increase as irrigation practices are changed to effect a salt balance.

A third factor to consider in some areas is the disposal of animal, food processing and industrial waste effluents on the land. Some of these effluents contain large quantities of salt that will certainly have a significant impact upon the salt balance of an area.

2.5 Water Quality for Irrigated Agriculture.

All irrigation waters contain dissolved salt and suspended materials in varying amounts. The total concentration and the important constituents determine the quality of water (Doneen, 1961). The principal cations in irrigation water are; calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) which is usually in low concentration in many waters. The anions are carbonate (CO_3), bicarbonate (HCO_3), chloride (Cl), sulphate (SO_4) and nitrate (NO_3) which is normally in low concentration. In addition boron (B) is an important anion in some areas. The above ions and other minor constituents are given considerable detail by Wilcox (1960) and by Bernstein (1964).

Irrigation water quality refers to a water's suitability for use (Ayers and Westcot, 1976). A good quality water has the potential to allow maximum yield under good soil and water management practices. The suitability of a water, from a quality standpoint, is determined by its potential to cause problems and is related to the special management practices needed or the yield reduction caused. Solution in most cases is at the farm level, meaning the evaluation must be done in terms of the specific use and potential hazard to crop production under the existing management capability and farm situation.

In general, ground waters contain more salts than the replenishing surface water. This is due to several factors but the principal ones are: i) leaching of salts applied in the surface water by rainfall or irrigation, and ii) by dissolving of minerals by the water percolating from the soil mantle above the ground water table. Salts will accumulate in the upper portions of a water table and if water tables exist within two metres from the soil surface they can become an important contributing source of additional salts in the crop root zone. When uncontrolled water tables exist within two metres depth, salinity problems occur even where irrigation water quality is good. With high water tables of poor quality, salts can be expected to accumulate rapidly in the crop root zone whereas with good quality groundwater they will still accumulate but at a much slower rate (Doneen, 1975).

2.6 Water Quality Associated Problems

Water quality problems though often complex, generally occur in four categories, namely; salinity, permeability toxicity and miscellaneous. Each may affect the crop singly or in a combination of two or more. Each of the problems is discussed briefly below as given by Ayers and Westcot (1976).

2.6.1 Salinity Problems.

A salinity problem occurs if the total quantity of salts in the irrigation water is high enough that salts accumulate in the crop root zone to the extent that yields are affected (Ayers and Westcot 1976). Crops have extra difficulty in extracting enough water from the salt affected soils. This reduced water uptake by the plant can result in slow or reduced growth and may be shown by symptoms similar in appearance to those of drought such as early wilting. In highly saline soils the level of available water may be very low or even zero. High salt content in irrigation water may also alter the soil pH to an extent that plant nutrients become unavailable or insoluble thus curtailing plant growth. Salinity therefore limits fertility of the soil and hinders agricultural development.

Badhe and Kadwe (1977) have reported that waters having EC values below 0.25 mS/cm are suitable for crops, those having values between 0.25 and 0.75 mS/cm are less suitable while those with values above 0.75 mS/cm should be used cautiously. Currently, however, the classification proposed by Richards (1954) and modified by Thorne and Peterson (1954) is the most widely used. In this system, the limits are given in mS/cm as: <0.25 - low salinity; 0.25 - 0.75 - moderate salinity; 0.75 - 2.25 - medium salinity; 2.25 - 4.00 - high salinity; 4.00 - 6.00 - very high salinity; >6.00 - excessively high salinity. Yaron *et al* (1973) cautions that the salinity ranges chosen to characterize irrigation water in a given area must be modified according to the local environmental conditions and that its total salt content only serves as a general qualitative assessment of its quality.

2.6.2 Permeability Problems

Ayers and Westcot (1976) have reported that a permeability problem occurs when the rate of water infiltration into the soil is reduced to such an extent that the crop is not adequately supplied with water and yield is reduced. The poor soil permeability makes it more difficult to supply the crop with water. Permeability problems are evaluated firstly from total salts in the water since low salt water can result in poor soil permeability due to the tremendous capacity of pure water to dissolve and remove calcium and other solubles in the soil and, secondly, from a comparison of the relative content of sodium to calcium and magnesium in the water. Calcium is known to cement soil particles thus maintaining a good soil structure. Furthermore, carbonates and bicarbonates can also influence soil permeability and are therefore evaluated. Irrigation waters rich in bicarbonates tend to precipitate insoluble calcium and magnesium in the soil as carbonates thus reducing their saturation at the exchange sites and leaving a higher proportion of sodium in the soil. In many cases, the evaluation of the sodium influence alone has proven to be in error.

A value that has come into wide use in predicting the permeability problem is the sodium adsorption ratio (SAR) which is based on the interaction between total salt concentration and sodium concentration. It is used to express the relative activity of sodium ions in exchange reactions in the soil.

$$SAR = \frac{Na^{+}}{\left[\frac{Ca^{2+}+Mg^{2+}}{2}\right]^{1/2}} \quad \ldots\ldots (2.10)$$

Where Na^{+} = concentration in me/l of sodium

Ca^{2+} = concentration in me/l of calcium

Mg^{2+} = concentration in me/l of magnesium

The above concept has been refined into SARadj (adjusted SAR) by Bower (1961). It includes the added effects of precipitation and mineralization of calcium in soils as related to CO_3 and HCO_3 concentrations.

$$SAR_{adj} = SAR\,[1+(8.4 - pH'c)]\,....(2.11)$$

$$pH'c = (pK2 - pKc) + p(Ca^{2+} + Mg^{2+}) + P(Alk)\,....(2.12)$$

Where pK2-pKc = Ca+Mg+Na in me/l

p(Ca+Mg) = Ca+Mg in me/l

P(Alk) = CO_3+HCO_3 in me/l

The ionic concentrations in me/l are obtained from water analysis. SARadj values less than 6.0 are found to cause no permeability problems. Values in the range of 6.0 to 9.0 suggest increasing problems while values above 9.0 suggest severe problems.

Recent studies have indicated that soil permeability, as affected by long-term irrigation will be influenced by the total salt concentration of the water and by the sodium and bicarbonate content. These are given in a term "permeability index" (PI) formulated by Doneen (1961).

$$PI = \frac{(Na+HCO_3)^{1/2}}{Ca+Mg+Na}*100\,.....(2.13)$$

2.6.3 Toxicity Problems

A toxicity problem occurs when certain constituents in the water are taken up by the crop and accumulate in amounts that result in a reduced yield. This refers to one or more specific ions in the water namely boron, chloride and sodium. When the ESP of the soil is greater than 15, the sodium causes soils to be impermeable to air and water and also influences soil workability. Sodium is a dispersive element in the soil. When water is applied to the soil, it disperses clay particles which block the soil pores. Sodium is also luxuriously consumed by plants. Most woody plants are sensitive to sodium (Ayers and Westcot, 1976).

Chloride has no effect on the physical properties of the soil but it is recommended that it be included in some regional water classification. This is because if it is taken in large amounts through the leaf, it causes leaf injury (Grillot, 1954).

Boron is toxic to plants even in small quantities and the range between beneficial and toxic concentration, for some plants, is narrow. Wilcox (1960) has reported the relative boron tolerance of a number of crops as determined by Eaton (1935). Boron levels of 2 ppm or more are known to be toxic to most plants. However, these standards are conservative for many situations as experience has shown that with open soils and good drainage, tolerant plants can thrive on levels as high as 3 ppm of boron. Relatively, legumes are salt sensitive but can tolerate more boron than cereals.

2.6.4 Miscellaneous Problems

Various other problems related to irrigation water quality occur with sufficient frequency that they should be specifically noted. These include excessive vegetative growth, lodging and delayed crop maturity resulting from excessive nitrogen in the water supply, white deposits on fruit or leaves due to sprinkler irrigation with high bicarbonate water and suspected abnormalities indicated by an unusual pH of the water.

Irrigation is generally practised in the arid and semi arid regions. The waters of these areas have a greater tendency to be of poor quality than those in humid regions (Doneen, 1961). However, irrigation even with good quality water may turn a good soil into saline or sodic condition (Macharia, 1982). Shainberg and Oster (1978) found out that application of 1000 mm of irrigation water containing 1000 g per m^3 of salt introduced ten tonnes of salt per hectare of land.

2.7 Irrigation Methods and Salt Build Up

Irrigation water may be applied to crops by flooding it on the field surface, by applying it beneath the soil surface, by spraying it under pressure or by applying it in drops.

The common methods of irrigation are given schematically as follows. Three of the frequently used methods are discussed below.

2.7.1. Surface Irrigation

Flood, basin, furrow and border methods apply water at intervals to allow the crop to utilize as much as 50% or more of the available water in the root zone before the next irrigation (Ayers and Westcot (1976). As water is used by the crop during each interval between irrigations the soils become drier and the soil water becomes saltier and therefore even less water is available to the crop. Irrigating more frequently may reduce salt build up but may also waste water, cause waterlogging and result in reduced yield.

2.7.2. Sprinkler irrigation

In this method, water is sprayed into the air and allowed to fall on the ground surface somewhat resembling rainfall. With portable or wheel-roll systems, irrigations are frequent enough to maintain low salinity and reduce problems such as crusting. Sprinklers often allow much more efficient agreement with crop needs (evapotranspiration and leaching), and drainage and high water table problems can be greatly reduced. This improves salinity control (Ayers and Westcot, 1976).

Sprinklers also do offer a hazard to sensitive crops when using poor quality water. Crops such as grapes, citrus and most tree crops are sensitive to relatively low concentrations of sodium and chloride and under low humidity conditions may absorb excessive and toxic amounts from the sprinkler applied water which wets the leaves. Salts concentrate on the leaves as water evaporates between rotations of the sprinkler. These salts are then absorbed and may cause damage.

2.7.3. Drip Irrigation

This is one of the latest methods of irrigations which is becoming increasingly popular in areas with water scarcity and salt problems (Michael, 1978). It is also used for specific conditions of an intensive irrigated agriculture (Yaron *et al* 1973). It is a method of watering plants frequently and with a volume of water approaching the consumptive use of the plants therefore minimizing such conventional losses as deep percolation, runoff and soil water evaporation. Water is supplied on almost a daily basis. Drip irrigation can be used with poor quality water. However, salts do accumulate both at the soil surface and within the soil at the outside edges of the area wetted by the emitters. With time the salt accumulation at the soil surface and in wetted fringe areas between emitters can become appreciable (Ayers and Westcot, 1976). Such accumulation is a hazard if moved by rain into the root zone of the crop or, in the case of annual crops, if a new planting is made in these salty areas without prior leaching. If rainfall is insufficient or infrequent salt problems may result. Leaching by sprinklers or surface flooding prior to planting has been effective in removing accumulated salts. This will require a second irrigation system and use of additional water but may allow continued production utilizing poor quality water.

2.8 Drainage and Salt Build Up

Adequate drainage is essential for salinity control. Excessive irrigation may cause the rising of the groundwater table with subsequent movement of water with salts to the soil surface by capillary action. Salinity resulting from high water tables (1.5 to 2.0 m) can often be prevented or eliminated by applying less water or by proper drainage. Drainage can either be artificial or natural. Artificial drainage is costly and drainage requirements should be carefully considered before a new area is brought under irrigation (Carter, 1975).

Both surface and subsurface drainage problems may occur. Surface drainage problems are usually characterized by ponding and waterlogging due to slopes that are too flat or due to slow water penetration (Ayers and Westcot, 1976). Subsurface ones occur due to the presence of a clay barrier, hardpan layer, bedrock or simply a subsoil textural change. With inadequate drainage to accompany irrigation, salinity results even with very good quality water.

2.9 Fertilizers and Salt Build Up

Chemical fertilizers, manures, sludge and soil amendments contain salts (Ayers and Westcot, 1976). These salts accumulate in the soil surface and may be washed into the root zone where they could pose salinity problems. The salts may also be washed into the groundwater table which, if high enough, may bring salts onto the surface by capillary action. Where salts are a problem, lower than normal fertilizer applications may be desirable and split fertilization recommended.

2.10. Response of Soils to Salinity and Sodicity

Saline and sodic soil conditions reduce the value and productivity of soils in the arid and semi arid regions of the world. This is due to their effect on the chemical and physical properties of the soil. The main chemical processes occurring in soils as a result of sodicity and salinity are:

(i) ionic exchange between cations in irrigation water and those present on the soil exchange complex.

(ii) Dissolution and precipitation of calcium carbonates.

(iii) Weathering of the primary minerals in exposed rocks of the earth's crust.

(iv) Upward movement of ions through capillary activity.

Among these processes, cation exchange is the most important process governing the accumulation of excessive sodium during irrigation with saline water (Michael, 1978). The accumulation of dispersive cations such as sodium in the soil solution and on the exchange phase affects soil physical properties such as structural stability, hydraulic conductivity and infiltration rate, which consequently affect crop production.

High sodium in soils causes the collapse of the soil structure when irrigation water is applied. This is as a result of the swelling and dispersion of clay minerals. The dispersed clay colloids lodge within the soil pores thus reducing the hydraulic conductivity and infiltration rate. McNeal and his co-workers (1966-1968) obtained a good correlation between expansible clays (type and content) and hydraulic losses due to exchangeable sodium. Shainberg and Letey (1984) found out that the hydraulic conductivity of a soil depends on both sodium and the total salt concentration of the percolating solution. High hydraulic conductivity may be maintained even at high exchangeable sodium percentage (ESP) values, if the solution concentration is above a critical level.

CHAPTER THREE

3.0 PRINCIPLES BEHIND SOIL AND WATER ANALYTICAL PROCEDURES.

3.1 Soil Chemical Analyses.

3.1.1. pH

The pH value of a soil or natural water is a measure of its acidity or alkalinity. More accurately stated, the pH value is a measure of the hydrogen-ion concentration in water. pH values are very important because pH influences many chemical elements and biological processes in the soil.

The optimum pH for most crops lies between 6.5 and 7.5. pH greater than 9 dissolves plant roots. The availability of vital nutrients is closely related to soil pH e.g acid soils are often low in calcium and magnesium. Some elements such as aluminium, iron, copper and zinc become toxic at low pH. pH values are used to determine the lime requirement of the soil in order to raise the pH value of acidic soils to a point that is better suited to effective crop productivity.

pH varies with the neutral salt concentration. It decreases during the hot dry season when soluble salts accumulate in the soil. These are subject to leaching during the relatively cool rainy season when pH increases again. It was specifically to offset the influence of seasonal variations in soluble salt concentration that Scofield and Taylor (1955) proposed a method for the determination of pH in 0.01M $CaCl_2$. The pH measured in the salt reflects better the intrinsic characteristic of the soil and the value obtained is virtually independent of the initial soil:water ratio. Peech (1965) also claims that a 0.01M $CaCl_2$ solution is approximately equivalent to the total electrolyte concentration of the soil solution of a non-saline soil at optimum fieldwork content, the pH measured in 0.01M $CaCl_2$ or in 1N KCl represents more nearly the pH of the soil solution under actual field conditions.

3.1.2. Electrical Conductivity (EC).

This is a measure of the total soluble salt concentration in the soil solution. A high degree of correlation exists between the EC and osmotic pressure of soil-water extract. The following relationships may be employed for the evaluation of salt concentration as given by Michael (1978).

1. Salt concentration, mg/l or ppm =

$$640 * Ec \ldots\ldots\ldots (3.1)$$

2.Total cation concentration, me/l =

$$60 * Ec \ldots\ldots\ldots (3.2)$$

3. Osmotic pressure, atmospheres =

$$0.36 + Ec \ldots\ldots\ldots\ldots (3.3)$$

The electrical conductivity is given in mS/cm.

3.1.3. Cation Exchange Capacity (CEC)

CEC is the total of all exchangeable cations adsorbed expressed in Cmol per kg of soil. Many soil fertility problems such as leaching of fertilizers, potassium fixation and liming are affected by the capacity of the soil to hold cations such as Ca, Mg, Al, Na, etc. in an exchangeable condition (Gupta, 1989). CEC measurements are commonly made as part of the overall assessment of the potential fertility of a soil and possible response to fertilizer application. Cation exchange in irrigated field occurs during percolation of water through the soil profile and the most important reaction in these soils is Na-Ca exchange (Levy, 1984)(Ed.).

3.1.4. Exchangeable Cations

The cations displaced during a cation-exchange reaction are termed `exchangeable bases' (Richards, 1954). The exchangeable bases (commonly Ca, Mg, K, and Na) are the primary nutrients. They also influence soil pH. Determinations of the amounts and proportions of the various exchangeable cations present in soils are useful because exchangeable cations markedly influence the physical and chemical properties of soils such as soil structure and nutrient uptake by crops (Landon, 1991).

