" THE SIGNIFICANCE OF THE GEOGRAPHIC AND GEOLOGIC FACTORS IN THE VARIATION OF GROUNDWATER CHEMISTRY IN KENYA "

GEORGE STEPHENSONS OBEGI ONGWENYI

A THESIS SUBMITTED IN FULFILMENT FOR
THE DEGREE OF MASTER OF SCIENCE
IN THE UNIVERSITY OF NAIROBI

1 9 7 3

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

....

George S.O. Ongweny
(Candidate)

This thesis has been submitted for examination with my approval as the University Supervisor.

....

A.R.T. Hove, M.Sc., Ph.D.
(University Supervisor)

ACKNOWLEDGEMENT

This thesis is the outcome of great assistance and cooperation by various institutions and individuals to whose help, I have the pleasure of giving my sincere thanks.

My gratitude and sincere thanks are due to both the University of Nairobi and the Mines and Geological Department for financial support in connection with field work, research and for the use of the necessary facilities in the compilation of the thesis. I wish also to record with great appreciation and satisfaction my thanks to both my Supervisors, Professor T. Dunne and Dr. A. Hove for the many discussions, tireless encouragement and advice on various aspects of this research. I would like to thank both Dr. L.A.J. Williams and Dr. A.M. de Quadros of the Geology Department whose views on certain aspects of the work were very helpful.

I am particularly grateful to Professor S.H. Ominde, all members of staff of the Geography Department and Dr. J. Walsh, Chief Geologist, Mines and Geological Department for their inspiration and constant assistance.

I also wish to record my appreciation for the valuable help received from Messrs. G. de Souza, W. Okatch and Miss J. Aoko of the Cartographic Section as well as the assistance I received one way or the other from other colleagues and friends.

Last but not least, my thanks are due to my father for his tireless support and encouragement in research work.

Nairobi.
March, 1973.

TABLE OF CONTENTS

LIST OF FIGURES

PAGE

LIST OF TABLES

SUMMARY

The first section of this thesis examines previous water studies in Kenya and other parts of the world. It also reviews relevant literature and attempts to interpret available water data. Methods adopted in the entire study are also outlined in this section.

The major physical controls of groundwater chemistry in Kenya are dealt with in the second section of this study. This does not, however, mean that these are the only factors that control the groundwater chemistry in Kenya.

Section three which is perhaps the most important part in the thesis is devoted to the examination of the relationship between groundwater chemistry and the major physical controls. It also analyzes problems of water quality necessary for water resource planning and development in Kenya.

SECTION I

1. INTRODUCTION.
2. COLLECTION AND ANALYSIS OF DATA.

CHAPTER I

INTRODUCTION

This Chapter deals with the following items:

1. Statement of the problem.
2. Organisation of the thesis.
3. Literature relevant to the interpretation of water chemistry.
4. Previous relevant work done in Kenya and other parts of East Africa.

1. STATEMENT OF THE PROBLEM

Many analyses have been made of the chemistry of both groundwater and surface waters in Kenya, but so far, there has been no systematic study of the variation of groundwater chemistry throughout the country. To meet this challenge, the aims of this study include:-

(a) Systematic study of the major controls of the variation of groundwater chemistry in the country.

(b) Relation of water chemistry to its major controlling factors, viz., climate, hydrology, rock type, soil, geomorphology and human activity.

(c) Systematic description of the chemistry of water mainly from boreholes and wells.

(d) Delimitation of water quality problems which would make water unsuitable for various uses.

In planning the development of Kenya's groundwater resources, it would be useful to have information on the following:-

(i) Statistical description of the probabilities of obtaining waters of various compositions in each geologic and climatic region from boreholes and wells. In this study this has been achieved by the use of distribution maps, frequency curves and by the use of such techniques as correlation and regression analysis. This would be of value for future drilling analysis and interpretation of the analyses.

(ii) Regional description of the quality of water for various uses (drinking, stock rearing, irrigation and industries of various kinds).

(iii) Chemical indices of pollution.

2. ORGANISATION OF THE THESIS

This thesis is divided into three main sections as follows:-

(i) Section one of the thesis which consists of chapters one and two deals with the introduction and methodology.

(ii) Section two of the thesis, comprising of chapters three, four and five, discusses systematically the major physical aspects which control the groundwater chemistry.

(iii) Section three, made up of chapters six and seven, examines the relationship between groundwater chemistry and the major physical aspects. Investigation of water quality problems and conclusions necessary for water resource planning and development are also examined in this section.

3. A REVIEW OF THE LITERATURE RELEVANT TO THE INTERPRETATION OF WATER CHEMISTRY

Ahrens (1965) has examined and discussed the geochemistry and statistical distribution of elements in various rock formations. "SiO_2 and K are negatively skewed in igneous rocks due to the presence of two or three juxtaposed truncated normal distributions", Ahrens, (1963).