3.1.5. Base Saturation.

This is the proportion of the CEC accounted for by exchangeable bases (Ca, Mg, K, and Na). This is more frequently used as an indication of soil fertility than the CEC. However, the base saturation does not distinguish between different bases and imbalances in their relative proportions can cause severe plant nutrition problems (Landon, 1991).

3.1.6. Soluble Salts.

Soluble salts (ions) more commonly determined are Na, Mg, Ca, K, CO_3 , HCO_3, Cl,SO_4, and less commonly, B and NO_3. Soluble salts are those that are readily available for plant uptake from the soil solution. Soluble salts, although composed of similar ions, are not synonymous with exchangeable ions since they are only found in the soil solution and are not held on soil exchange sites (Bower and Wilcox (1965).

3.1.7. Organic Matter.

Soil organic matter refers to the organic fraction of the soil. It includes plant, animal, and microbial residue at various stages of decomposition. Climate and vegetation are the most important factors affecting the soil organic content under natural conditions. On average, soil organic matter contains 58 % organic carbon giving a conversion factor of 1.72. The importance of organic carbon determination, therefore, lies in its indication of organic content of the soil which is generally used as an index of soil fertility. With the most routine method for organic carbon determination, the Walkley-Black method, the recovery of organic carbon is conventionally taken as 75%, giving a conversion factor of 1.333. Organic matter of soils of arid regions is usually low under virgin conditions (Richards, 1954).

3.2. Soil Physical Analyses.

3.2.1. Particle Size Analysis.

The solid phase of soils consists of discrete units called primary soil particles. These particles may vary widely in size, shape and composition. The particle size distribution or texture, determines to a large extent the physical and chemical behaviour of soils. Soils are given soil textural classes according to weight percentage of sand, silt and clay as given in a textural triangle. The main separates are:-

Clay < 2 μm

Silt < 2-50 μm

Sand < 50-2000 μm

The determination of the amounts of the various soil separates in a soil sample is called particle size analysis (Day, 1953 and 1965).

3.2.2. Bulk Density (ρb)

Soil bulk density,(ρb), is the ratio of the mass of dry solids to the bulk volume of the soil. The bulk volume includes the volume of the solids and of the pore space. Bulk density values are widely used for the conversion of water percentage by weight to content by volume for the calculation of porosity and void ratio when the particle density is known. Bulk density varies with structural condition of the soil, particularly that related to packing.

3.2.3. Porosity (f)

While bulk density *per se* is a satisfactory measure of the state of compaction of a soil, a knowledge of the soil particle density allows the porosity and void ratio to be calculated; the latter two being of more interest to crop production and consolidation of soils respectively (Dekkev, 1991.) An adequate supply of soil solution and soil air especially oxygen to plant roots is essential for plant growth. Soil solution and air are stored and transported within the soil pores. Also plant roots exist in the soil pores. Harrod (1975) found out that sandy soils with a total pore space less than 40% are liable to restrict root growth.

3.2.4 Infiltration Rate (i)

This is the vertical intake of water into a soil, usually at the soil surface. Its measurement forms a vital part of many surveys involving irrigation development or soil conservation, e.g in determining the most efficient method(s) of application of irrigation water, crop water demands and in runoff calculations. It is also an important component of the hydrologic cycle crucial to most hydrologic processes e.g soil water content, runoff and soil erosion (Boers *et al*, 1992). Knowledge of infiltration process is therefore a prerequisite for efficient soil and water management (Hillel, 1980b).

Infiltration rate is dependent on many factors among them being vegetation, slope, bulk density and initial soil moisture (Parr and Bertrand, 1960; Warrick, 1983). According to

Horton (1940) and Wood and Blackburn (1981), infiltration rate is mainly governed by conditions at or near the soil surface. Numerous formulations have been proposed over the years in repeated attempts to express infiltration rate as a function of time or of the total quantity of water infiltrated into the soil. Thus:-

$$i - dI/dt \text{ ....(3.4)}$$

Where i = infiltration rate (cm/hr)

I = cumulative volume of water infiltrated in time t per unit area of soil surface (cm^3)

Three of the equations proposed were used in a bid to find out which of them fitted best with the observed infiltration rate values. The three were:-

1. The power function formulated by Kostiakov (1932).

$$i - Bt^{-1} \text{........(3.5)}$$

Where B and t are the characterizing constants.

This strictly empirical function provides an infinite initial infiltration rate but implies that it approaches zero as t increases, rather than a constant non-zero steady state infiltration rate (i_c).

2. The Mitscherlic equation formulated by Horton (1940).

$$i - i_c + (i_o - i_c) e^{\cdot t} \text{......(3.6)}$$

Where i_c, i_o and t are the characterizing constants.

The term e^{*t} determines how quickly infiltration rate will decrease from initial (i_o) to the steady state (I_c). This equation is cumbersome in practice since it contains three constants which must be evaluated experimentally.

3. The logistic equation formulated by Philip (1957c).

$$i - i_c + S/2t^{1/2} \ldots\ldots (3.7)$$

Where i_o and S are the constants. Here the infiltration rate is once again represented as infinite at zero time. The finite initial infiltration rate of Horton's equation was in this study found to be more realistic and it fitted best with the observed values. The larger number of characterizing constants in the equation helps to provide a better description of the phenomenon (Skaggs *et al*, 1969). A similar mathematical fit of infiltration rate formulations has been performed by Kironchi *et al* (1993) for Kenyan soils.

Two other equations by Green and Ampt (1911) and by Holtan (1961) both quoted by Hillel (1980b) were not used in the mathematical fits because the former was found to be too shallow and is intended to predict infiltration rate from a ponded surface while the latter contains a characterizing constant 'M' (water storage capacity of the soil) whose determination was not made clear by Holtan.

3.2.5. Antecedent Moisture Content (w).

Direct or indirect measure of soil water content are needed in practically every type of soil study. In the laboratory, determination and reporting many physical and chemical properties of soil necessitates knowledge of water content (Gardner, 1986).

The antecedent water content affects the behaviour of infiltration rate hence the `wet run' and the `dry run' curves differentiated by Hillel (1980b). The wetter the soil is initially, the lower will be the initial infiltration rate and the quicker will be the attainment of the final (basic or constant) rate which is itself generally independent of the initial water content (Hillel, 1982).

3.2.6. Saturated Hydraulic Conductivity (K).

The hydraulic conductivity of a soil is the ability of a soil to conduct water. It defines the volume of water which will pass through unit cross-sectional area of a soil in unit time, given a unit difference in water potential (hydraulic head). It is of considerable importance since it gives an indication of the rate of movement of water to plant roots, the flow of water to drains and wells and the evaporation of water from the soil surface. Comparison made of the hydraulic conductivity rates of different soil horizons gives a guide to water movement and possible drainage problems within soil profiles.

3.2.7. Soil Moisture Retention.

The moisture content of a sample of soil is usually defined as the amount of water lost when dried at 105°C (Landon, 1991). Although useful, such information is not a clear indication of the availability of water for plant growth. The difference exists because the water release and retention characteristics may be different for different soils. Soil moisture tension, the force per unit area that must be exerted to remove water from a soil, is given in bars, atmospheres or Pascals.

The water retention function is primarily dependent upon texture and structure (Salter and Williams, 1965; Macharia, 1982 and Sessanga, 1982). Storage of water by soils is a result of attractive forces between the solid and liquid phases. The solid (matrix) forces enable the soil to hold water against forces or processes such as gravity, evaporation, uptake by plant roots etc. (Dekkev, 1991).

Salt increases the energy that must be expended by the plant to extract water from the soil and to make biochemical adjustments necessary to grow under stress. This energy is diverted from the processes that lead to normal growth and yield. The influence of water content upon the soil water suction is different for different soils. The relationship between the two is shown in `moisture characteristic curves' (Childs, 1940).

Organic matter, due to its hydrophillic nature, influences the capacity of a soil to retain available water irrespective of its texture and mineralogical composition (Salter and Williams, 1963). Sanchez (1976) showed that water retention increased with organic matter. Organic matter has a direct effect through its hydrophilic nature and indirect effect through its modification of the soil structure. Kironchi *et al* (1995) observed that vegetation cover, soil type and land use have an influence on water retention and availability to plants.

3.3 Water Quality Determinations.

3.3.1 pH.

This is taken as an indication of the alkalinity or acidity of the water which will consequently affect the pH of soil solution.

3.3.2 Electrical Conductivity (EC)

The total concentration of soluble salts in irrigation waters has been used in classifying water i.e. its suitability for irrigation purposes. Waters in the range of 0.75-2.20 mS/cm are widely used and satisfactory crop growth is obtained under good management and favourable conditions, but saline conditions will develop if drainage and leaching are inadequate (Richards,1954). Any increase in water salinity will result in an increase in average soil salinity ($r = 0.84$). Such an increase may have little practical significance, unless the salt content rises sufficiently to affect crop yield. However, the gradual and irreversible salinization or sodification of the soil might have been the process responsible for destruction of the once thriving agricultural production based on the irrigation ofriver valleys.

3.3.3 Soluble bicarbonates, carbonates, chlorides and hydroxides

In waters containing high bicarbonate ion, there is a tendency for Ca and Mg to precipitate as carbonates as the soil solution becomes more concentrated i.e., after plant uptake or evaporation. The concentration of Ca and Mg are thus reduced and the relative proportion of Na is increased. Any residual carbonate (residual sodium carbonate - RSC) is paired with Na and this leads to the destruction of the soil structure (Eaton,1950). Carbonates and hydroxides are only found in highly alkaline soils whose pH is greater than 8.4. Waters high in chloride may cause leaf injury particularly to fruit trees if sprinkler irrigation is practised.

CHAPTER FOUR

4.0. MATERIALS AND METHODS.

4.1. Area of Study.

4.1.1. Location:

The Tana and AThi Rivers Development Authority (TARDA) Pilot Irrigation Project is situated about 250 km South East of Nairobi. It is located about 24 km off the Nairobi-Mombasa highway at the Southern portion of Makueni District and adjacent to a tributary of the Athi River - the Kibwezi River.

4.1.2. Area of Land:

The total land area is 170 ha, 51 ha of which are under irrigation. It was formally state land but is now owned by the parastatal,the Tana and Athi Rivers Development Authority (TARDA). It was acquired in 1984.

4.1.3. Topography:

The land consists of gently undulating terrain ranging in altitude from 700 - 900 meters above sea level. It slopes south-eastwards towards the coast with the general land slope being 2-5% and is dissected by several dry water courses.

4.1.4 Vegetation.

Shrubland predominates: *Commiphora*, *Grecoia*, *G. boschia* and several *Acacia* species are common woody components. The baobab tree is a common species too. Common grasses are *Chloris roxburghiana*, *Eragrostis superva*, *Cenchrus cilliaris* and *Aristida* species.

4.1.5. Climate.

This is typical of the semi-arid regions and represents many other zones with similar ecological conditions in Kenya i.e precipitation received is between 250 and 750 mm per year. It is in transition between Ecozones V and VI.

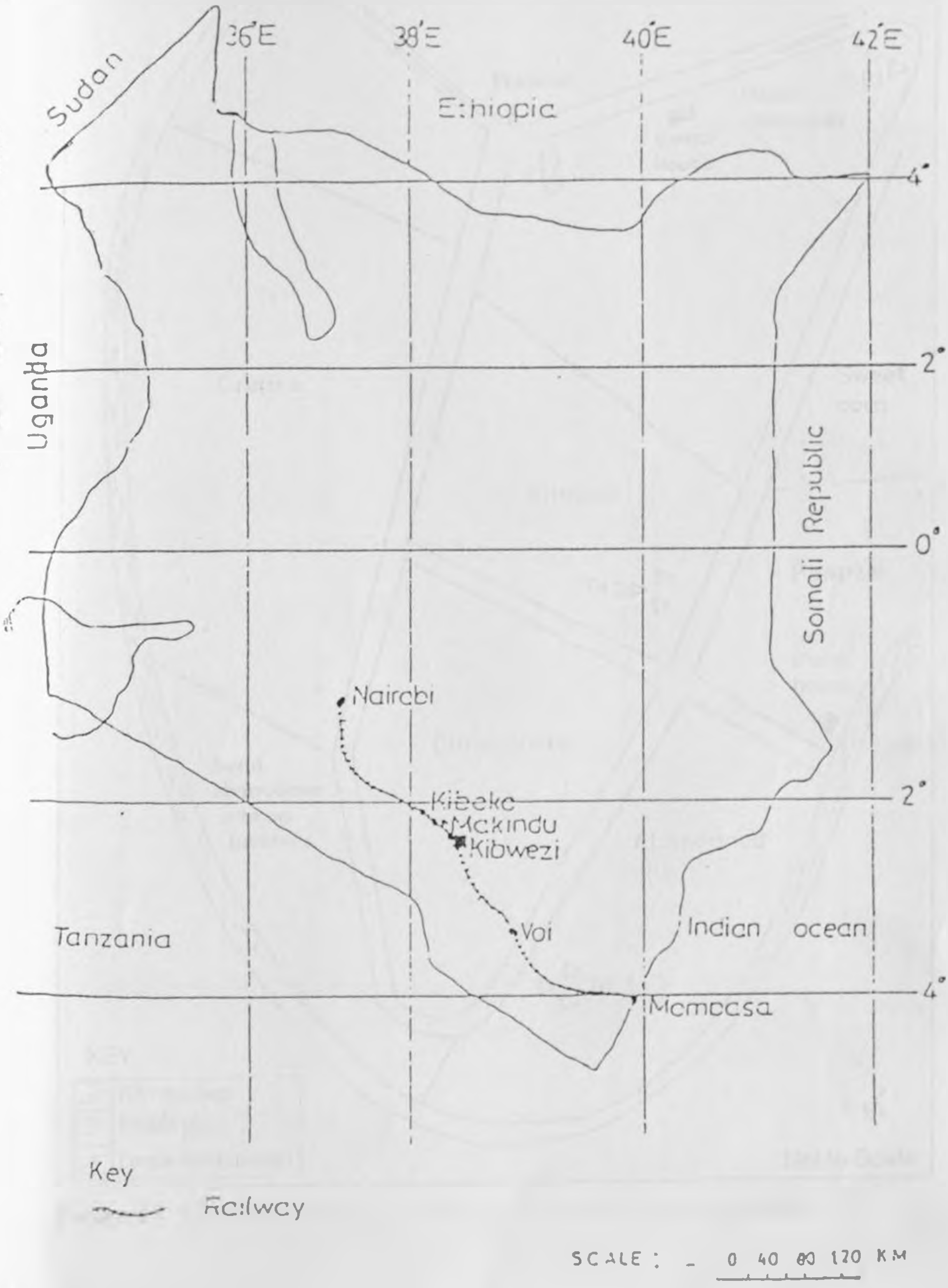
The mean monthly totals of precipitation shows a marked bimodal distribution of rainfall during the year, with peaks occurring in November-December (short rains) and March-May (long rains). The dry spell falls in the months of June-October. On average 90% of the annual precipitation falls during the six months from November-April. Evaporation rates exceed rainfall during eleven months of the year, whereas crop water requirement can be fully met only during the month of November. The mean meteorological data for the station since it started to 1994 is shown below.

4.1.6. Soils.

According to D'Costa (1990), the area falls on the soil mapping unit UB-LVx-b ,which means:- Upland, Basement System Rocks, Chromic Luvisols (FAO - UNESCO) with a slope of 2-5%. The soils are well drained, moderately deep to deep, dark reddish brown, friable gravelly sandy clay to clay, in places with rock outcrops.

The soil survey done by a joint Kenya-Israel team in 1990 on the adjacent Kibwezi University Dryland Field Station describes this soil further as having the following characteristics:-

Figure 1. The approximate location of the study area of Kibwezi on a map of Kenya.



■ General Location of TARDA in Kibwezi on a Kenyan Map

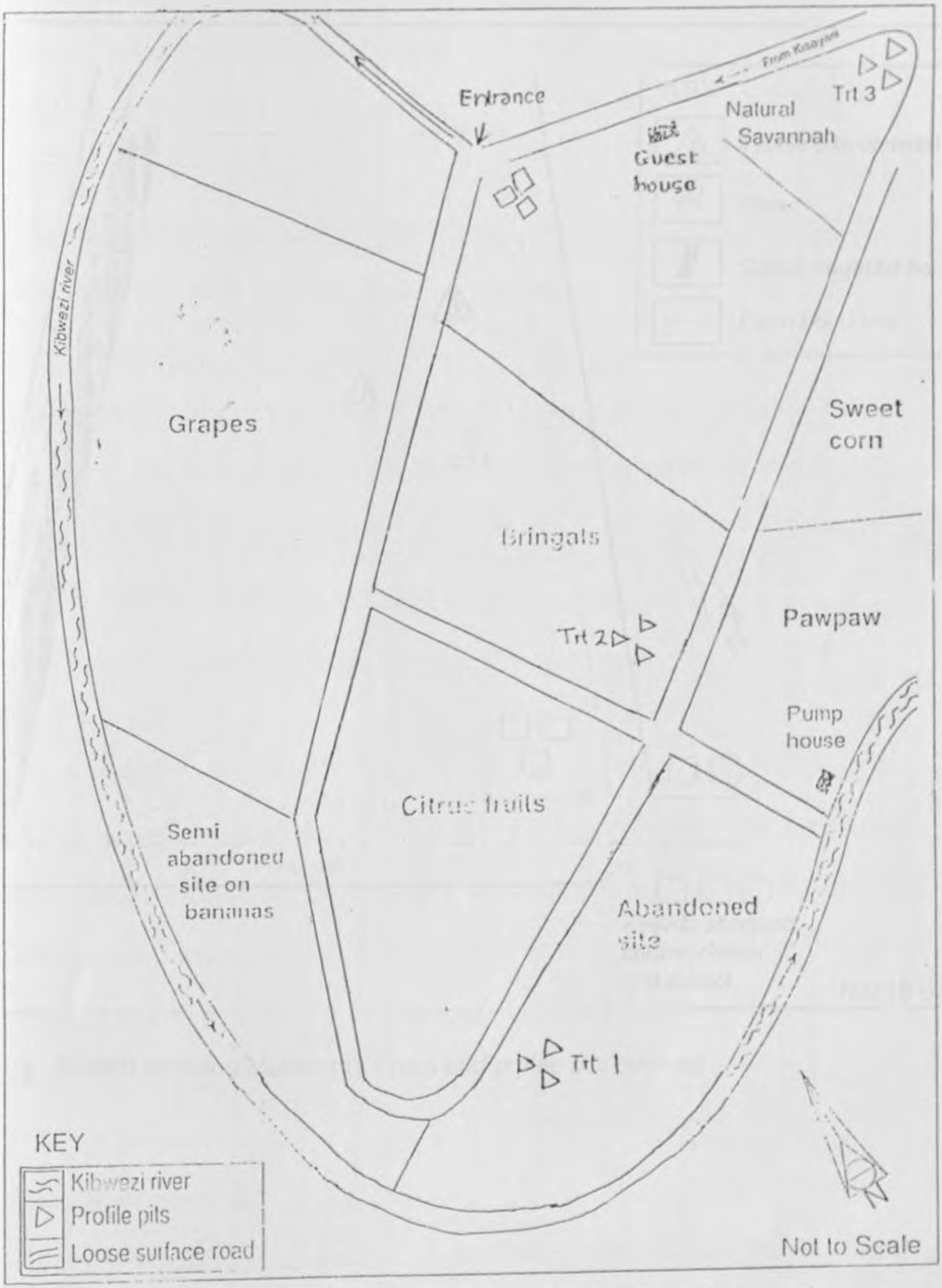


Figure 2 Sketch of TARDA showing land use and profile pits opened

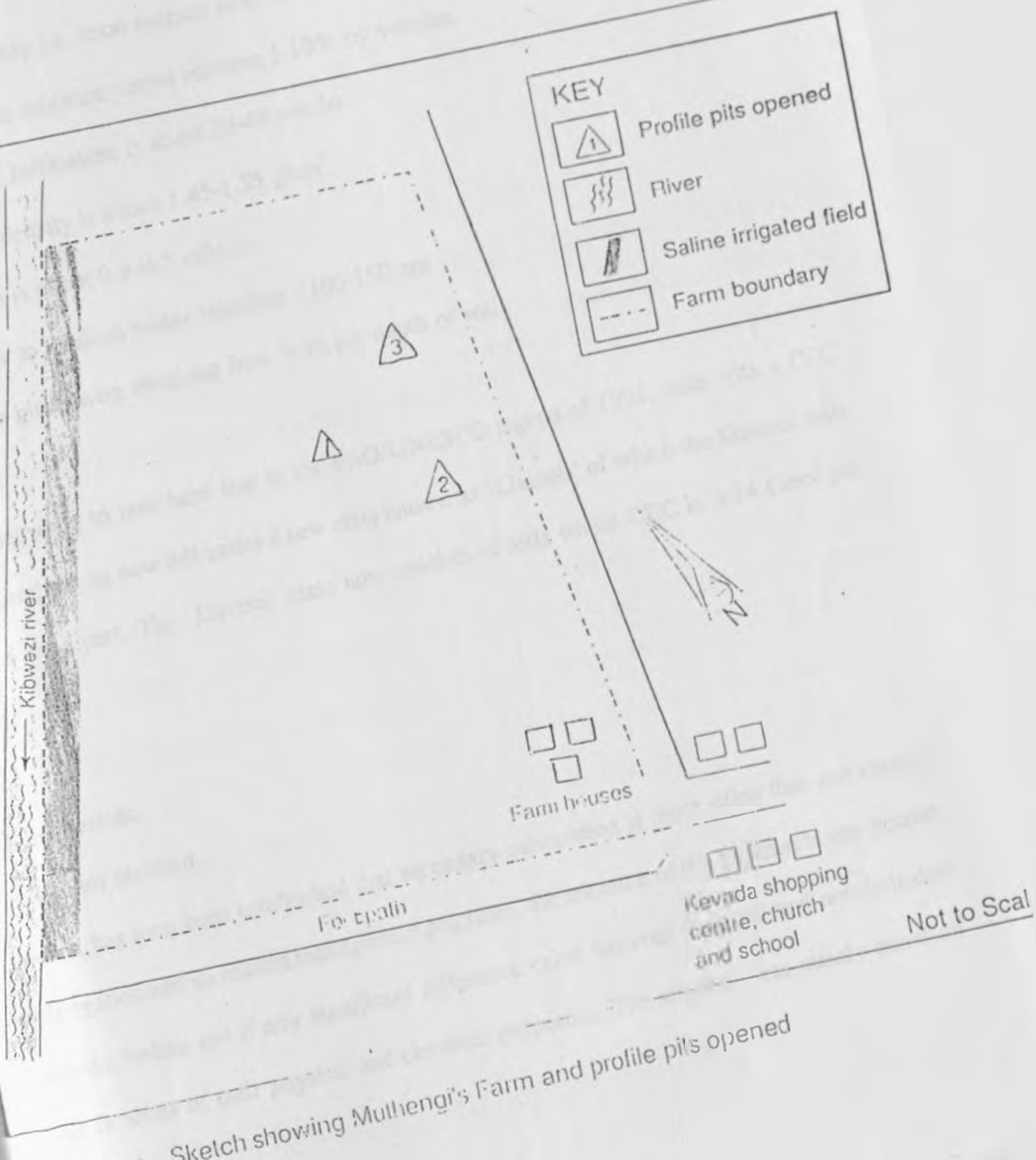


Figure 3 Sketch showing Muthengi's Farm and profile pits opened

- low fertility i.e. total nutrient reserve is low.
- available moisture varies between 5-10% by volume.
- rate of infiltration is about 20-40 mm/hr
- bulk density is about 1.45-1.55 g/cm^3
- ECe is about 0.3-0.5 mS/cm
- low to medium water retention - 100-150 cm

The results given were obtained from 0-20 cm depth of soil.

It is worthwhile to note here that in the FAO/UNESCO legend of 1991, soils with a CEC <24 Cmol per kg now fall under a new class known as `Lixisols' of which the Kibwezi soils studied are a part. The `Luvisol' class now consists of soils whose CEC is >24 Cmol per kg.

4.2. Materials.

4.2.1. Soil Studied.

Since it has long been established that secondary salinization is more often than not caused by irrigation and its related management practices, the selection of the treatments was geared towards finding out if any significant difference exists between irrigated and non-irrigated soils in terms of their physical and chemical properties. The selection was mainly based on existing fields.

4.2.2. Investigation Method.

The completely randomized design was used. Sites currently under different land uses were chosen to represent treatments. Four treatments were chosen and they are:-

1. Abandoned cropland (Trt 1)
2. Irrigated cropland (Trt 2)
3. Natural savanna (Trt 3)
4. Non-irrigated cropland (Trt 4)

The four sites were as close as possible to minimize the drastic variations which are so common in soil studies and especially those affected by salt. Costat was used for the analysis of variance and Duncan's Multiple Range Test used for the separation of means (Steel and Torrie, 1980). Although it is unfortunate that a certain arbitrariness is likely to characterize investigation methods of salt affected soils as pointed out by Banerjee (1958), it is in my opinion unavoidable.

4.2.3. Soil Sampling.

Profile pits at representative sites were exposed and described according to the USDA Soil Survey Manual (1951). Three pits were dug per treatment to a depth of 1.5 meters if such depth could be reached. Soils were sampled from each horizon and about 5 kg placed in polythene bags. These disturbed soils were later air dried in the laboratory and passed through 2 mm sieves. The soil laboratory analyses were performed on the fractions that passed through the sieves.

Undisturbed samples were collected from each horizon using metal core rings vertically driven into the soil using a hammer. A stepwise sequence of horizons was prepared. Four core-samples per horizon were collected. Samples that were used to determine moisture content were augered from each horizon.

Soil salinity and sodicity are typically among the most variable properties of soils and their variation within a field are generally greater than analytical errors. Thus, the reliability of analytical data for salinity and sodicity appraisal is often limited by sampling error.

4.2.4. Water Sampling.

No groundwater was reached at 2 metres depth therefore no ground water was sampled. Clean bottles were used to draw water from the river but were first rinsed two or three times with the water to be sampled. They were then tightly stoppered. Details of samples were labelled on the bottles e.g. the name of the river, source, and time of collection. Chemical analyses were done on suitable aliquots and the quality of the water classified according to Ayers and Westcot (1976).

4.3. Analytical Methods.

4.3.1. Chemical Analyses.

4.3.1.1 pH determination.

pH was determined both in water and in 1N KCl using a glass electrode pH metre (Peech, 1965). The ratio of soil:water/KCl was 1:2.5. The mixture was shaken mechanically for 30 minutes and then left to stand for 30 minutes before introducing the electrode into the supernatant suspension. A river water aliquot was taken for the same determination.

4.3.1.2 EC determination.

A conductivity bridge was used for 1:2.5 soil/water suspension and for the water. The soil/water mixture was shaken for one hour and left to stand overnight before readings were taken. The EC obtained at room temperature was corrected to the standard 25°C using factors given by Richards (1954). The method is similar to the one given by Loveday (1974) and Jackson (1958).

4.3.1.3 CEC, Exchangeable Cations and BSP

The method adopted is as given by Rhodes (1986). 5 grams of soils were leached using 50 ml of NH_4OAC adjusted at pH 8.2. Five portions of this solution were added and the leachate was collected in a 250 ml volumetric flask and made to mark with NH_4OAC. Exchangeable cations were determined from this leachate. The atomic spectrophotometer (AAS) was used to determine Ca and Mg while Na and K were determined using the flame photometer.

The soil was then washed with five portions of 95 % ethanol and the leachate kept back for redistillation. The soil was then leached with 100 ml of 1N KCl adjusted at pH 2, administering the KCl in four portions of 25 ml each. The leachate was collected in a 100 ml volumetric flask and made to the mark with KCl. An aliquot of 5 ml was pipetted and distilled and the distillate (liquid ammonia) was collected in 1 % boric acid and back titrated with 0.05N H_2SO_4. THe CEC was then calculated as follows:-

$$CEC=\frac{Titre*Normality\ of\ H_2SO_4*dilution*100g\ of\ soil}{ml\ of\ aliquot*weight\ of\ soil}\ldots(4.1)$$

The BSP was calculated from the following formula:-

$$BS(\%)=\frac{[Ca+Mg+Na+K]}{CEC}\ldots\ldots.(4.2)$$

Where Ca, Mg and K are exchangeable values given in me/100g

The exchangeable sodium percentage (ESP) was calculated as follows:-

$$\frac{ExchangeableNa}{CEC} \times 100 \ldots\ldots\ldots\ldots (4.3)$$

4.3.1.4 Soluble Salts.

A 1:2.5 soil/water mixture was shaken for one hour and then filtered. The filtrate was used for the determination of soluble K, Na, Ca, Mg, OH, CO_3 HCO_3 and Cl. The anions were determined as follows while adopting the method given by Rhodes (1986).

50 ml aliquots were used for each ion determination. For OH, CO_3 and HCO_3 determination, the aliquot was titrated with 0.05 N H_2SO_4 using phenolphthalein and methyl orange as indicators; while for Cl determination, the solution was titrated with 0.05N $AgNO_3$ using 2% K_2CrO_4 as indicator. Water aliquots were determined in the same way for the same ions. The necessary dilutions and blank titrations were used in calculation.

$$(OH, CO_3, HCO_3) = \frac{(1000 * N \text{ of } H_2SO_4 * (T-B) * D}{ml \text{ of aliquot}} \ldots\ldots 4.3$$

$$me/l \text{ of } Cl = \frac{1000 * N \text{ of } AgNO_3 * (T-B) * D}{ml \text{ of aliquot}} \ldots\ldots 4.4$$

Where T = Titre (volume of H_2SO_4 or $AgNO_3$ used)

B = Blank titre

D = Dilution factor

N = Normality

4.3.1.5 Soil Organic Carbon (SOC).

The method adopted is that given by Walkley and Black (1934). Soil samples sieved through 2 mm sieves were passed through 0.5 mm sieves and used for organic carbon determination. One gram of each of these fine samples was oxidized with potassium dichromate and unreacted dichromate titrated against 0.5N ferrous sulphate. The organic carbon was then calculated as follows as given by Nelson and Sommers (1982).

$$C(\%) = \frac{MeK_2Cr_2O_7 - meFeSO_4 * 0.03*100*100*f}{weight\ of\ dry\ soil\ used} \quad ...4.5$$

Where f = 1.33

me = Normality * mls of solution used.

4.3.2. Physical Analyses.

4.3.2.1 Particle Size Analysis.

The hydrometer method was used (Gee and Baunder, 1986). The samples were treated with hydrogen peroxide to destroy organic matter component. The residual sample was dispersed by a sodium salt (sodium hexametaphosphate) and by mechanical shaking for at least 4-6 hours. The percentage silt, clay, and sand were calculated as follows:-

$$Sand(\%) = 100 - [H_1 + 0.2(T_1 - 68) - 2]2 \quad ....(4.6)$$

$$clay(\%) - [H_2+0.2(T_2-68)-2]2 \ldots\ldots\ldots (4.7)$$

$$silt(\%) - 100-(\%sand+\%clay) \ldots\ldots (4.8)$$

Where H_1 = Hydrometer reading at 40 seconds (g/cm^3)

T_1 = Temperature reading at 40 seconds(°C)

H_2 = Hydrometer reading at 3 hours (g/cm^3)

T_2 = Temperature reading at 3 hours(°C)

Temperature correction is 0.2 (T_1 or T_2 - 68) where T_1 and T_2 are given in °F while the salt correction is -2.0.

4.3.2.2 Bulk Density (ρb).

Two of the undisturbed samples collected per horizon were oven dried at 105°C for 24 hours. The bulk density was calculated as given by Blake and Hartge (1986).

$$\rho b - \frac{Ms}{Vt} \ldots\ldots\ldots\ldots\ldots (4.9)$$

Where ρb = bulk density in g /cm^3

Ms = weight of oven dry sample in g

Vt = volume of sample as determined by the volume of core-ring in cm^3

4.3.2.3 Porosity (f).

Total porosity was calculated from the bulk density values and taking the particle density as 2.65 g/cm^3. The calculation is as follows:-

Where ρp = particle density in g/cm^3 and ρb is as defined before.

$$f(\%) = [1-\frac{\rho b}{\rho p}] * 100 \ldots\ldots (4.10)$$

4.3.2.4 Infiltration Rate (i).

The infiltration rates were determined by the double ring infiltrometer method (Bouwer, 1986). Three infiltrometer measurements were run next to the profile pits. They were run for a minimum of three hours at gradually increasing intervals. Only the wet run was determined since, throughout this study, there were heavy downpours especially in the nights. The tests were under constant head throughout. Infiltration rates were then calculated as given by Danielson and Sutherland (1986).

$$i = \frac{\Delta Q}{At} \ldots\ldots\ldots (4.11)$$

Where i = infiltration rate in cm/hr

ΔQ = change of volume in the reservoir in cm^3

A = area of the inner ring in cm^2

t = time in hours

4.3.2.5 Antecedent Moisture Content (w).

Moisture content was determined by the gravimetric method (Gardner, 1986). The wet samples were weighed and then reweighed after being oven dried at 105°C. The water content was then calculated as follows:-

$$w\% = \frac{Ww-Wd}{Wd-Wc} * 100 \ldots\ldots\ldots (4.12)$$

Where w = gravimetric water content (%)

Ww = weight of wet sample + can

Wd = weight of dry sample + can

Wc = weight of can alone

All weights are given in grams.