Adequate evidence to show that the lognormal-type distributions are very common and that views against this postulate are not valid have been contented by Ahrens, (1957). Calculation of the abundance of elements in specific geologic materials depends on the accuracy with which such abundances are estimated and the magnitude of dispersion of the concentration of the elements in question. In examining the frequency distribution of various elements in Canadian granite, Ontario diabase and New England granite, Ahrens, (1953), has noted that positive skewness is realized when dispersion is large and hence the distribution of the concentration of given elements is not normal but becomes normal provided the variate of the concentration is not normal. This leads to the fundamental law of geochemistry advanced by Ahrens, (1953), in which the concentration of an element is lognormally distributed in a specific igneous rock. Its subsidiary law is that in which the abundance of an element in an igneous rock is always greater than its most prevalent concentration and the difference may be large or small depending on the magnitude of dispersion of its concentration.

Vistelius, (1960), in examining the value of frequency distributions in geochemistry, has disputed Ahrens' postulates on the grounds that:- (a) the number of observations for constructing the frequency curves or histograms is too small and does not conform to the goodness of fit test; (b) large positive skewness does not necessarily mean or imply log-normality. Instead he postulates that, of the two groups of distributions, one is that of the fixed stage of the geochemical process where the distributions are normal and the second group of distributions is that of mixed products of many stages of geochemical processes.

Although Aubrey (1954) agrees in principle with the lognormal laws advanced by Ahrens (1954), he has noted that they are more applicable to minor elements, for example, Cu and V than the major ones as Fe_2O_3, Al_2O_3 and SiO_2.

On the whole, however, the trend is towards lognormality.

In his studies, of the value distribution of economic minerals in Witwatersrand Gold Reefs, Cousins (1956), has noted that the distribution of these minerals in ore bodies tends to follow the lognormal probability curve. This is regardless of the origin of mineralization. He has also observed that the study of the distribution of parameters leads to useful information regarding the character, and genesis of a mineral deposit and the relationship between the various minerals. He continues to appreciate the fact that the lognormal frequency distributions are not confined to mineral deposits alone but the same law governs the distribution patterns of a vast number of diverse statistical measurements.

Mineral associations and the nature of distributions, as fundamental geochemical aspects, to be borne in mind in geochemical prospecting, have been determined by Lepeltier (1965) in Guatemala. He made use of the cumulative frequency curves and correlation diagrams which proved to be very useful.

Allen (1945) has examined the simple mathematical relationships governing the lognormal laws. He has also reviewed some of the problems raised by the earlier scholars in this field.

Tenant and White (1959) have suggested that if geochemical data plotted on logarithmic probability paper results in a single straight line, it is an indication of a lognormal distribution. Breaks in such a line suggest that more than one lognormal distributions occur in the data.

A bimodal distribution curve was obtained from the plotting of the pH values of springs from Yellowstone National Park, parts of Western United States, New Zealand, and Iceland. The curve provided evidence for the existence of two main types of thermal springs, Brock (1971). The two types were acid sulphate springs and neutral bicarbonate ones.

The comparison and analysis of geochemical data by use of t-and u-tests have been examined and discussed by Shaw and Bankie (1954). Hoel (1959), has reviewed procedures for linear correlation and regression analysis.

The distribution and composition of elements in the earth's crust and the principles governing their genesis have been examined by Krauskopf (1967), Mason (1966), Barnes (1967), Parker (1967), Helgeson (1964) and Hawkes (1959). Clarke (1924), has dealt with the classification and interpretion of water, rocks, minerals, hydrocarbons, including coal and the principles governing their natural distribution. Garrels and Christ (1965), have given a detailed account of solutions, minerals and equilibria, emphasizing mainly the application of thermodynamics to the many natural systems of geological and geochemical concern.

The evaluation of water resources by scarce data was examined at the Cento Conference in 1969. Dunne and Calkins (1970), have looked into the salt tracing techniques for estimation of stream velocities in Danville, Canada. Harmun (1953), has discussed new research methods and techniques in hydrology, with emphasis on the chemistry of waters of the ocean and hot springs.

Methods of presenting water quality analyses, sampling procedures, accuracy of the analyses, the interpretation of water analyses, problems of water quality and pollution have been discussed in detail by the American Public Health Association, (APHA), Davis and De Weist (1966), Rainwater and Thatcher (1960), Hem (1969) and Todd (1959).

Anderson and Hawkes (1958) have postulated that the relative mobility of an element in the cycle of weathering may be defined as the comparative rate at which it moves from its source in the present rock to the stable environment of a sedimentary basin. Mobility may be affected by the hardness of the material in question and the solutions present. In Polynouis expression,

$$\text{Relative Mobility} = \frac{\text{per cent of elements in the rock}}{\text{per cent of element in the water}}.$$

The value of a geological aquifer, according to Buchan (1963), is determined by the formations, texture, thickness, extent, structural position, nature and area of outcrop. He continues to point out that the amount of rainfall necessary for its replenishment is equally important. Furthermore, the characteristics looked for in any formation is storage capacity and permeability. For example, quartz sand provides groundwater with small amounts of solids in solution, whereas chalk, being more soluble, provides groundwater with several hundred parts per million of dissolved solids in which Calcium Carbonate predominates. In clay, dissolved solids are dominated by sodium salts.

Thomas (1956), has shown the effect of man's activities on both the quantity and quality of water.

Back (1960), in discussing the origin of hydrochemical facies of groundwater on the Atlantic Coastal Plain, has shown that the kinds as well as the concentration of ions in solution result from the chemical processes responding to the geology and hydrology of a given region. He has recognized Ca-Mg facies, Ca-Na facies and $\text{Cl-So}_4\text{-HCo}_3$facies.

In classifying water by genesis, Donald and Waring (1963), have noted that basic rocks have long ratios of Ca/Na and Mg/Ca because of the dominance of ferromagnesian minerals with or without Calcic plagioclase. They have further indicated that the composition of water is affected by biological, geological, climatic and chemical factors. Davis (1964), has suggested that the amount of silica in groundwater is primarily dependent on the rock and mineral types in contact with the water. The largest amounts are in volcanic rocks followed by plutonic and sedimentary rocks containing fledspars and volcanic fragments. Small amounts of silica are from marine sandstones and least from carbonate rocks. He has also continued to suggest that the relative concentration of various ions has some influence on the amount of silica in natural waters. This is in general agreement with Seaber (1965), who has noted that the proportion of cations and anions reflect the environmental effects and can be used as diagnostic indicators of hydrothermal relations. Siever (1957), concurs with Seaber (1965), when he notes that the primary source of silica in solution is the chemical weathering of silicate minerals formed at high temperatures and pressures. He also observes that most natural waters are under-saturated with amorphous silica and much of the ocean is under-saturated with respect to quartz.

Gorham (1955, 1961) has examined the effects of climate, topography, geology, relative mobility of elements, the chemistry of rain and biology on the quality of water.

Swarzenski (1968) has delineated fresh and saline groundwater zones in the Punjab region of Western Pakistan, mainly using the concentration of total dissolved solids. Gorrel (1958), has classified water into fresh, brackish, salty and brine on the basis of sodium chloride content. Penn (1971), has indicated that to describe the source and distribution of major ions in the sub-artic lake system in Canada, description of carbonate equilibrium is important.

The relationship of stream runoff to total dissolved solids for major streams in the world has been worked out by Durum, Heidel and Tison (1961). Hendrickson and Krieger (1960) have concluded that the relationship between the chemical quality of water to stream discharge provides the key to the general understanding of the hydrology and geochemistry of a drainage basin. They have further observed that there is an inverse relationship between the concentration of total dissolved solids and the quality of the water being discharged by the stream in question. This is in agreement with Langbein and Dawdy (1964), who have suggested that the amount of total dissolved solids in relation to suspended load in streams depends on the environmental factors such as humidity, rock type, time and quality of the water. They have shown how data collected from drainage basins in the United States has been used to predict how runoff and sediment yields will change with the variation in mean annual temperature and precipitation. Langbein (1949), developed a curve by which estimation of annual runoff can be done on the basis of temperature and precipitation.

Lohr and Love (1952) have examined the quality and ionic composition of water in the United States. Steel (1960) has also examined water quality problems.

In studying the chemical composition of river and lake waters in the world, Livingstone (1963), has suggested that the temporal variation of water quality is associated with runoff, rain chemistry, rock type, groundwater seepage and time.

Miller (1961), when studying solutes in small streams draining single rock types in Sangre de Cristo Range, New Mexico, has indicated that bicarbonate is a major constituent in water and has further shown that NO_3 and Cl are of atmospheric origin. He has further looked into the problem of relative mobility and the general relationship between altitude, runoff, denudation and total dissolved solids in a drainage area.

Okoth (1966) has examined the relationship between conductivity and precipitation in River Hagåån in Sweden.

Ollier (1963 has noted that thermal expansion and contraction may be a significant agent of weathering, thereby, emphasizing the importance of temperature on weathering.

The nature and usefulness of hot springs in Japan has been examined by Yatumitsu (1965).

4. PREVIOUS WORK DONE IN KENYA AND OTHER PARTS OF EAST AFRICA

Sikes (1934), in carrying out a general survey of the underground water resources of Kenya, has noted that the increase of runoff cannot fail to have a detrimental influence on the underground water resources. He has suggested that individual springs in metamorphic regions are non-existant but De Quadros (1972), in his study of the structure and stratigraphy of the Namanga area (unpublished Ph.D., thesis, University of Nairobi) has found a number of springs in this metamorphic area. According to the findings of Sikes:-

(a) In the Basement Complex, water is always found in soft siliceous and micaceous gneiss or schist if at all it occurs. In granitic rocks it is mainly fortuitous, though when weathered, small supplies usually occur if the catchment area is good. In general water from the Basement Complex rocks is of excellent quality.

(b) In volcanic rocks (other than those on the Rift Valley) water is usually found in the disintegrated rocks at old land surfaces between sheets of lava or tuff. It may be under considerable or negligible pressure.

(c) In the Rift Valley, water, if it is encountered at all is usually at considerable depth and not under much pressure except at specially favourable localities. Lava streams which have flowed down the pre-existing valleys, especially if the water is basic, often yield well, enter below the lava or on the weathered zone near its surface. In all the occurrence of underground water in these rocks has been bound up with a number of circumstances which vary greatly with type, conditions or deposition and subsequent alteration and faulting as well as topographical features prevailing at the locality. But the factor which has been found to have the greatest significance in respect to the existence of available groundwater in the Cenozoic Volcanic Series, is the presence of acient land surfaces below volcanic beds.