4.3.2.6 Saturated Hydraulic Conductivity (Ksat).

Saturated hydraulic conductivity was determined in the laboratory by the constant head method as outlined by Klute and Dirksen (1986). A simple multiple core system was used and measurements were made on direct application of Darcy's law. A hydraulic head difference was measured. The time taken to effect the measured flux was taken. The calculation of Ksat is as follows:

$$Ksat = \frac{QL}{AtH} \ldots\ldots\ldots\ldots\ldots (4.13)$$

Where Ksat = saturated hydraulic conductivity in cm/hr

Q = volume of water collected in cm^3

t = time taken to collect Q in hours

A = cross-sectional area of the ring in cm^2

L = length of soil column in cm

H = $\Delta h + L$ where Δh is the hydraulic head in cm.

4.3.2.7 Soil Water Retention.

The method used is adopted from Klute (1986). The core-rings carrying undisturbed samples were used for this determination. After soaking the samples in a basin of the irrigation water for 24 hours, they were weighed when completely saturated and then placed in pressure plate apparatus. The desired suction pressure was applied and the samples weighed after all the water had been driven out. The suction was done at pressures of 10, 30, 50, 70, 100, 300, 500, 700, 1000, and 1500 kPascals.

Soil water retention in each sample was calculated using the following equation:-

$$Q = \frac{Wt(i) - Wt(od)}{Vs * \rho w} \ldots\ldots\ldots (4.14)$$

Where Q = volumetric water content in cm^3/cm^3

$Wt(i)$ = weight of sample at corresponding soil water suction

$Wt(od)$ = weight of sample at oven dry.

ρw = density of water in g/cm^3

Vs = volume of soil sample = volume of core-ring in cm^3

CHAPTER FIVE

5.0 RESULTS AND DISCUSSIONS

The results are presented in various Appendices, Tables and Figures. The discussion has been divided into two sections. The first describes results obtained from the irrigation water quality while the second entails results obtained from the first horizons (0-39 cm) and the third horizons (79-150 cm). Majority of the profile pits opened had three horizons each. The results obtained from this study showed that the values for the second horizons were intermediate between those of the first and the third horizons. To find out if any real differences occurred with depth among the parameters analyzed, the two horizons (first and third) were used for the analyses of variance, correlation and regression.

5.1. Irrigation Water Quality.

The results for the chemical characteristics of Kibwezi River in 1990/1991 and 1994 are given in Table 1a and 1b. It is noticed that majority of the parameters have increased in proportion and/or quantity in the five-year period. The electrical conductivity (EC) is observed to have increased from 0.65 to 0.94 mS/cm. This classifies the water as having medium salinity. The adjusted sodium adsorption ratio (SARadj) was 6.72. This river water falls in category 2 denoted as C2-S1 and described as medium salinity and low sodium hazard.

Table 1a. Chemical characteristics of Kibwezi River in 1990 and 1991.

pH	EC (mS/cm)	CATIONS (me/l)						SAR adj	ANIONS (me/l)			
		Ca	Mg	Ca+Mg	Ca:Mg	Na	K		CO_3	HCO_3	Cl	SO_4
8.8	0.65	0.42	1.83	2.25	1:4	3.48	1.18	5.61	2.00	0.07	0.10	0.46

Source: Faculty of Agriculture, 1990; Ekirapa and Muga, 1991.

Table 1b. Chemical characteristics of Kibwezi River in 1994.

pH	EC (mS/cm)	CATIONS (me/l)						pH*c	SAR adj	SSP	ANIONS (me/l)		
		Ca	Mg	Ca+Mg	Ca:Mg	Na	K				CO_3	HCO_3	Cl
8.3	0.94	0.54	2.17	2.92	1:4	3.87	3.64	7.3	6.72	57	0	5.0	9.0

Similar analytical techniques as those used in 1990/1991 were adopted during this study. Sulphates were not determined in 1994 because of lack of the necessary laboratory facilities. A particular thing to note from this results is the high level of Na as compared to other cations. This implies that more Na than the other cations is added to the soil. Mg is also observed to be in higher proportion than Ca. At the same level of sodium adsorption ratio (SARadj) but with varying proportions of Ca and Mg, adsorption of Na by soils and clay minerals is more at higher Mg:Ca ratios. This is because the replaceability of Mg is more than that of Ca but its bonding energy is generally less than that of Ca allowing more Na adsorption. In such conditions Ca and Mg tend to be lower in proportion at the exchange sites when compared with Na.

High bicarbonate ions in the irrigation water tend to precipitate Ca and Mg as their carbonates as the soil solution becomes more concentrated i.e. after plant uptake or evaporation. This leads to a further reduction in the concentration of Ca and Mg and the relative increase in the Na proportion in the soil. This is supported by the high soil exchangeable sodium percentage (ESP) obtained from the abandoned field. ESP values of upto 59 were observed. The low infiltration rates observed in the abandoned field (Trt 1) further support this (see Figure 5).

The change in this water's chemical composition is mainly attributed to the land use along the river banks. With increased agricultural activity to meet the ever increasing population growth, more and more land is opened up for cultivation and more fertilizers are used in an endevour to produce more food. Drainage waters from these lands get their way back to the river. Such water has more salts than the irrigation water. Moreover, a sisal estate uses the Kibwezi river water for its activities and drains its wastes (mainly sisal sap) into this river. The decrease in pH was mainly attributed to this. The lower pH is responsible for the loss of carbonate ions which are only detected under pH values greater than 8.4.

Irrigation waters with high Na result in higher accumulation of Na in the soil exchange complex with respect to other cations. This consequently results to reduced porosity, aeration and impeded water movement within the soil matrix as a result of soil structure destruction and blockage of pores. Crops grown on such soils suffer adversely from poor aeration and waterlogging conditions which cause poor root development and consequently poor uptake of water and nutrients. Sodium taken in higher proportions as compared with other ionic nutrients results to what is termed as "sodium injury". This may have contributed to the crop failure that resulted to the abandonment of one of the fields (Trt 1). A soluble sodium percentage (SSP) of upto 57 was observed (see Appendix 3). Chloride ions which are mainly associated with sodium ions were also found to be high (9.0 me/l) (Appendix 1). Chloride ions are also injurious to plants.

5.2. Physical and Chemical Parameters of the Soil.

5.2.1. Chemical Parameters.

5.2.1.1 pH.

From Appendix 1, it is observed that the mean pH in 1:2.5 soil/water ratio ranged between 6.8 and 7.8 for the first horizons (0-39 cm) and between 6.7 and 8.0 for the third horizons (79-150 cm). The former pH range is described as neutral to slightly alkaline. This pH is favourable to most crops. The latter pH range is described as neutral to moderately alkaline. This alkalinity degree tends to inhibit the uptake of micronutrients from the soil by plants.

The pH for all the treatments except Trt 2 was found to be significantly different at $P=<0.05$ (Table 2). The relatively higher pH for Trt 2 is attributed to high soluble sodium in the irrigation water used. The abandoned site (Trt 1) on the other hand has a lower pH than would be expected. This is attributed to the washing down of salts by heavy rains that were persistent (see Appendix 8). The salts are believed to be brought to the upper horizons through capillary action in the dry season.

The pH for Trt 1 and Trt 2 in the third horizons were found to be significantly different at $P=<0.05$ from those of Trt 3 and Trt 4 (Table 3). This is attributed to the high sodium introduced into the soil via the irrigation water used together with the high ESP in equilibrium with the soluble sodium.

5.2.1.2 Electrical Conductivity (EC).

The EC is a measure of the total soluble salts. The mean EC ranged from 0.09 to 0.3 mS/cm for the first horizons and from 0.06 to 1.43 mS/cm in the third horizons (Appendix 1). It is observed that EC increases down the profile. This is due to the washing down of salts by the heavy rains that were so prevalent. Both the above ranges reveal that the soils are not saline.

The EC was found to be insignificantly different at $P=<0.05$ for all treatments in the first horizons (Table 2). However the EC of the third horizons of Trt 1 was significantly different at $P=<0.05$ from all the other treatments (Table 3). Though not classified as a saline soil, this relatively high EC brings out an appraisal of salt build up in Trt 1 when compared to the other treatments. It therefore calls for concern because it is gradually worsening rather than rapidly changing the soil conditions.

Table 2. Means of measured parameters for the first horizons (0-39 cm)

Trt	EC mS/cm	ESP	SSP	CEC Cmol/ kg	SAR	RSC	Bd g/cm^3	Ksat cm/hr	SOC wt/wt
1	0.27^{b}	5.10^{a}	27.0^{a}	10.7^{a}	0.40^{a}	1.53_{a}	1.37^{a}	13.9^{b}	0.66^{a}
2	0.20^{b}	4.30^{a}	35.0^{a}	12.7^{a}	0.64^{a}	1.53^{a}	1.54^{a}	1.50^{c}	0.59^{a}
3	0.09^{b}	6.30^{a}	17.3^{a}	5.70^{b}	0.46^{a}	0.33^{a}	1.37^{b}	31.2^{a}	0.87^{a}
4	0.13^{b}	6.78^{a}	26.3^{a}	4.70^{b}	0.35^{a}	1.27^{a}	1.57^{b}	2.60^{c}	0.26^{b}

Table 2. continued.

Trt	pHw	pHk	%sa	%si	%cl
1	7.51^{ab}	6.38^{a}	74.33^{a}	6.67^{a}	19.00^{a}
2	7.84^{a}	6.89^{a}	73.00^{a}	6.67^{a}	20.00^{a}
3	6.82^{ab}	5.69^{a}	82.33^{a}	7.33^{a}	10.33^{a}
4	7.35^{ab}	6.13^{a}	86.67^{a}	5.33^{a}	8.00^{a}

Means with the same letter superscript
are not significantly different at $P=<0.05$
according to Duncan's multiple range test.

Table 3. Means of measured parameters for the third horizons (79-150 cm)

Trt	EC (mS/cm)	ESP	SSP	CEC (Cmol/kg)	SAR	RSC	Bd (g/cm^3)
1	1.43^{a}	27.33^{a}	93.67^{a}	18.33^{a}	17.19^{a}	4.23^{a}	1.50^{b}
2	0.27^{b}	4.33^{c}	39.33^{c}	10.33^{b}	0.73^{b}	0.68^{b}	1.57^{ab}
3	0.20^{b}	4.67^{bc}	23.33^{c}	10.33^{b}	0.92^{b}	0.98^{b}	1.41^{c}
4	0.06^{b}	7.33^{b}	26.33^{c}	7.33^{c}	0.09^{b}	1.49^{b}	1.57^{b}

Table 3. continued.

Trt	Ksat (cm/hr)	SOC (wt/wt)	pHw	pHk	%Sa	%Si	%Cl
1	0.17^{b}	0.18^{b}	8.06^{a}	7.08^{a}	61.67^{a}	8.0^{a}	30.33^{b}
2	0.24^{a}	0.26^{ab}	7.79^{a}	6.32^{a}	63.67^{a}	6.0^{a}	30.33^{b}
3	0.27^{a}	0.41^{a}	6.78^{b}	5.44^{b}	45.67^{b}	6.67^{a}	47.67^{a}
4	0.34^{a}	0.3^{ab}	6.89^{b}	6.32^{a}	61.33^{a}	4.67^{a}	34.0^{b}

Means with the same letter superscript are not significantly different at $P=<0.05$ according to Duncan's multiple range test.

5.2.1.3 Cation Exchange Capacity (CEC).

The mean CEC was found to be between 4 and 12 Cmol/kg of soil for the first horizons and between 7 and 18 in the third horizons (Appendix 2). The CEC is higher in the irrigated fields than in the non-irrigated ones. This was attributed to the ions added to the soil together with the irrigation water and their subsequent adsorption on the soil exchange sites.

Table 2 shows that there was a significant difference at $P=<0.05$ between the mean CEC for irrigated fields (Trt 1 and Trt 2) and the non-irrigated ones (Trt 3 and Trt 4) for the first horizons. For the third horizons however, Trt 1 showed a significant difference at $P=<0.05$

for irrigated fields (Trt 1 and Trt 2) and the non-irrigated ones (Trt 3 and Trt 4) for the first horizons. For the third horizons however, Trt 1 showed a significant difference at $P=<0.05$ from all the other treatments (Table 3).

5.2.1.4 Exchangeable Cations.

A look at Appendix 2 shows that exchangeable Ca and Mg are generally higher in proportion than Na and K for all the treatments. A notable observation however, is the significant difference at $P=<0.05$ for all treatments in the third horizons (Table 3). Even more interesting is the high ESP of Trt 1 in the third horizons (mean ESP as high as 27 was observed). This further supports the washing down of salts and their subsequent adsorption at lower depths.

5.2.1.5 Base Saturation Percentage (BSP).

The BSP was observed to be >50 for all the treatments (Appendix 2). This value, although it implies a relatively fertile soil, does not distinguish between different bases and imbalances in their relative proportions can cause severe problems. Appendix 3 shows that there are high soluble Na salts especially in Trt 1 (SSP as high as 97 was observed), followed by those of K, Mg and Ca respectively. These result to higher CEC values and BSP values are likely to be greater than 100. When soluble salts are high they should be subtracted from the exchangeable values obtained. Leaching of soluble salts prior to CEC measurement is not recommended because of hydrolysis effects even if alcohol is used.

5.2.1.6 Soil Organic Carbon (SOC).

Mean SOC values range from 0.26 to 0.87% in the first horizons and from 0.18 to 0.41%

Table 8. Correlation coefficients of measured parameters with infiltration rate values obtained using Horton's equation for the first horizons (0-39 cm)

	EC	Bd	Ca	Mg	K	Na	SAR	CEC	ESP	Ksat	SOC	Sa	Si	C
EC	1.00													
Bd	-0.35	1.00												
Ca	0.49	-0.26	1.00											
Mg	0.47	-0.39	0.9**	1.00										
K	0.8**	-0.53	0.59	0.45	1.00									
Na	0.30	-0.52	0.59	0.59	0.44	1.00								
SAR	0.66*	-0.29	0.23	0.22	-0.19	0.07	1.00							
CEC	0.41	-0.05	0.9**	0.9**	0.43	0.58	0.10	1.00						
ESP	-0.23	-0.12	-0.25	-0.37	-0.12	-0.03	-0.25	-0.23	1.00					
Ksat	-0.21	-0.7*	-0.25	-0.31	-0.01	0.30	0.10	-0.36	0.09	1.00				
SOC	-0.34	-0.34	0.18	0.21	-0.08	0.41	-0.16	0.13	-0.14	0.8**	1.00			
Sa	-0.16	0.16	-0.7*	-0.54	-0.34	-0.52	0.05	0.8**	0.05	0.13	-0.15	1.00		
Si	-0.45	-0.39	0.21	0.18	0.10	0.45	-0.04	0.32	0.13	0.20	0.17	-0.50	1.00	
Cl	0.18	-0.07	0.69*	0.53	0.34	0.44	-0.05	0.8**	-0.09	-0.20	0.18	-1**	0.27	1.00

* Correlation at 5 significance level
** Correlation at 1 significance level.

5.2.2.5 Antecedent Moisture Content (w).

Water content was generally very low with the highest being 25% and the lowest 11% (Appendix 4). This low levels of moisture are attributed to the sandy nature of the soils together with their low SOC. It can also be due to the high evaporation rates common in this

From Tables 2 and 3 it is observed that Trt 1 and Trt 3 have the lowest mean bulk density while Trt 2 and Trt 4 have the highest in both the first and third horizons. This is attributed to the fact that Trt 1 and Trt 3 are under natural vegetation with good rooting systems and higher SOC. They have also not undergone any mechanical compaction in the recent past.

5.2.2.3 Porosity (f).

Porosity values range from 38 to 53% (Appendix 4). The lowest porosity is found in Trt 1 and the highest in Trt 3. Sandy soils with a total pore space <40% are liable to restrict root growth due to excessive strength. Appendix 4 shows that all the second horizons in Trt 1 have porosity <40%. This is due to the illuviation of clay, together with the salts high in sodium, into these horizons (see Appendix 7a). High sodium levels in the soil (greater than 15% exchangeable sodium) leads to the dispersion of clay particles which clog the soil pores.