(d) The Duruma Sandstone is a good water carrier but the water is liable to be bitter and sometimes too saline for use. The water is chiefly mineralized by Calcium Sulphate, Magnesium Sulphate and Sodium Chloride. This is in agreement with the findings of Sanders (1957).

(e) Drilling into the Jurassic shales is clearly unlikely to be productive of good water. The occasional beds of limestone and sandstone appear only to hold water too brackish for use. Hard water which is sufficiently free from dissolved salts to be potable is transmitted in solution channels, or aquifers through the Pleistocene coral limestone and breccia and not infrequently emerges as springs at the high water mark along the coast. The fresh water is usually only a shallow layer on top of the sea water and overpumping or deepening wells usually result in an increase in the salinity by admixture with underlying salt water.

(f) Cenozoic sedimentary rocks of the coast contain water which is highly mineralized and slightly bitter, strongly charged with Calcium and Magnesium sulphate and Sodium Chloride. The use of this water for household purposes is as such limited.

(g) Good yields have been obtained from Cenozoic sediments (inland) at shallow depths when and where there is an obviously good catchment.

In conclusion, it is noted that except in cases of formations near the Coast, where the water tends to be saline and in the Rift Valley, the groundwater of Kenya is in general of good quality and the yields are excellent.

McCall (1957), reviewing the geology and groundwater conditions in the Nakuru area, has noted that Sikes (1934), based his conclusions regarding groundwater potentialities in the Rift Valley on the very meagre evidence provided by 23 boreholes. Sikes conclusions were affected by two great misconceptions. Firstly, he overestimated the thermal conditions. It has been shown that the steam areas are limited to the immediate vicinity of the recent Centres of Vulcanicity,though high temperature conditions are widespread throughout the Rift Valley. The second, and far more significant misconception, was the idea that the groundwater of the Rift Valley is an entirely separate system from that of the high country flanking it on either side. McCall (1957) has demonstrated that the Rift Valley on the Nakuru area, though an area of internal surface drainage, obtains its main recharge of groudnwater not from the rain that falls within it, but from the rain that waters its high flanks. He considered that any water reaching the valley floor would at once sink to great depths to be later returned to the atmosphere as steam from invisible fumaroles. Sikes considered that old land surfaces between the lava flows provided the main aquifers. But according to McCall (1957), whilst this type of aquifer undoubtedly occurs, it is now known that the principal aquifers are sediments extending to several hundred feet in thickness, rather than the very limited weathered zones forming old land surfaces between the lava flows. In examining the groundwater conditions, he has indicated that there is a hydrostatic connection between the underground water bodies throughout the greater part of the area. He has further noted that the hydrostatic level does not usually vary when a second aquifer is stuck in a borehole. This indicates a connection between successive aquifers on depth. In dealing with the relation of faulting to groundwater conditions, he has noted that faults are open fracture zones, normally devoid of impervious clay filling and they thus act principally as conduits rather than as barriers. In this are boreholes situated along the major fault scarps in particular, often yield hot water and hot springs. Springs exist at several places along the Subukia-Bahati Scarp. The relation between thermal conditioning and faulting is explained by the fact that hot juvenile gases rise from the deeper zone of the crust through the openings provided by fault zones and mingle with groundwater which is thus heated up to considerable temperatures.

The problem of erosion in relation to other ecological factors with a view of formulating the policies for water resource planning and development in Uganda, have been discussed by Wayland, Brasnett, Bisset and Martin (1938). Kanthack (1945) has examined the possibilities of obtaining water from various streams for Nairobi but the problem is complicated by the limitation of hydrolcgical data necessary for water resource planning for the city. Parsons (1945) has looked into the principles governing the hydrological cycle. He has further discussed the geophysical methods of groundwater investigations in East Africa.

In dealing with rural water supplies in Africa, Dixey (1946) has emphasized the fact that groundwater supplies are very closely affected by the interrelated factors of geology, relief and soils. He has further given definitions of wells, boreholes, cisterns, dams and general policies regarding water planning and develcpment. Munger (1950), has examined the water problems of Kitui District and has suggested sinking of wells to tap groundwater so as to alleviate the shortage of water in the District.

Table I-1 contains sulphate concentrations for various East African lakes as given by Beauchamp, (1953).

TABLE I-1 SULPHATE CONCENTRATIONS OF GIVEN EAST AFRICAN LAKES

Number	Lake	SO_4 Concentration in PPM
1	L. Victoria	0.18 - 1.88
2	L. Tanganyika	4
3	L. Rukwa	2.9
4	L. Bangweulu	2.3
5	L. Mweru	Trace
6	L. George	0.5
7	L. Albert	0.2
8	L. Naivasha	17
9	L. Baringo	40
10	L. Nakuru	253
11	L. Magadi	253

The larger African lakes (1-7 above) show low sulphate concentrations and it has been suggested that the sulphate deficiency may affect the growth of the phytoplanktons. Lakes of the Gregory Rift (8-11) have relatively high amounts of sulphate because all these lakes owe their chemical composition to the leaching of surrounding soil. These lakes have no outlet, hence the high concentration of salts. Stevens (1932) has discussed the nature, origin and composition of Lake Magadi and its alkaline springs.

Temperley (1966) has discussed the geology and groundwater conditions in the Kibwezi-Chyulu area and has stated that the almost complete canalisation of the overflow of this groundwater reservoir into the Mzima locality is attributed to the configuration of the land surface burried beneath the volcanic rocks.

In dealing with the classification and composition and origin of thermal springs in Tanzania, James (1967), has observed that thermal springs are of great interest from three points of view:

(a) Brines containing high concentrations of any of the chemical components such as NaCl, are of potential value.

(b) In an arid country such as Tanzania, thermal springs with water of low concentrations of solutes and high rates of flow are frequently used as township water supplies with no purification of the water being necessary.

(c) Since most of the material carried by the spring waters is thought to be juvenile in origin, a study of their trace element assemblage might yield valuable information regarding the distribution of related mineralization on the crust.

Although chemical analyses in Tanzania have been made since 1926, few are sufficiently complete to be of use in calculating the probable chemical composition of the solutes. The salts in solution in groundwater are essentially those of Ca and Mg, whereas the soluble salts in the thermal waters are essentially those of Na and K. The high Na and K salt components of the solutes of thermal springs is also thought to be of juvenile derivation. A significant aspect of the geology of these springs is that they are mostly situated in crystalline Precambrian rocks. This is in agreement with the findings of De Quadros, (1972). James (1967) has suggested further that an empirical relationship exists between the temperature of natural thermal springs and their rate of evolution of helium and carbon dioxide, expressed as:

$$\log f(He) = \frac{T-1}{39} \quad \text{and} \quad \log f(Co_2) = \frac{T-4.5}{15.8}$$

where f is the rate of evolution of the gas and T the temperature (^{o}C) of the spring waters. This relationship suggests that helium and carbon dioxide are of juvenile origin.

Analysing mineral and thermal waters of Kenya, Walsh (1969) has indicated that thermal waters are connected with vulcanicity of the area in question. They are considered, according to him, to be meteoric in origin, being heated by CO_2 gas emanating from the syenitic magma. Attemps are being made to explore the possibilities of generating thermo-electric power from the steam emanating from this hydro-thermal springs in the Lake Hannington area by a joint venture between United Nations Development Programme and East African Power and Lighting Company Limited. Trona Crust of L. Magadi is a natural evaporating pan fed by hot springs. It has been exploited for many years for soda ash and common salt. Table 1-2 summarizes the chemical composition of some of the thermal springs as given by Walsh (1969).

Gillman (1943) has distinguished three modes of groundwater occurrences in Tanzania, namely:- Groundwater Cutcrops, Shallow groundwater and Deep-seated groundwater. He bases his subdivision on depth alone without taking into account other environmental factors which influence the occurrence of groundwater. Such a classification is not useful for planning purposes for the mere qualitative statements do not show the actual composition of the groundwater. He has continued to speak of pollution problems by the introduction of sisal industry without any data to justify his conclusions. The recommendations given for water resource planning should have been based on water chemistry and biological analyses of the water.

Gevaerts (1957, 1964) has done pioneering work by assessing not only the quality but also the quantity of groundwater in the various geological units in the Nairobi area. Representative analyses of the groundwater in different parts of Nairobi, according to Gevaerts (1964), are given in Table 1-3.

TABLE 1-2 CHEMICAL COMPOSITION OF SOME OF THE THERMAL SPRINGS

(grams per litre)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Na^+	1.228	.056	.065	.857	2.895	.008	1.99	.	.034			1.252		10.441	8.706	7.625	12.690		1.002	6.90
Ca^{2+}	.010						.007	.010		.005	.010							.077		
Al^{3+}, Fe^{3+}	.008																	.013		
Fe^{2+}		Trace	.0015	.0002	.0001	.0014	Trace	.0001	.0001	Nil	Trace		.0014							Nil
Mg^{2+}	.006						.002	.006		Nil	Nil							Trace		
CO_3^{2-}		.028	Nil	.138	3.090	Nil	.261		Nil			1.245		1.95	1.49	4.65	8.70	.495	.092	
HCO_3^-		.080	.192	1.708	3.577	.023			.104					15.21	12.15	4.22	4.57		1.343	
Cl^-	.452	.027	.014	.254	1.370	.004	.016	.001	.007	.003	.006	.463	.004	5.05	4.27	3.60	6.18	2.560	.230	1.60
SO_4^{2-}	.143	.005	.015	.032	.095	Nil	.033	.0005	.008	.006	.004	.104	Trace	.176	.195	.61	.195	Nil	.087	High
SiO_2		.001	.080	.050	Nil	.060	.090		.072	.035	.090							.075	.095	.120
F^-		.018	.005	.045	.181	.0004	.017		.0005	.0006	.0018	.095		.121	.067	.054	.108	.0094	.024	.100
$CaCl_2$		1.54	.255	2.499	9.900	.031	.455	.322	.138	.055	.135		Nil							4.37
NH_3		.0005	.0001	.0003	.0024	.0019		Trace	Nil	Nil	Nil		.035							Trace
pH		10.4	6.9	8.9	9.5	6.3	8.3	6.7	7.5	7.8	6.7		6.9							8.9
Temp. °C	50?	83	31	125	93	85	65	22	39	35	35?	35?	93	85	45	36	40	65?	49	75
Flow l/sec														905	640	210	1100		450	