5.2.2.4 Infiltration Rate (i).

The results for the mean infiltration rates per treatment per time are given in Appendix 5. Due to the high temperatures prevailing during the time of this study, the infiltrometer data was sometimes inconsistent as a result of the expansion of the plastic infiltrometer. Table 4 gives the calculated means of replicates for the four treatments using three infiltration rate equations namely, Horton's, Kostiakov's and Philip's. Table 5 and Figures 4a to 4d show that Horton's equation fitted best with the observed values ($r^2=0.950$). Thus the analysis of variance given in Table 6 constitutes results obtained using Horton's equation.

Table 4. Means of constants fitted to Kostiakov's, Horton's and Philip's equations.

Trt	Kostiakov	Horton	Philip
1	a= 15.97	a= 8.07	a= 13.90
	b= -0.19	b= 20.49	b= 5.81
	r^2=0.52	c= 0.64	r^2=0.38
		r^2=0.64	
2	a= 11.76	a= 13.82	a= 9.56
	b= -0.23	b= 22.82	b= 5.93
	r^2=0.73	c= -16.25	r^2=0.79
		r^2=0.72	
3	a= 29.04	a= 25.49	a= 12.76
	b= -0.23	b= 42.08	b= 1.57
	r^2=0.83	c= -3.85	r^2=0.17
		r^2=0.83	
4	a= 13.49	a= 10.44	a= 12.761
	b= -0.06	b= 25.11	b= 1.573
	r^2=0.14	c= -0.16	r^2= 0.169
		r^2=0.13	

* $i = Bt^{-1}$ (Kostiakov)

$i = i_c + (i_o - i_c) e^{*t}$ (Horton)

$i = i_c + S/2t^{1/2}$ (Philip)

Table 5. Overall agreements of Kostiakov's, Horton's and Philip's equations with the observed infiltration values

Equation	Kostiakov	Horton	Philip
r^2	0.946	0.950	0.925

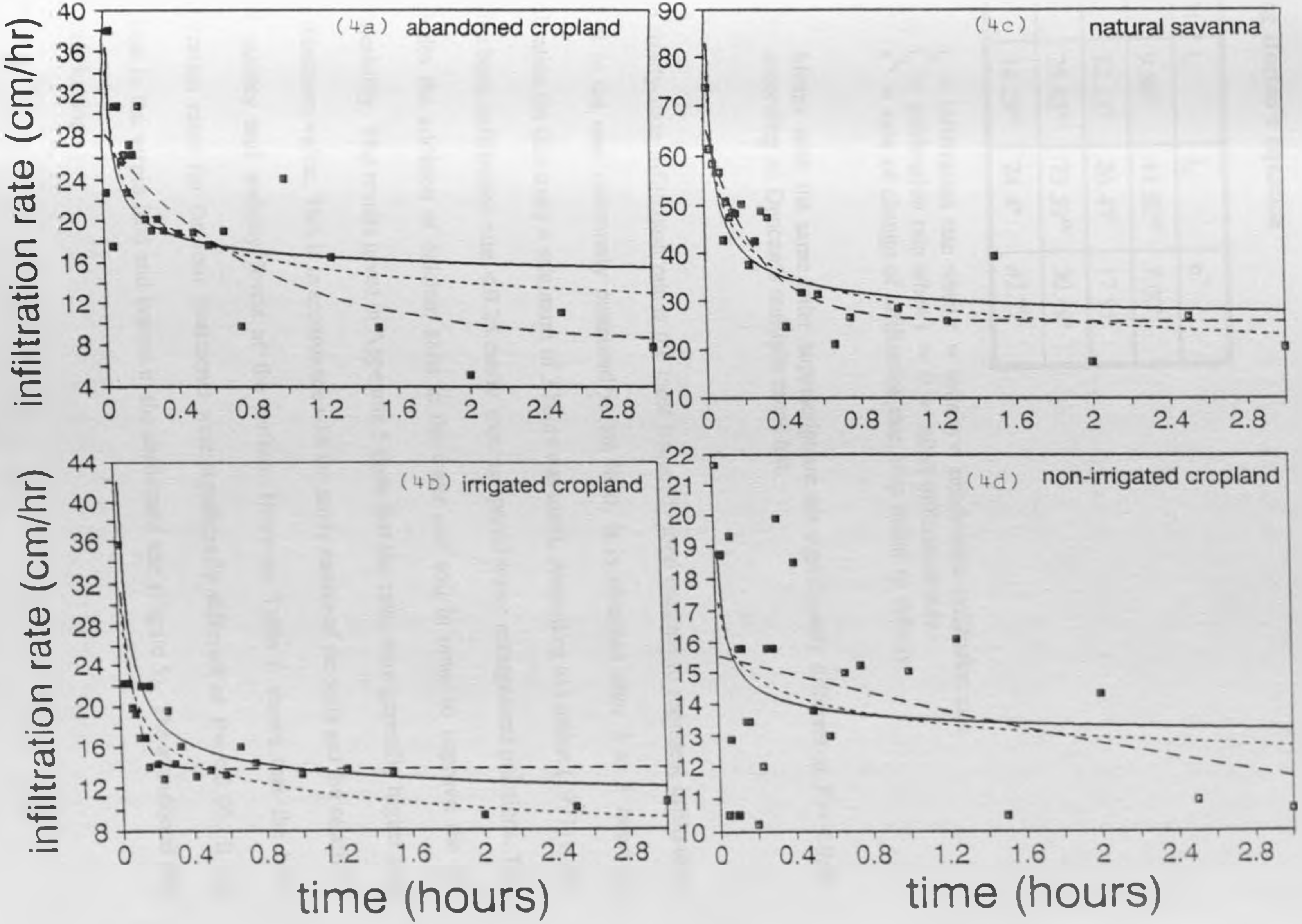


Fig. 4a-4d - Graphic fits of Kostiacov's Horton's and Philip's Equation to observed infiltration rate

Table 6. Means of infiltration rates in cm/hr for the first horizons (0-39 cm) obtained using Horton's equation

Trt	i_c	i_o	e^{*t}
1	9.86^{a}	41.82^{ab}	7.00^{a}
2	12.21^{b}	26.47^{b}	17.95^{a}
3	25.85^{b}	73.59^{ab}	30.49^{a}
4	14.29^{ab}	24.4^{a}	42.7^{b}

i_c = infiltration rate when t = infinity= steady-state infiltration rate
i_o = infiltration rate when t = 0 = initail infiltration rate
e^{*t} = rate of change of infiltration rate from initial to infinity.

Means with the same letter superscript are not significantly different at $P=<0.05$ according to Duncan's multiple range test.

The steady-state infiltration rate is the most frequently used quantity to represent infiltration and it is the one commonly measured in the field. It is obtained after 3 to 5 hours of infiltration (in this study a minimum of 3 hours was used). According to Landon (1991) a soil with a basic infiltration rate <0.25 cm/hr requires special water management practices. This includes the addition of calcium salts to the water and soil in order to improve the soil permeability. The results given in Appendix 5 show that the rates were generally higher than the minimum value. This is in accordance with the sandy nature of the soils and the relatively low salinity and sodicity levels at the surface. However Table 6 shows that the basic infiltration rates for the four treatments were significantly different at $P=<0.05$. It was highest in the virgin land and lowest in the abandoned site (Figure 5). The abandoned site, despite having

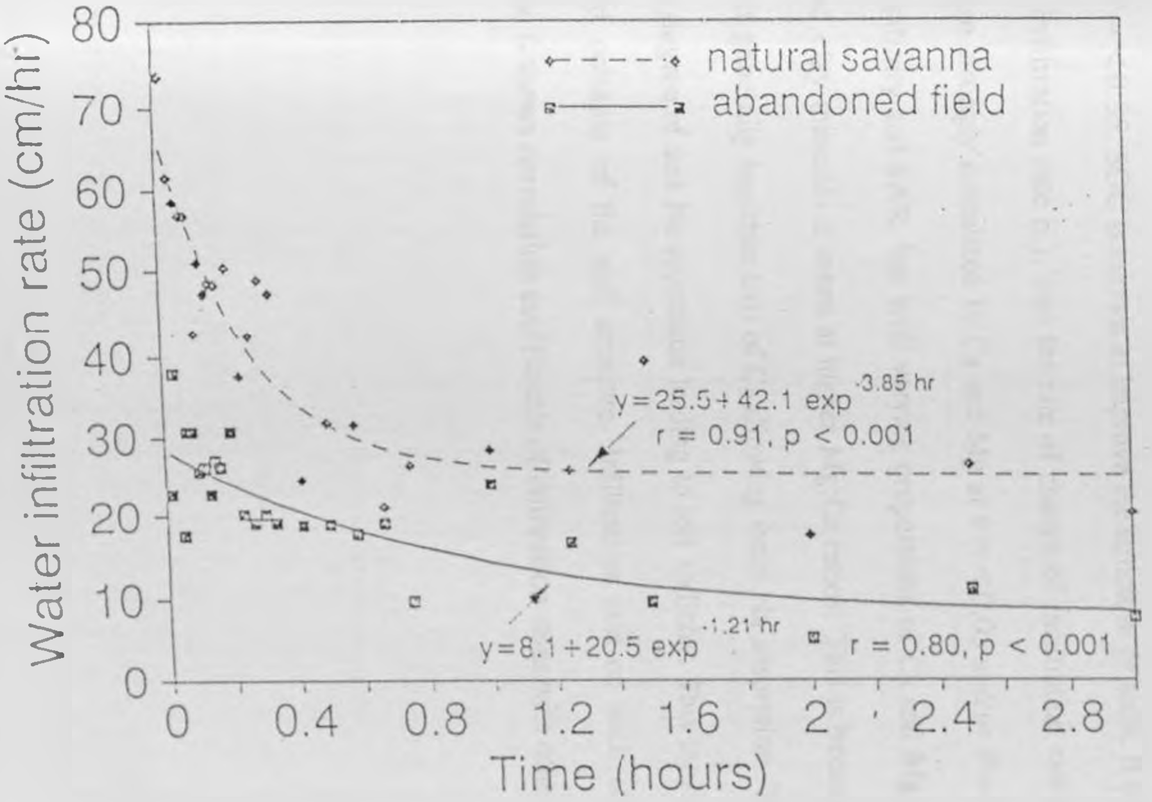


Fig 5. Mean Water Infiltration Rates of Two Contrasting Treatments fitted to Horton's equation

the lowest bulk density at the surface horizons (see Appendix 4) has the lowest infiltration rate. This is attributed to the collapse of the soil structure on the application of the irrigation water thus inhibiting water entry into the soil. This together with its high sodicity level and low SOC has contributed to its lower infiltration rate.

It is observed from Table 7 that SOC was strongly correlated with the three quantities of infiltration at $P = < 0.05$. SOC is known to improve the structure of soils. It is also observed that the initial infiltration rate (i_o), and the rate of change of infiltration rate from initial to infinity (e^{*t}), are strongly correlated to Ca and Mg at $P = < 0.05$ and/or $P = < 0.01$. At the same level of salinity and SAR, but with varying proportions of Ca and Mg, adsorption of Na by soils and clay minerals is more at higher Mg:Ca ratios. This is because the bonding energy of Mg is generally less than that of Ca allowing more Na adsorption. The result is the increase in the degree of soil Na saturation leading to soil sodicity. This inevitably results to destruction and collapse of the soil structure. Infiltration rate on such soils is severely curtailed. Table 8 shows correlation coefficients of infiltration rates with other measured soil parameters.

Table 8. Correlation coefficients of measured parameters with infiltration rate values obtained using Horton's equation for the first horizons (0-39 cm)

	EC	Bd	Ca	Mg	K	Na	SAR	CEC	ESP	Ksat	SOC	Sa	Si	C
EC	1.00													
Bd	-0.35	1.00												
Ca	0.49	-0.26	1.00											
Mg	0.47	-0.39	0.9^{**}	1.00										
K	0.8^{**}	-0.53	0.59	0.45	1.00									
Na	0.30	-0.52	0.59	0.59	0.44	1.00								
SAR	0.66^{*}	-0.29	0.23	0.22	-0.19	0.07	1.00							
CEC	0.41	-0.05	0.9^{**}	0.9^{**}	0.43	0.58	0.10	1.00						
ESP	-0.23	-0.12	-0.25	-0.37	-0.12	-0.03	-0.25	-0.23	1.00					
Ksat	-0.21	-0.7^{*}	-0.25	-0.31	-0.01	0.30	0.10	-0.36	0.09	1.00				
SOC	-0.34	-0.34	0.18	0.21	-0.08	0.41	-0.16	0.13	-0.14	0.8^{**}	1.00			
Sa	-0.16	0.16	-0.7^{*}	-0.54	-0.34	-0.52	0.05	0.8^{**}	0.05	0.13	-0.15	1.00		
Si	-0.45	-0.39	0.21	0.18	0.10	0.45	-0.04	0.32	0.13	0.20	0.17	-0.50	1.00	
Cl	0.18	-0.07	0.69^{*}	0.53	0.34	0.44	-0.05	0.8^{**}	-0.09	-0.20	0.18	-1^{**}	0.27	1.00

* Correlation at 5 significance level
** Correlation at 1 significance level.

5.2.2.5 Antecedent Moisture Content (w).

Water content was generally very low with the highest being 25% and the lowest 11% (Appendix 4). This low levels of moisture are attributed to the sandy nature of the soils together with their low SOC. It can also be due to the high evaporation rates common in this region. The insignificant difference in the texture of the soils coincides with the insignificant difference in their moisture content.

5.2.2.6 Saturated Hydraulic Conductivity (Ksat).

The mean saturated hydraulic conductivity was found to decrease with depth (see Appendix 4). The Ksat of Trt 1 and Trt 3 are observed to be higher than those of Trt 2 and Trt 4. This is attributed to the lower bulk density, higher SOC and lack of recent compaction of the former fields. The Ksat was found to be insignificantly different at $P=<0.05$ for Trt 2 and Trt 4 in the first horizons but insignificantly different at $P=<0.05$ for all treatments in the third horizons except Trt 1 which exhibited the lowest Ksat. The high sodium salt levels in irrigated fields cause dispersion of clay particles which block the soil pores. This reduces water movement within the soil. It was observed from this study that Ksat is less sensitive to sodicity than infiltration rate.

Ksat was strongly correlated to SOC at $P=<0.01$ (Table 7). The greatly reduced SOC in the third horizons is most likely the cause of the reduced Ksat. The SOC was also found to be insignificantly different at $P=<0.05$ for all treatments except Trt 3 which exhibited the highest SOC values.

5.2.2.7 Soil Water Retention.

Soil water retention was higher in irrigated fields (Trt 1 and Trt 2) than on non irrigated ones (Trt 3 and Trt 4) for all treatments and horizons (Figures 6a and 6b). There was a drastic decrease in water retention between 0 and 100 kPa followed by slight gradual decreases thereafter. This is attributed to the first emptying of large soil pores and then of the small ones. There was even lesser decreases in water retention between 1000 and 1500 kPa.

Irrigated fields, by virtue of their higher sodium salts, have poor soil structure with dispersed clays that block soil pores. This results to many small pores which tend to retain more water in a manner similar to clayey soils. The presence of salts tend to increase the soil osmotic pressure meaning that greater energy is required for plant roots to extract water from the soil.

The greater water retention for the irrigated fields implies that less water is released for plant uptake i.e. less water is available to plants. In fact plants would tend to lose water by osmosis rather than extract it from the soil. To counteract this tendency, plants use up more valuable energy in extracting water from the soil. This denies other physiological processes of the greatly needed energy leading to poor growth and/or complete crop failure.