1 - Near L. Rudolf
2 - Ol Kokwe Island, Lake Baringo
3 - Lobei, L. Hannington
4 - Kiborit, L. Hannington
5 - Kwaibeipei, L. Hannington
6 - Arus, Baringo District
7 - Kureswa, Kamasian Hills
8 - Koben, Tinderet
9 - Fitzgerald's Farm, Solai
10 - Wellmount, Thomson's Falls
11 - Mereroni, Bahati
12 - Cole's Farm, Elmenteita
13 - Eburru (Condensed steam)
14 - Little Magadi
15 - N.W. Lagoon, Magadi
16 - Fish Springs, Magadi
17 - Bird Rock, Magadi
18 - Jombo, Kwale District
19 - Kapedo, Baringo District
20 - Homa Bay, L. Victoria

SOURCE: Geological Survey of Kenya.

(ANALYSES IN PPM)

BOREHOLE LOCALITY	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PH	6.0	6.9	7.5	8.5	8.6	8.1	6.9	6.1	8.2	7.5	8.3	8.9	8.9	5.9
TOTAL SOLIDS DRIED AT 180°C	112	320	260	?	520	327	523	658	1545	255	1506	1090	1720	121
CHLORIDES (Cl)	6	26	16	12	47	12	12	2	88	8	78	214	243	16
SULPHATES (SO_4)	4	16	8	?	15	-	16	-	18	11	53	252	420	8
TOTAL HARDNESS ($CaCO_3$)	24	65	20	10	10	9	127	378	10	75	15	12	30	25
EXCESS ALKALINITY (Na_2CO_3)	15	91	107	155	273	184	247	174	1200	85	1240	295	566	16
FLUORIDES (F)	0.5	1.3	6.7	13.7	10.6	10.9	1.1	1.1	20.9	0.4	14.0	12.1	24.0	0.3
FREE CO_2	P*	-	-	-	-	-	-	490	-	-	-	-	-	P*

1-Limuru Trachyte Series (Boreholes 1566,2690,3009 Limuru)
2-Kerichwa Valley Series (Boreholes 1623 Karen)
3-Nairobi Trachyte (Borehole 1050 W. Langata)
4-Nairobi Trachyte (Boreholes 1987, 2031 Nairobi)
5-Nairobi Trachyte (6 Boreholes, Embakasi Airport)
6-Ruaraka (Boreholes 565,589,1681,1717,1859,2056,2517)
7-Kahawa (Boreholes 2335, 2337)
8-Kamiti (Boreholes 1340, 1466,2386,2671)
9-Thika (Borehole 2560)
10-Fort Hall Water Supply (Borehole 2868)
11-Kapiti Phonolite Zone (Borehole 2922)
12-Athi River (Boreholes 2192,2474)
13-North of Athi River Station (Borehole 1937)
14-West of Ondiri-Lari Fault (Boreholes 540,796,2379,2466, 2658,3170)

* Present

Gevaerts major conclusions are as follows:

(a) From table 1-3 it may be concluded that that groundwater in the Nairobi area is of good quality throughout, except for its fluoride content, which is in excess of the desirable limit of 1.5 ppm, over a large part of the area.

(b) The water quality varies not only in space but also in depth as well as within the geologic units examined.

(c) All water stuck in the Cenozoic formations contain sodium bicarbonate, usually alkaline in character, but where free carbon dioxide is present, pH may be as low as 6.1 inspite of the excess alkalinity, a high degree being introduced into the Kamiti-Kahawa aquifer near the base of the Upper Athi Series.

(d) A high chloride and sulphate content is encountered in water from Kapiti Phonolite Series. Since the Cl and SO_4 content in the phonolite itself is not more than about 0.01 and 0.03 per cent respectively, it is obvious that the salts have been derived from the lacustrine deposits intercalated within the lavas.

(e) Boreholes reaching the Basement struck unpotable water with a carbonate hardness of 346 and 357 ppm respectively and a chlorine and sulphate content of 1220 and 720 ppm respectively.

Though the permanent hardness is rather typical of Basement water, the chlorides and sulphates should have largely been derived from the sediments.

(f) In his thirteen areas within the Nairobi Conservation area, it is the Upper Athi Series that form the main aquifer.

CONCLUSION

The water development work in Kenya lies within the Water Department of the Ministry of Agriculture. It is clear from the preceeding discussion that proper interpretation of water resources needs not only the knowledge of hydrology, geology and geochemistry but also of other environmental sciences. Adequate information on water resources is necessary for proper utilisation of Kenya waters. Thus, the systematic description of the occurrence and quality of these waters, which is the main objective of this study, is essential for the planning and development of water resources of Kenya.

CHAPTER II

COLLECTION AND ANALYSIS OF DATA

1. SAMPLING

Geochemistry is a fruitful field for the application of statistical methods which provide the best techniques for handling the large quantities of data. The three basic geochemical procedures, sampling, analyzing and comparing of results, are governed by statistical theory, Shaw and Bankie (1954). This sub-section of this chapter is dealing with the first item, i.e. sampling.

In this study, where the hydrogeochemistry of the country is the major consideration, a decision as to how many samples should be collected from given geological units is required. Except for administrative limitations in funds and manpower, this decision on the present work is based on the amount of data already available from the Kenya Government agencies such as the Mines and Geological Department, the Government Chemist, Water Department and the National Agricultural Laboratories. Other data on water chemistry has been obtained from various private and official publications. The hydrologic and climatic data have been mainly obtained from the Water Department and the East African Meteorological Department. Rock chemistry data has been obtained from the Mines and Geological Department.

Although the type of investigation, purpose of study and anticipated variation, in chemical quality of water determine to a large degree the location of the surface water or groundwater sampling sites and the frequency of sample collections, a completely comprehensive answer to the degree of coverage is not practical. Samples of groundwater should be collected at intervals so that no important change in quality could pass unnoticed between sampling times. This requisite immediately gives rise to two additional questions. What magnitude of change is important and what are the physical and economic factors that must be considered in obtaining the records. By necessity the sampling schedule adopted is a compromise between the accuracy and detail required in the water quality record and the funds and personnel available for the work.

In the random sampling procedure, used in this study, one geochemical principle of sampling has been adopted, i.e. the more the samples the better. As a general principle, it is best to utilize as many sources as possible suitable for the collection of representative samples, Hem (1969). It is then most apparent that no bias in the sampling procedure has or is likely to be introduced.

This investigation is based on over 7,000 groundwater chemistry analyses taken from more than 500 boreholes and wells, in different parts of the country, 800 rock chemistry analyses and more than 2,000 hydrometeorologic analyses collected from the various sources which have been indicated above. These are not large numbers particularly when some elements show enormous dispersion when handling the whole country. An attempt has been made, however, to have representative samples that can be statistically handled. Even though this investigation can in some respects be viewed as only a modest beginning, some interesting and significant conclusions emerge from the analysis of available data.

2. LIMITATIONS ARISING FROM THE DATA AVAILABLE

(a) To describe in detail the chemistry of groundwater of a country covering 225,000 square miles, more than 7,000 water chemistry analyses are obviously required. For it has been shown by Gevaerts (1964) that water chemistry varies not only from place to place with depth but also with time. It is therefore necessary to have more samples within given geologic unit so as to be able to get a detailed picture of the chemistry of the water. In the present study both the level of study, finance and time could not allow for such a detailed investigation. It is true that in areas with acute water problems such as the arid North Eastern Province and parts of the north-western part of the country, either there are extremely few analyses available for these areas or they are not at all available. These few are not sufficient to give concluding statements regarding the quality of the water in these areas. There is, however, a concentration of data from the well-watered parts of the country. This is particularly so in the Nairobi region, parts of the Rift Valley and Coast province. The problem of the sparsity of data will be overcome as more development in other economic spheres is enhanced in the arid and semi-arid parts of the country.

(b) Since some of the original boreholes and wells records do not indicate the exact geographical location of these boreholes and wells, this can lead to misinterpretation of the groundwater quality. Every effort has, however, been made to locate the locality of all the boreholes and wells. In some cases the Kenya Gazeteer on Standard Geographic names, and the Kenya National Atlas have been used in overcoming this problem. To supplement this information, searching inquiries as to the location of a given borehole or well have been made. This problem is further sorted out when the analyses are compared and fitted to the respective geologic units. Another problem which arises is the exact aquifer from which the water was drawn but where depth measurement records exist, the problem has been eliminated and also knowing the geology, one can sort out some of the analyses.

(c) The third problem is the determination of accuracy of the results of analyses. This is particularly necessary when the results have to be compared and interpreted. Rainwater and Thatcher (1960) have given five methods of checking the accuracy of the results and these are reviewed briefly below.

(i) Chemical balancing of the chemical equivalents of major Ions.

Since water is a chemically balanced system, the sum of equivalents of cations in solution equals the sum of the anions. If all the predominant ions have been determined, the equivalents per million should reasonably balance. This method was the only one left for checking the accuracy in this study, although in some analyses not all the ions had been determined and this presented some problem.

(ii) Relation of residue on evaporation to calculated dissolved solids.

Comparison of the residue on evaporation and dissolved solids calculated from the analytical statement is a rough check of the comprehensiveness of an analysis. This has, however, got its limitations. For example , the behaviour of acid waters and iron compounds during evaporation complicates the relation between residue on evaporation and calculated dissolved solids.

(iii) Specific-Conductance Relation

For most natural waters of mixed type, the specific conductance in micromhoms multiplied by a factor of 0.65 ± 0.1 approximates the residue on evaporation in parts per million. This does not, however, approach an exact relation because the conductance of a solution is dependent on the type and total quantity of ions in solution.