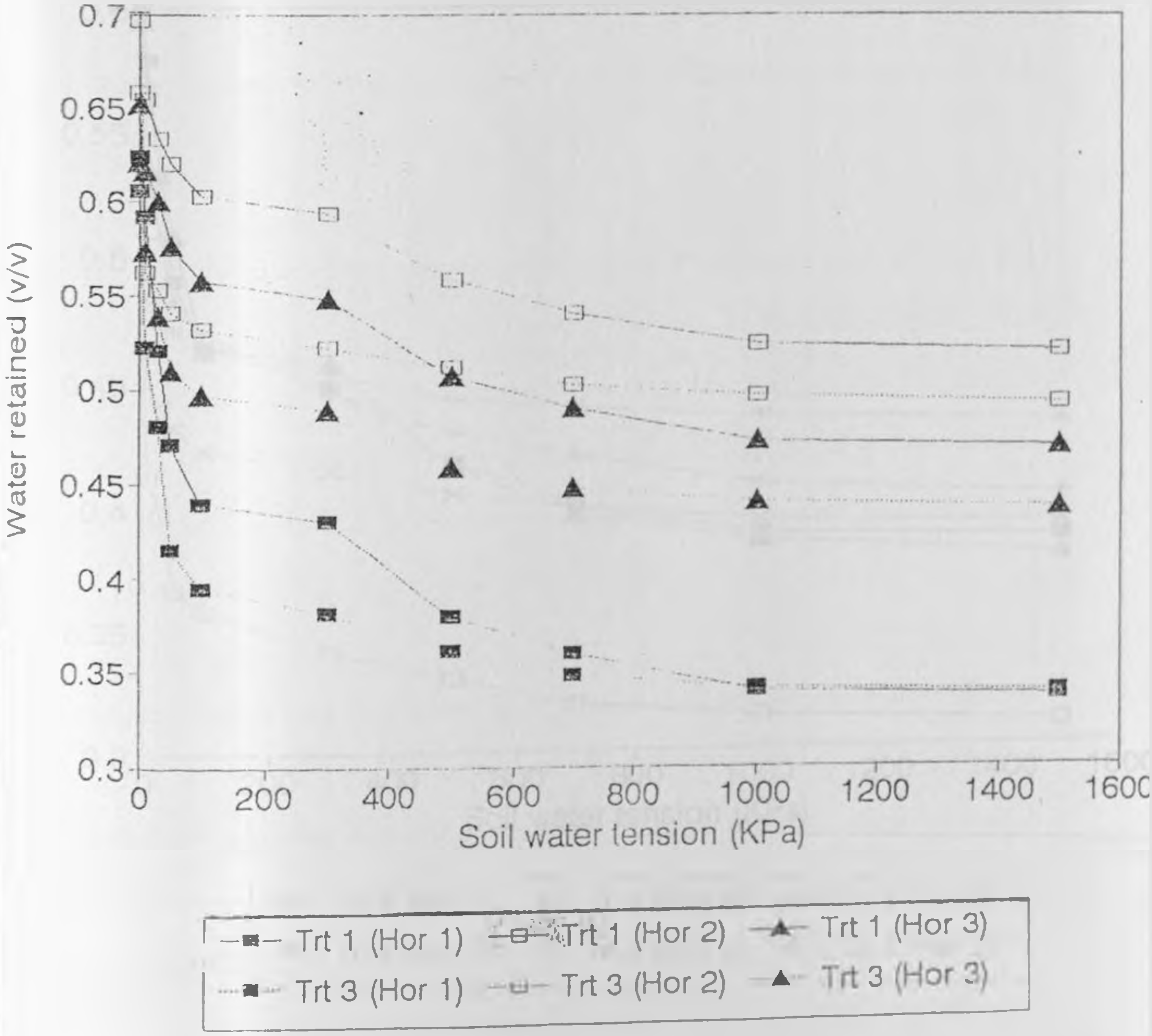


Fig. 6a. Soil moisture retention curves for two contrasting treatments (Trt. 1 and Trt. 3).

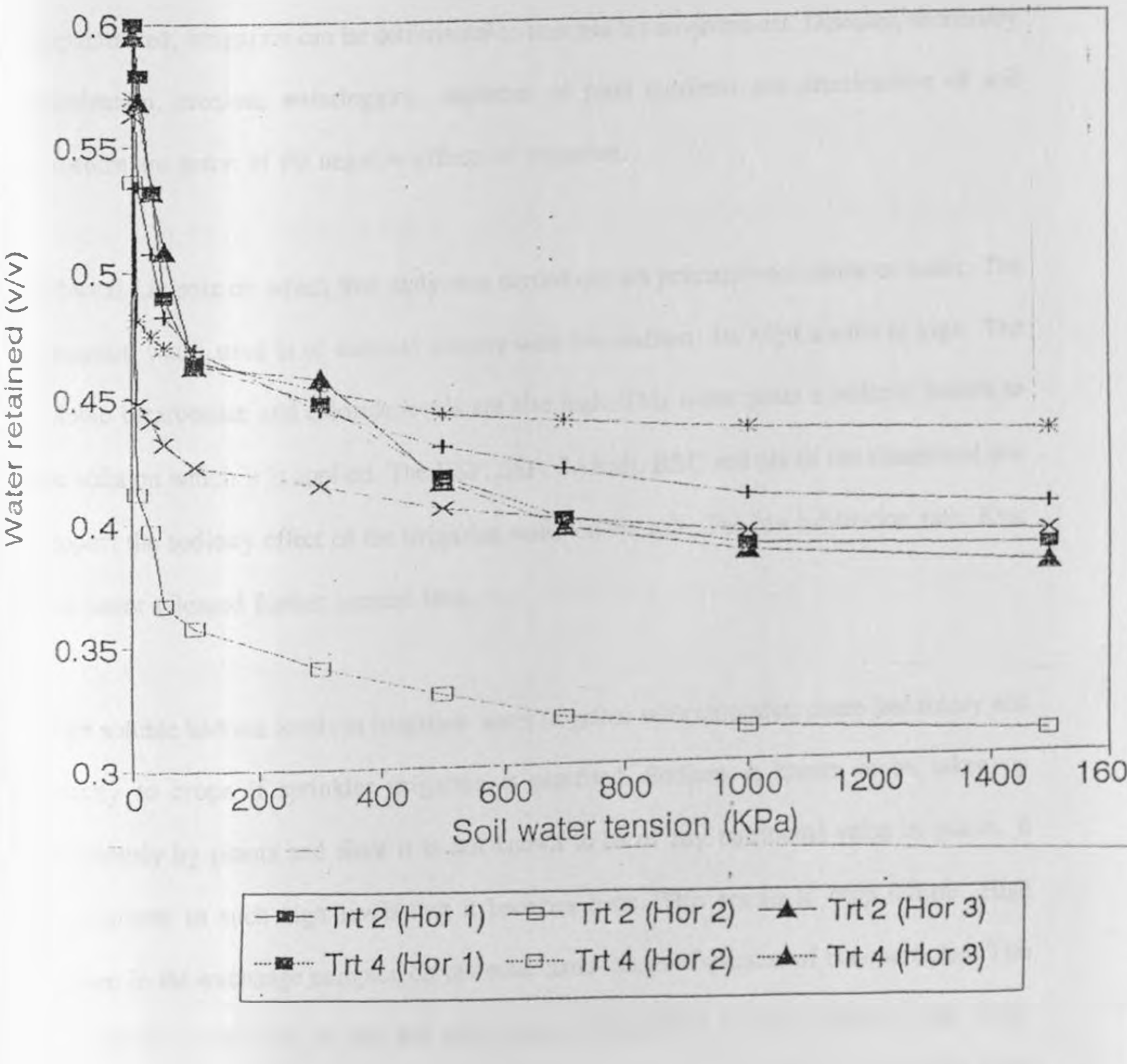


Fig. 6b. Soil moisture retention curves for two contrasting treatments (Trt. 2 and Trt. 4).

CHAPTER SIX

6.0 SUMMARY AND CONCLUSIONS

Irrigation projects are expensive to plan and implement therefore care must be taken to maintain them. Irrigation is beneficial in that it provides for the production of food in regions where rainfall cannot meet the crop water requirement. However, if not properly planned and implemented, irrigation can be detrimental to man and his environment. Diseases, secondary salinization, erosion, waterlogging, depletion of plant nutrients and deterioration of soil structure are some of the negative effects of irrigation.

Kibwezi Lixisols on which this study was carried out are primarily not saline or sodic. The irrigation water used is of medium salinity with low sodium. Its Mg:Ca ratio is high. The soluble bicarbonate and chloride levels are also high. This water poses a sodicity hazard to the soils on which it is applied. The ESP, SSP, SARadj, RSC and pH of the abandoned site support the sodicity effect of the irrigation water on the soil. The low infiltration rate, Ksat and water released further support this.

High soluble sodium levels in irrigation water (together with chlorides) cause leaf injury and toxicity to crops if sprinkler irrigation is practised. Sodium is known to be taken up luxuriously by plants and since it is not known to be of any nutritional value in plants, it accumulates to such high levels that it becomes toxic. This results to crop failure. High sodium in the exchange complex on the other hand causes dispersion of clay particles. This leads to the blockage of the soil pores and consequently to poor aeration and water conductivity. Crops grown on such soils are bound to fail except under good soil and water management.

The sandy nature of the soils is expected to modify the effects of Na. However, coarse textured soils with low salts (especially those of Ca and Mg) have low aggregation. The application of water thus leads to the collapse of the soil structure and curtails any further entry of water into the soil. This may be reason why the ground water level does not rise appreciably enough to be detected despite the fact that large amounts of water are being applied.

Although Richards (1954) grouped Ca and Mg together as similar ions beneficial in developing and maintaining soil structure, Mg was found in this study to cause soil structure deterioration and develop a Mg solonetz. Similar findings were observed by McNeal *et al* (1968), Chi *et al* (1977) and Abder-Rahman and Powell (1979). Paliwal (1972) observed that about 73% of the 4162 samples of poor quality water of Rajasthan had more Mg than Ca.

Further research work should be carried out to determine other causes of seondary salinization in Kibwezi.

CHAPTER SEVEN

7.0 RECOMMENDATIONS

1. Chemical amendments especially calcium salts should be added to the irrigation water. Gypsum ($CaSO_4.2H_2O$) is a cheap, efficient and available calcium salt. It has low solubility. It may be beneficial to add gypsum to the soil periodically. The calcium replaces sodium from the exchange complex.

2. Organic matter should be added to the soils. This can be in form of manure such as ploughing in green weeds or poor crop and animal dung. Organic matter improves the soil structure therefore improving aeration, water movement and root development.

3. Tolerant crops and grases should be grown. Such crops include beet, wheat, cotton, barley and tomatoes while grasses include the rhodes grass. Sensitive crops such as deciduous fruits, nuts, avocadoes and citrus should be avoided. Occasional deep ploughing of the abandoned field would help in loosening of the strength of the sub-soil.

4. Irrigation water should be applied just to meet the crop water requirement without leaching away the salts. Excessive water applications can result to waterlogging conditions and/or the raising of the groundwater table.

5. If crop rotation is practised then heavy applications of water should be administered on fields formally under drip irrigation prior to planting the new crop. This leads to the leaching away of salts at the periphery of emmiters.

CHAPTER EIGHT

8.0 REFERENCES

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APPENDICES

Appendix 1. pH, EC, Soluble Anions and RSC of soil suspensions

Prof. No	Soil depth (cm)	pH water	pH KCl	EC_e (mS/cm)	Soluble Anions (me/l)			RSC
					CO_3	HCO_3	Cl	
Trt 1								
1	0-30	8.10	7.15	0.5	-	2.0	12.0	1.70
	30-48	8.33	7.18	1.0	-	3.0	5.5	2.89
	48-80	8.38	7.53	1.6	-	5.0	10.0	4.80
	80-150	8.26	7.24	0.2	-	5.0	8.5	5.00
2	0-34	7.35	6.03	0.2	-	1.0	3.0	0.93
	34-81	7.55	6.73	0.2	-	1.0	12.0	0.93
	81-140	8.01	7.49	1.2	-	3.0	3.5	2.94
3	0-39	7.07	5.97	0.1	-	2.0	1.0	1.97
	39-73	8.28	6.42	0.4	-	2.0	5.5	1.89
	73-140	7.90	6.51	1.5	-	5.0	9.5	4.93
Trt 2								
4	0-29	7.53	6.29	0.2	-	1.0	1.0	0.70
	29-82	8.09	6.40	0.3	-	1.0	3.0	1.00
5	0-11	7.75	6.83	0.1	-	2.0	3.0	1.99
	11-79	8.21	6.90	0.2	-	1.0	4.0	0.99
	79-109	7.80	6.16	0.4	-	0.5	1.5	0.03
6	0-27	8.24	7.56	0.3	-	2.0	2.5	1.90
	27-60	7.82	6.82	0.2	-	2.0	3.5	1.96
	60-150	7.49	6.41	0.1	-	1.0	3.6	1.00

Appendix 1. Continued.

Prof. No	Soil depth (cm)	pH water	pH KCl	EC_e (mS/cm)	Soluble Anions (me/l)			RSC
					CO_3	HCO_3	Cl	
Trt 3								
7	0-30	6.86	5.72	0.10	-	-	-	-
	30-99	6.39	5.76	0.20	-	1.00	2.5	0.97
	99-131	7.19	5.20	0.50	-	-	1.5	-
8	0-32	6.66	5.13	0.06	-	1.00	1.0	0.98
	32-85	6.50	5.49	0.05	-	2.00	2.0	0.98
	85-135	6.20	5.62	0.04	-	-	-	-
9	0-33	6.94	6.21	0.10	-	2.50	2.5	-
	33-95	6.0	5.25	0.08	-	1.50	1.5	0.97
	95-150	6.93	5.49	0.05	-	1.00	1.0	1.00
Trt 4								
10	0-35	7.21	6.47	0.09	-	2.00	2.0	1.96
	35-65	7.02	6.83	0.10	-	1.50	1.0	1.50
	65-140	7.16	6.45	0.10	-	2.50	2.0	2.50
11	0-36	6.95	5.08	0.09	-	1.00	6.0	0.96
	36-67	6.79	5.31	0.05	-	1.00	0.5	0.98
	67-150	6.21	5.72	0.04	-	1.00	5.0	0.97
12	0-33	7.90	6.85	0.20	-	1.00	2.5	0.89
	33-58	7.37	6.94	0.08	-	1.00	1.0	0.92
	58-113	7.30	6.87	0.05	-	1.00	2.0	0.99

Appendix 2. Soil Organic carbon, CEC, Exchangeable cations and ESP of soil.

Prof. No	Soil Depth (cm)	SOC (%wt/wt)	Exchangeable Cations (me/100g)				Total Cations (me/l)	CEC (Cmol/kg)	ESP	BSP
			Na	K	Ca	Mg				
Trt 1										
1	0-30	0.42	0.69	1.82	5.40	3.56	11.5	11	6.3	>100
	30-48	0.28	8.25	2.75	1.85	2.37	15.2	16	54	95
	48-80	0.05	12.0	3.00	4.00	1.42	20.4	22	59	93
	80-150	0.18	5.54	4.25	6.59	2.28	18.5	19	30	97
2	0-34	0.64	0.50	1.50	5.10	3.62	10.7	11	4.0	97
	34-81	0.39	0.25	1.40	7.99	3.63	13.1	14	20.0	93
	81-140	0.22	4.75	2.50	6.85	4.30	18.4	19	25.0	97
3	0-39	0.53	0.50	1.00	5.10	3.71	10.3	10	5.0	>100
	39-73	0.42	3.50	2.50	2.15	3.42	11.6	14	25.0	83
	73-150	0.14	8.00	3.00	2.40	3.12	16.5	17	17.0	97
Trt 2										
4	0-29	0.64	0.50	0.50	5.45	4.58	11.0	13	4.0	85
	29-82	0.38	0.50	1.00	5.50	4.71	11.7	10	4.0	>100
5	0-11	0.62	0.50	0.50	5.30	3.77	10.1	14	5.0	72
	11-79	0.32	0.01	0.50	3.65	3.92	9.07	10	1.0	91
	79-109	0.24	0.50	1.00	5.60	4.71	11.8	10	5.0	>100
6	0-27	0.51	0.50	1.00	4.45	4.50	10.4	11	4.0	94
	27-60	0.30	0.50	1.00	3.10	4.51	9.14	9	5.0	>100
	60-150	0.15	0.50	1.00	4.05	3.94	9.49	11	4.0	86

Appendix 2. Continued.

Prof. No	Soil depth (cm)	SOC (%wt/wt)	Exchangeable Cations (me/100g)				Total Cation (me/l)	CEC (Cmol/kg)	ESP	BSP
			Na	K	Ca	Mg				
Trt 3										
7	0-30	0.94	0.50	0.50	2.37	2.60	5.97	7	7	85
	30-99	0.35	0.75	1.00	2.87	3.79	8.41	8	9	89
	99-131	0.58	0.50	0.50	5.40	4.5	10.9	12	4	91
8	0-32	0.85	0.50	0.50	1.80	1.87	4.67	4	4	>100
	32-85	0.44	1.00	1.00	1.72	4.10	7.82	8	12	98
	85-135	0.35	0.50	0.50	2.37	4.58	7.95	10	8	79
9	0-33	0.81	0.50	0.50	3.50	2.21	6.71	6	10	>100
	33-95	0.44	1.00	1.00	2.80	4.58	9.38	10	5	94
	95-150	0.30	0.50	0.50	2.92	4.58	8.50	9	8	94
Trt 4										
10	0-35	0.24	0.50	0.50	2.15	1.94	5.09	6	8	75
	35-65	0.32	0.50	0.50	1.25	1.87	4.12	6	8	69
	65-140	0.28	0.50	0.50	3.32	2.60	6.92	6	8	>100
11	0-36	0.18	Tr	0.50	1.67	1.37	3.54	4	12	88
	36-67	0.30	Tr	0.50	1.67	1.37	3.57	4	-	89
	67-150	0.21	Tr	0.50	2.07	3.52	6.09	8	-	76
12	0-33	0.37	Tr	0.50	2.00	1.87	4.37	4	-	>100
	33-58	0.46	Tr	0.50	2.02	2.29	4.80	4	-	>100
	58-113	0.41	Tr	0.50	3.07	4.02	7.59	8	-	95

Appendix 3. Soluble Cations, SSP, pH*c, SAR and SARadj of soil suspensions.

Prof. No	Soil depth (cm)	Soluble Cations (me/l)				SSP	SAR
		Ca	Mg	Na	K		
Trt 1							
1	0-30-	Tr	0.03	0.61	0.36	48	1.57
	30-48	Tr	0.11	0.80	0.85	95	3.41
	48-80	Tr	0.02	8.04	0.18	95	25.2
	80-150	0.02	0.07	13.9	0.36	97	98.3
2	0-34	Tr	0.07	0.09	0.31	19	0.48
	34-81	Tr	0.03	0.49	0.51	46	2.62
	81-140	0.03	0.03	8.49	0.31	96	49.0
3	0-39	Tr	0.11	0.06	0.33	14	0.49
	39-73	Tr	0.07	2.39	0.85	71	10.1
	73-140	Tr	0.87	4.78	0.64	87	25.5
Trt 2							
4	0-29	0.80	0.22	0.30	0.26	35	1.29
	29-82	Tr	Tr	0.43	0.48	47	-
5	0-11	Tr	0.01	0.28	0.49	36	3.96
	11-79	Tr	0.01	1.69	0.04	97	23.9
	79-109	0.16	0.31	0.43	0.31	35	0.89
6	0-27	0.06	0.04	0.65	0.23	82	2.91
	27-60	0.01	0.03	0.02	0.15	9.0	0.14
	60-150	Tr	Tr	0.61	0.36	63	1.00

Appendix 3. Continued.

Prof. No	Soil depth (cm)	Soluble Cations (me/l)				SSP	SAR
		Ca	Mg	Na	K		
Trt 3							
7	0-30	0.01	0.02	0.02	0.18	9	0.16
	30-99	0.01	0.02	0.06	0.08	35	0.49
	99-131	0.01	0.02	0.26	0.11	65	2.12
8	0-32	Tr	0.02	0.04	0.11	23	0.4
	32-85	Tr	0.02	0.02	0.08	17	0.2
	85-135	0.01	0.05	0.02	0.04	17	0.11
9	0-33	0.01	0.02	0.04	0.13	20	0.33
	33-95	0.01	0.02	0.4	0.13	71	3.26
	95-150	Tr	Tr	0.05	0.13	28	0.0
Trt 4							
10	0-35	0.02	0.22	0.04	0.11	21	0.28
	35-65	Tr	Tr	0.17	1.28	12	0.0
	65-140	Tr	Tr	0.17	0.64	21	0.0
11	0-36	0.01	0.03	0.02	0.15	9	0.14
	36-67	Tr	0.02	0.11	0.08	52	1.1
	67-150	0.03	Tr	0.11	0.08	52	0.9
12	0-33	Tr	0.11	0.61	0.51	49	2.6
	33-58	Tr	0.08	0.28	0.49	33	1.4
	58-113	Tr	0.01	0.06	0.06	46	0.85

Appendix 4. Physical properties of the soils.

Prof. No	Soil depth (cm)	Texture			Textural class	Bulk density (g/cm^3)	Porosity (%)	Ksat (cm/hr)	Water content (%)
		%Sand	%Silt	%Clay					
Trt 1									
1	0-30	73	6	21	SL	1.27	52	14.4	20.7
	30-48	63	10	27	SCL	1.61	39	0.04	22.0
	48-80	61	4	35	SCL	1.50	43	0.10	20.4
	80-150	59	8	33	SCL	1.44	46	0.19	9.00
2	0-34	71	10	19	SL	1.33	50	13.3	21.0
	34-81	65	8	27	SCL	1.64	38	0.08	22.2
	81-140	59	10	31	SCL	1.55	41	0.18	20.5
3	0-39	79	4	17	LS	1.51	43	13.9	21.1
	39-73	68	6	26	SCL	1.58	39	0.02	15.5
	73-140	67	6	27	SCL	1.50	43	0.14	20.0
Trt 2									
4	0-29	81	6	13	LS	1.53	42	0.88	18.4
	29-82	57	8	35	SCL	1.55	41	0.11	21.5
5	0-11	57	8	35	SCL	1.56	41	0.85	22.5
	11-79	59	14	37	SC	1.55	41	0.22	20.1
	79-109	69	4	27	SCL	1.58	40	0.46	19.8
6	0-27	81	6	12	LS	1.54	42	2.77	17.2
	27-60	75	6	18	SL	1.56	41	1.57	18.6
	60-150	65	6	29	SCL	1.57	41	0.16	12.9

Appendix 4. Continued.

Prof. No	Soil depth (cm)	Texture			Textural class	Bulk density (g/cm^{3})	Porosity (%)	Ksat (cm/hr)	Water content (%)
		%Sand	%Silt	%Clay					
Trt 3									
7	0-30	79	10	11	LS	1.44	46	30.0	20.3
	30-99	43	6	51	C	1.50	43	0.73	23.9
	99-131	51	10	39	SC	1.37	48	0.38	23.3
8	0-32	85	4	11	LS	1.44	46	32.2	17.2
	32-85	51	4	45	SC	1.54	42	1.34	21.3
	85-135	41	4	55	C	1.40	47	0.17	24.6
9	0-33	83	8	9	LS	1.24	53	32.4	18.5
	33-95	47	6	47	SC	1.53	42	0.26	24.4
	95-150	45	6	49	C	1.46	45	0.26	25.0
Trt 4									
10	0-35	83	8	9	LS	1.56	41	0.76	16.8
	35-65	87	6	7	LS	1.64	41	0.06	11.9
	65-140	65	4	31	SCL	1.63	38	0.21	19.4
11	0-36	87	4	9	LS	1.57	41	2.60	17.2
	36-67	77	2	21	LS	1.59	40	0.57	11.9
	67-150	63	6	31	SCL	1.56	41	0.71	20.5
12	0-33	90	4	6	LS	1.58	40	4.43	11.3
	33-58	90	2	8	LS	1.53	42	1.19	13.4
	58-113	56	4	40	SC	1.57	41	0.09	21.0

Appendix 5. Mean infiltration rates (cm/hr) per treatment per time.

Minutes	Trt 1	Trt 2	Trt 3	Trt 4
1	22.820	35.707	73.753	21.657
2	38.034	22.245	61.467	18.729
3	17.553	22.245	58.540	10.534
4	30.721	19.905	56.788	12.874
5	30.721	19.317	56.788	19.317
6	25.748	16.978	42.738	10.534
7	26.330	21.957	50.933	15.802
8	22.820	16.978	47.417	15.802
9	27.212	14.050	48.594	13.462
10	26.330	21.957	39.235	13.462
12	30.721	14.344	94.259	10.240
14	20.187	12.880	37.759	11.998
16	19.017	19.762	42.444	15.802
18	20.187	14.344	48.881	15.802
20	19.017	16.096	47.417	19.899
25	18.724	13.114	24.582	18.494
30	18.842	13.700	31.841	13.810
35	17.671	13.232	31.493	12.992
40	18.957	16.039	21.074	14.981
45	9.716	14.403	26.456	15.213
60	24.104	13.270	28.371	15.019
75	16.500	13.777	25.836	16.113
90	9.596	13.465	39.455	10.494
120	5.170	9.464	17.539	14.290
150	11.039	10.186	26.714	10.965
180	7.783	10.654	20.486	10.691

Appendix 6. Soil Moisture Characteristics.

Trt	Hor	Tension in kPa									
		0	10	30	50	100	300	500	700	1000	1500
1	1	0.624	0.592	0.521	0.471	0.440	0.431	0.380	0.360	0.340	0.337
	2	0.658	0.654	0.633	0.620	0.603	0.594	0.558	0.540	0.524	0.521
	3	0.621	0.616	0.600	0.576	0.557	0.548	0.507	0.490	0.473	0.470
2	1	0.600	0.579	0.532	0.490	0.464	0.458	0.418	0.400	0.388	0.385
	2	0.595	0.534	0.507	0.482	0.469	0.462	0.467	0.420	0.408	0.402
	3	0.570	0.481	0.475	0.470	0.465	0.453	0.443	0.439	0.434	0.432
3	1	0.606	0.522	0.481	0.416	0.394	0.381	0.361	0.348	0.341	0.339
	2	0.697	0.562	0.553	0.541	0.532	0.522	0.512	0.503	0.497	0.493
	3	0.651	0.573	0.539	0.510	0.497	0.489	0.459	0.448	0.441	0.438
4	1	0.536	0.421	0.397	0.367	0.358	0.341	0.330	0.319	0.313	0.309
	2	0.63	0.448	0.441	0.432	0.423	0.415	0.405	0.400	0.393	0.391
	3	0.595	0.568	0.532	0.508	0.463	0.458	0.416	0.396	0.385	0.378

Appendix 7a: Representative Soil Profile Description of Abandoned Kibwezi Solonetz (Trt 1).

General Site Information

Observation No.and date : 2; 7/12/94
Soil classification (FAO/UNESCO) : Solonetz
Geological formation : Basement System Rocks
Parent material : Gneisses
Local petrography : Upland
Macro relief: Slope : Flat to very gently undulating. 0-2%, linear, regular.
Micro relief : None
Land use/vegetation : Previously under irrigation, now abandoned, under *Cenchrus ciliaris* and *Acacia drepanolobium*
Erosion : Nil
Ground water table level : Deep
surface sealing/crusting/ Cracking : Limited
Drainage class : Well drained
Effective soil depth : > 150 cm

Soil Profile Description

A 0-30 cm	Dark reddish brown (10R 3/2) moist; sandy clay; fine weak subangular blocky; friable moist, slightly sticky and slightly plastic wet; many common pores; few fine medium roots; gradual wavy transition to:
B_{na} 30-48 cm	Dark reddish brown (2.5YR 3/4) moist; sandy clay loam; coarse subangular blocky; friable moist, slightly sticky and slightly plastic wet; common fine to medium pores; common very fine to fine roots; gradual wavy transition to:
B_{na} 48-80 cm	Reddish brown (2.5YR 4/6) moist; sandy clay loam; weak to moderate medium subangular blocky; friable moist, slightly sticky wet; common fine to medium pores; few very fine to fine roots; common medium iron concretions; clear drastic transition to:
B_{na} 80-150 cm	Reddish brown (2.5YR 4/6) moist; sandy clay loam; moderately strong subangular blocky; friable moist, slightly sticky wet; common fine to medium pores; few very fine roots; common medium iron concretions.

Remarks: Subangular blocks break to sharp edged blocks.

Appendix 7b: Representative Soil Profile Description of Kibwezi Lixisol under irrigation (Trt 2)

General Site Information

Observation No. and date : 5; 8/12/94
Soil classification
(FAO/UNESCO) : Haplic Lixisol
Geological formation : Basement System Rocks
Parent material : Gneisses
Local petrography : Upland
Macro relief: Slope : Gently undulating upland, 1-3%, linear, regular.
Micro relief : None
Land use/vegetation : Under irrigation (*Solanum melongena*)
Erosion : Nil
Ground water table level : Deep
surface sealing/crusting/
Cracking : Limited
Drainage class : Well drained
Effective soil depth : 82 cm

Soil Profile Description

A 0-29 cm	Dark reddish brown (2.5YR 3/4) moist; loamy sand; medium moderate subangular blocky; loose moist, non sticky and non plastic wet; many fine to medium pores; common fine, many medium roots; common medium iron concretions; clear wavy transition to:
B 29-82 cm	Dark red (10R 3/4) moist; sandy clay loam; medium moderate subangular blocky; friable moist, sticky and plastic wet; many fine to medium pores; common coarse roots; many large iron concretions; drastic clear transition to:
C 82+ cm	Parent material

Remarks: Surface sealing is evident.

Appendix 7c: Representative Soil Profile Description of Virgin (natural savanna) Kibwezi Lixisol (Trt 3).

General Site Information

Observation No. and date : 8; 9/12/94
Soil classification (FAO/UNESCO) : Haplic Lixisol
Geological formation : Basement System Rocks
Parent material : Gneisses
Local petrography : Upland
Macro relief: Slope : Gently undulating upland, 2-5%, linear, regular.
Micro relief : None
Land use/vegetation : Under natural savanna with *Commiphora* tree and *Cenchrus* grass species dominating
Erosion : Slight sheet erosion
Ground water table level : Deep
surface sealing/crusting/ Cracking : Limited
Drainage class : Well drained
Effective soil depth : 131 cm

Soil Profile Description

A 0-30 cm	Very dark reddish brown (7.5R 2/2) moist; loamy sand; many weak subangular blocky; loose moist, non sticky and non plastic wet; many coarse, common medium pores; many coarse, many medium roots; broken clear transition to:
B_{t1} 30-99 cm	Dark reddish brown (7.5R 3/6) moist; sandy clay; common strong subangular blocky; friable moist, slightly sticky and slightly plastic wet; common medium to coarse pores; few medium to coarse roots; many medium to coarse iron concretions; smooth gradual transition to:
B_{t2} 99-131 cm	Dark reddish brown (7.5R 3/6) moist; clay; many strong subangular blocky; friable moist, very sticky, very plastic wet; common fine, few fine to medium pores; few fine to medium roots; common medium iron and manganese concretions; clear drastic transition to:
C 131 cm	Parent material

Remarks: Soils are very rich in soil fauna such as the giant millipede about 25 cm long and about an inch wide.

Appendix 7d: Representative Soil Profile Description of Kibwezi Lixisol under Rainfed Crop Production (Trt 4).

General Site Information

Observation No. : 11; 11/12/94
Soil classification (FAO/UNESCO) : Haplic Lixisol
Geological formation : Basement System Rocks
Parent material : Gneisses
Local petrography : Upland
Macro relief: Slope : Undulating upland, 5-8%, linear, regular.
Micro relief : None
Land use/vegetation : Under rainfed crop production (maize - *Zea mays*)
Erosion : Slight gulley erosion
Ground water table level : Deep
surface sealing/crusting/ Cracking : Limited
Drainage class : Well drained
Effective soil depth : 140 cm

Soil Profile Description

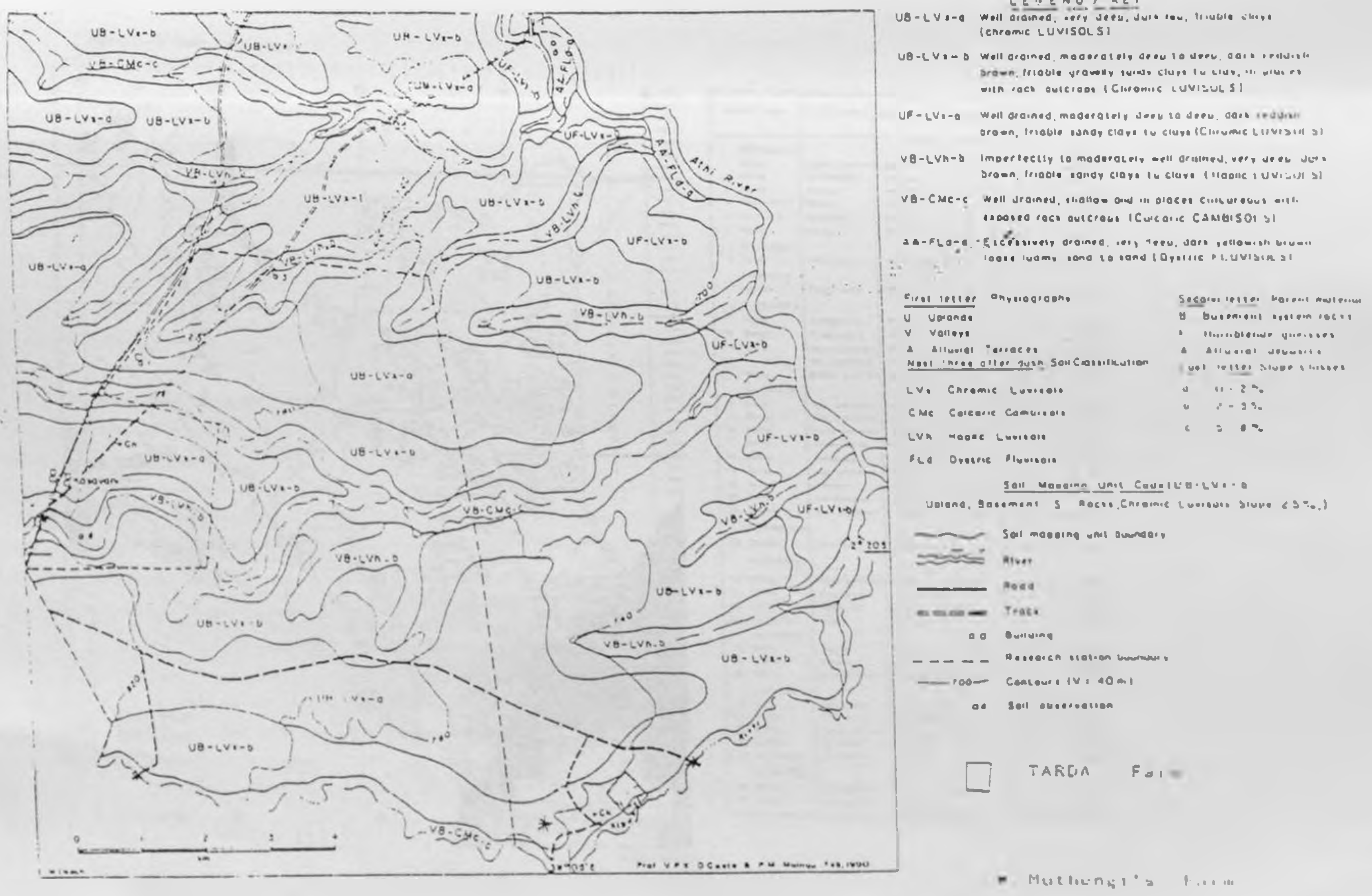
A 0-35 cm	Dark reddish brown (2.5YR 3/3) moist; loamy sand; many very weak subangular blocky; loose moist, non sticky and non plastic wet; common coarse, many medium, many fine pores; many fine to moderate roots; smooth clear transition to:
B_{t1} 35-65 cm	Dark reddish brown (2.5YR 5/6) moist; loamy sand; common moderate to strong subangular blocky; friable moist, sticky and plastic wet; many common medium pores; few fine roots; few small iron concretions; drastic wavy transition to:
B_{t2} 65-140 cm	Dark reddish brown (2.5YR 5/6) moist; sandy clay; many strong subangular blocky; friable moist, slightly sticky, slightly plastic wet; fine medium, few coarse pores; few fine roots; few small iron concretions; drastic clear transition to:
C 140 cm	Parent material

Remarks: Very prominent quartz at the surface.

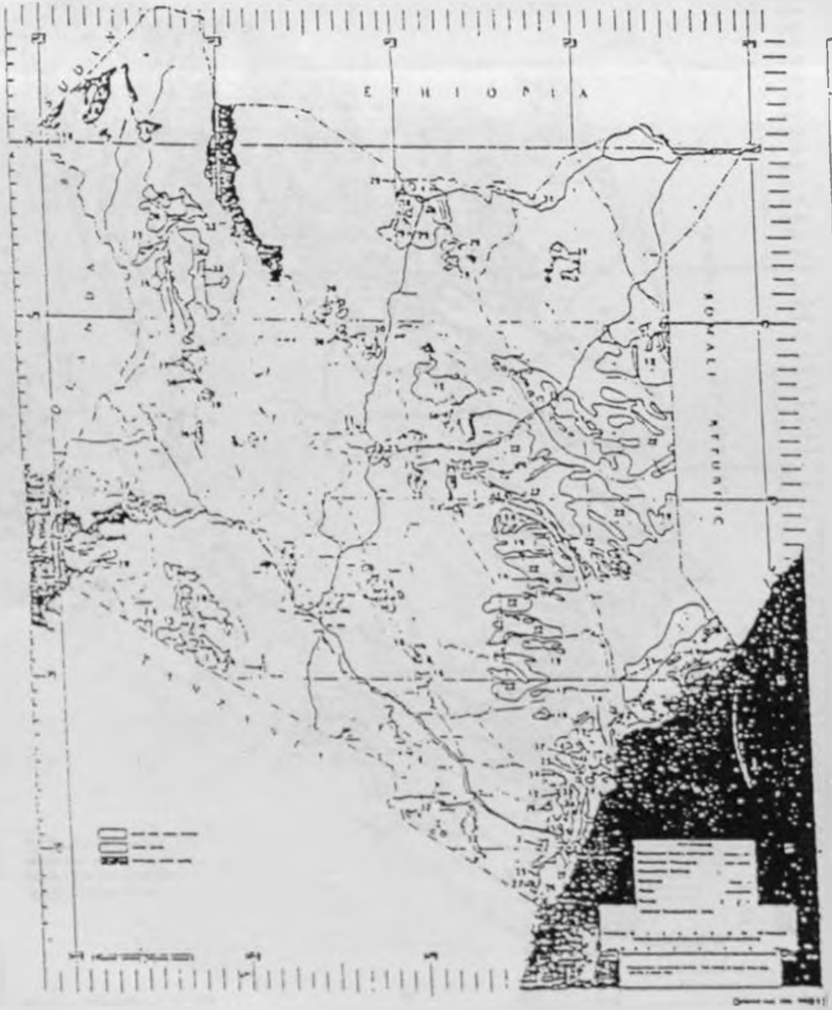
Appendix 8. Mean climatical data for TARDA in Kibwezi for the period 1985-1994.

Month	Temperature (°C)	Wind speed (km/hr)	Evaporation (mm)	Rainfall (mm)
January	21.9	2.3	3.3	69.6
February	25.1	2.8	5.9	26.8
March	26.8	3.0	5.7	60.8
April	25.4	3.4	4.2	94.3
May	23.1	3.2	4.0	31.6
June	22.2	3.5	3.9	2.7
July	19.3	4.2	4.2	0
August	21.4	4.8	4.6	4.4
September	22.9	5.3	5.5	1.3
October	24.9	5.1	5.9	33.4
November	22.6	2.9	2.8	151.9
December	21.9	1.8	2.4	162.6

Appendix 9. Preliminary soil survey of Kibwezi Dryland Field Station

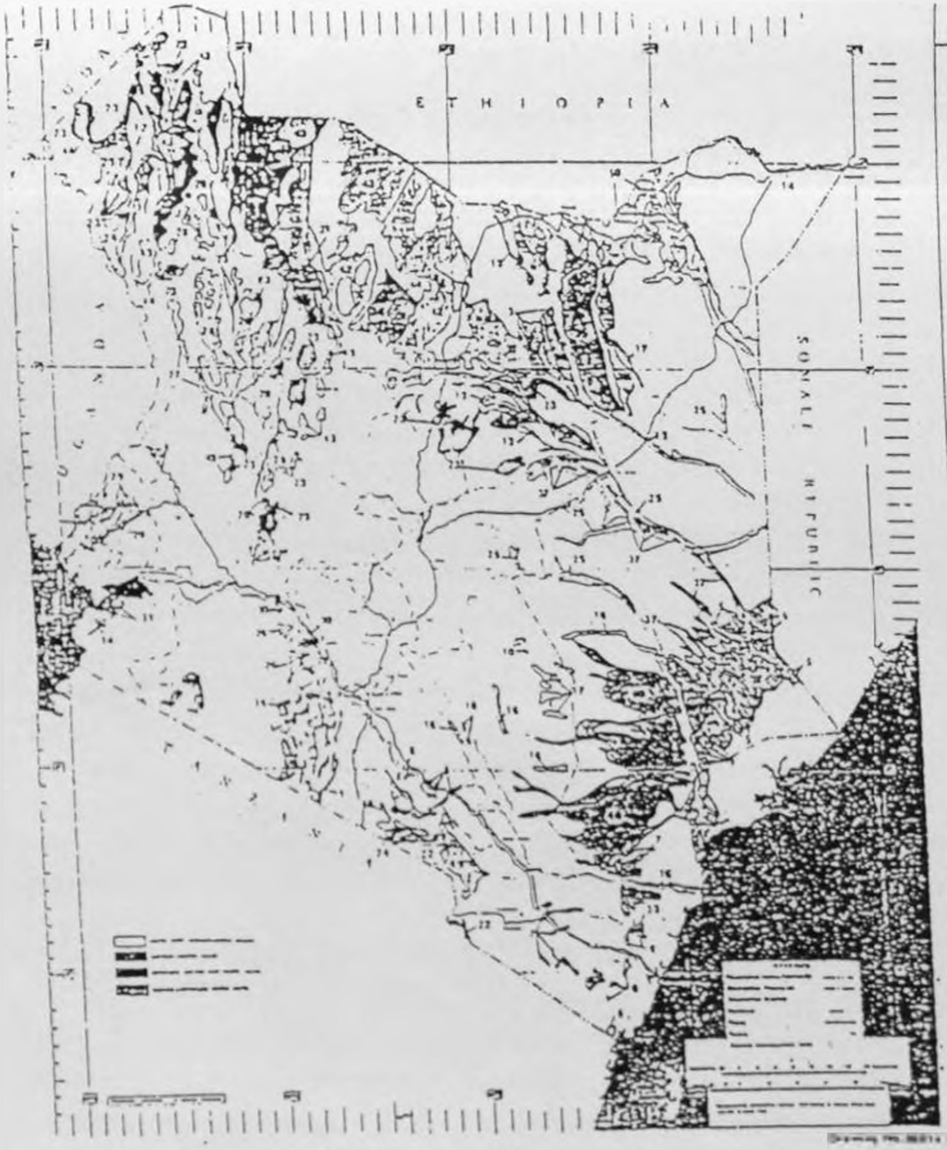


Appendix 10. Sodic soils in Kenya



mapping unit	parent material	physiography	drainage	agro-climatic zone	extent (ha)
VERTISOLS					
1 [illegible]	[illegible]	Uplands	D	IV	[illegible]
2 [illegible]	[illegible]	Uplands	[illegible]	VI	[illegible]
3 [illegible]	Alluvium	Floodplains	A	IV	[illegible]
4 [illegible]	Basalts	Plains	[illegible]	VI	[illegible]
5 [illegible]	[illegible]	Plains	C	[illegible]	[illegible]
6 [illegible]	[illegible]	Plains	C	[illegible]	[illegible]
FLUVISOLS					
7 [illegible]	[illegible]	Floodplains	C	V	[illegible]
ANDOSOLS					
[illegible]	Pyroclastics	Plains	C	V	[illegible]
PLANOSOLS					
9 [illegible]	Pyroclastics	Plateaus	[illegible]	[illegible]	[illegible]
10 [illegible]	Pyroclastics	Plains	D	V	[illegible]
11 [illegible]	[illegible]	Plains	A	V	[illegible]
12 [illegible]	[illegible]	Plains	A	VII	[illegible]
13 [illegible]	[illegible]	Plains	D	IV	[illegible]
SOLONETZ					
14 [illegible]	[illegible]	[illegible]	A	VII	[illegible]
15 [illegible]	[illegible]	Uplands	[illegible]	V	[illegible]
16 [illegible]	[illegible]	Uplands	DC	V	[illegible]
17 [illegible]	[illegible]	[illegible]	C	[illegible]	[illegible]
18 [illegible]	Volcanics	Plains	[illegible]	VII	[illegible]
19 [illegible]	[illegible]	Plains	[illegible]	VII	[illegible]
20 [illegible]	[illegible]	Plains	C	[illegible]	[illegible]
21 [illegible]	[illegible]	[illegible]	C	[illegible]	[illegible]
22 [illegible]	[illegible]	Plains	[illegible]	VII	[illegible]
CHERNOZEMS					
23 [illegible]	Volcanics	[illegible]	[illegible]	V	[illegible]
PHAEOZEMS					
24 [illegible]	[illegible]	Uplands	D	IV	[illegible]
25 [illegible]	[illegible]	Uplands	A	V	[illegible]
26 [illegible]	[illegible]	Plains	A	III	[illegible]
27 [illegible]	[illegible]	Uplands	A	III	[illegible]
XEROSOLS					
28 [illegible]	[illegible]	Plateaus	DC	VI	[illegible]
29 [illegible]	[illegible]	Plains	[illegible]	VII	[illegible]
30 [illegible]	[illegible]	[illegible]	DC	VI	[illegible]
LUVISOLS					
31 [illegible]	[illegible]	Footslopes	[illegible]	VI	[illegible]
32 [illegible]	[illegible]	[illegible]	[illegible]	VII	[illegible]
33 [illegible]	[illegible]	Plains	[illegible]	VII	[illegible]
34 [illegible]	[illegible]	Plains	[illegible]	VI	[illegible]
35 [illegible]	[illegible]	Uplands	A	V	[illegible]
CAMBISOLS					
36 [illegible]	[illegible]	[illegible]	C	V	[illegible]
37 [illegible]	[illegible]	Uplands	[illegible]	V	[illegible]

Appendix 11. Saline sodic soils in Kenya



	mapping unit	parent material	physiography	altitude	agro-climatic zone	extent (ha)
	VERTISOLS					
1	V-Z/vo	Volcanics	Bottomlands	BC	V	103 316
2	Vc/ba1	Basalts	Plains	D	IV	17 250
3	Vc/ba2	Basalts	Plains	B	VII	15 820
4	Vc/sh	Shales	Plains	B	V	42 270
5	Vc/bs	Bay sediments	Plains	A	VI	407 348
6	Vc/al	Alluvium	Floodplains	AB	V	144 250
7	Vc/al	Alluvium	Floodplains	AB	V	240 328
8	Vc-Vc/vo	Volcanics	Bottomlands	C	V	19 250
9	Vc/me	Metamorphics	Bottomlands	D	III	8 000
10	Vc/me	Metamorphics	Bottomlands	B	V	24 880
	FLUVISOLS					
11	Je/ba	Basalts	Floodplains	B	V	23 940
12	Je/vo	Volcanics	Floodplains	B	VII	348 760
13	Je-Gc/ba	Basalts	Floodplains	AB	VII	270 540
14	Je-Zg/li	Limestones	Floodplains	B	VII	19 940
15	Je/py	Pyroclastics	Floodplains	BC	VI	99 540
16	Je/me	Metamorphics	Floodplains	B	V	16 344
17	Je/al	Alluvium	Floodplains	B	VII	45 000
	SOLONCHAKS					
18	Z/al	Alluvium	Plains	BC	VII	15 940
19	Z/va	Various	Plains	B	VII	1 170
20	Z-J/al	Alluvium	Floodplains	B	V	129 300
21	Zg/va	Various	Plains	C	VI	23 500
22	Zg/va	Various	Swamps	BC	VI	44 240
23	Zo/vo	Volcanics	Piedmont plains	BC	VII	1 247 850
24	Zo-So/va	Various	Plains	C	VI	32 940
	GLEYSOLS					
25	Gc/al	Alluvium	Floodplains	AB	VII	130 390
	REGOSOLS					
26	Re/vo	Volcanics	Uplands	B	IV	54 300
27	Re-Sg/me	Metamorphics	Uplands	BC	VI	444 990
28	Re-Sg/va	Various	Uplands	BC	VII	127 940
	PLANOSOLS					
29	We-Vc/me	Metamorphics	Bottomlands	C	I	166 470
	SOLONETZ					
30	S/va	Various	Plains	D	I	34 540
31	So-Xh/va	Various	Badlands	B	VII	303 670
32	Sg/py	Pyroclastics	Plains	C	VI	2 700
33	Sg/bs	Bay sediments	Plains	A	VI	94 940
34	Sm/va	Various	Plains	B	III	10 000
35	So/me1	Metamorphics	Plains	B	VII	887 890
36	So/me2	Metamorphics	Plains	B	VII	100 000
37	So/bs	Bay sediments	Plains	A	VI	1 036 540
38	So/va	Various	Plains	B	VII	328 470
39	So-Lv/la	Lagoonal deposits	Plains	A	IV	34 320
40	So-Re-Vc/bs	Bay sediments	Plains	AB	VI	1,142,140
	PHAEOZEMS					
41	Hl/me	Metamorphics	Plains	B	VI	146,530
	XEROSOLS					
42	Xh/vo	Volcanics	Footslopes	B	VII	1 147 950
43	Xh/ba	Basalts	Plateaus	B	VII	396 540
44	Xh/vo	Volcanics	Footslopes	B	VII	20 820
45	Xh-Lo-Gc/al	Alluvium	Plains	B	VII	330 670
46	Xh/me	Metamorphics	Plains	B	VII	10 840
	LUVISOLS					
47	Lc-Vc/me	Metamorphics	Plains	B	VI	63,990
48	Lc-Vc/al	Alluvium	Plains	C	VI	30,040
49	Lc-Vc/ba	Basalts	Uplands	BC	VI	290 820
50	Lo-Je/al	Alluvium	Plains	B	VII	330 530