(iv) Interrelation of constituents of water from the same source

As samples from the same source come through the laboratory, the analyst begins to recognize pattern of water quality. This may be the relation of calcium to bicarbonate, sodium to chloride or other relations that appear true. This method was used to supplement the first one discussed above for this particular study.

(v) Method of checking partial analysis

There is no way of checking or verifying results when only a few of the constituents are determined. There is no simple adequate method for checking a partial analysis. Interrelation of constituents in water from the same source and relations of certain constituents to specific conductance or water discharge may be useful as guides but the ability of the analyst is the only good control. In this study comparison of the partial analyses with the complete ones in terms of the constituents determined more or less placed a given analysis in its particular group.

In conclusion, however, measurements of accuracy are difficult to make and are best treated by comparisons of the analyses of standard samples, which have been analyzed by several methods in numerous laboratories.

(d) Since the quality of groundwater is influenced not only by man, rock, type, hydrology and climate, certain data necessary for interpretation of water chemistry is lacking. These include rain chemistry data and water balance data for the country which were being computed at the time of writing up this thesis.

3. METHODS OF EXPRESSING ANALYSES

(a) General Expression

Various terms and units are commonly employed in the expression of data obtained from chemical analyses of water. An understanding of the more frequently used methods of expression is required for proper interpretation of these data.

Water analyses most commonly deal with samples in which the total amount of dissolved solids constitutes only a small fraction of one per cent of the total weight in the sample. A water analysis is intended to be a statement of the composition of a water solution and it is therefore appropriate to use an ionic form of statement of analysis. In accordance with the dissociation concept, water analyses are now generally expressed in concentrations of individual ions for those substances known to be dissociated in solution. Substances whose form in solution is unknown or which may be suspected to occur in undissociated or even in colloidal form are commonly reported either as oxides or as uncombined elements.

Substances commonly determined in water analyses and expressed as ions, include the cations (positively charged ions), for example, calcium, magnesium, sodium and potassium and the anions (negatively charged ions) for example, sulphate, chloride, fluoride, nitrate and those contributing to alkalinity which are usually expressed in terms of an equivalent amount of carbonate and bicarbonate. Other substances such as arsenic, barium, boron, bromide, chromium, copper, iodine, iron, lead, mangenese, phosphate, selenium, silica, strontium and zinc are some of which are determined as part of a routine complete analysis but most of which are not generally determined, are reported in ionic terms if the substances are known to occur in that form. Dissolved gases such as carbon dioxide and hydrogen sulphide, when determined, are usually reported in undissociated form.

The acidity of water may be expressed as a concentration of hydrogen ions (pH) or in terms of the equivalent concentration of sulphuric acid. Hardness in water and sometimes alkalinity is conventionally expressed in terms of equivalent quantities of calcium carbonate. Other properties included in the water analysis include colour, specific conductance, total dissolved solids, loss on ignition, specific gravity, suspended matter, turbidity, biochemical oxygen demand and per cent sodium plus potassium.

(b) Units of expression

In most laboratories, the analyses are expressed in parts per million (ppm). One part per million means one part by weight of dissolved matter in a million parts by weight of solution, such as one kilogram of dissolved solids in one million kilograms of water or one ton of dissolved solids in one million tons of water. The measure is, therefore, independent of the units used. All our data has been converted to parts per million.

A measure which is similar to PPM but, however, dependent on units is milligram per liter. This is the most commonly used unit in the laboratory in as much as the water sample is measured in fractions of a liter and chemical constituents are determined in milligrams. Parts per million and milligrams per liter are numerically almost the same if the concentration of dissolved solids is low and the specific gravity of the water is nearly 1.0, Davis and De Weist, (1966).

A further unit of measure is convenient for many geochemical studies, for example, classification of water by use of trilinear diagrams, Piper (1944), is the equivalents per million (EPM) or more exactly milligram equivalents per kilogram. If derived from milligrams per liter, the unit is called milligram equivalents per liter. Equivalents per million, according to Hem (1969), Rainwater and Thatcher (1960), Quagliano (1958) and Partington (1960), are calculated by dividing parts per million by the equivalent weight of the ion under consideration.

Rainwater and Thatcher (1960) have given factors by which chemical equivalents per million are computed by multiplying the reported concentration of individual constituents in parts per million by the reciprocal of their combining weights and these are given in Table II-1.

TABLE II-1

FACTORS FOR CONVERTING PARTS PER MILLION TO EQUIVALENTS PER MILLION

(1954 atomic weights)

Ion	Sum of atomic weights	Multiply ppm by-	Ion	Sum of Atomic weights	Multiply ppm by-
Al^{+3}	26.98	0.11119	K^{+1}	39.100	0.02558
Br^{-1}	79.916	.01251	Li^{+1}	6.940	.14409
Ca^{+2}	40.08	.04990	Mg^{+2}	24.32	.08224
Cl^{-1}	35.457	.02820	Mn^{+2}	54.94	.03640
CO_3^{-2}	60.011	.03333	Mn^{+4}	54.94	.07281
F^{-1}	19.00	.05263	Na^{+1}	22.991	.04350
Fe^{+2}	55.85	.03581	NO_3^{-1}	62.008	.01613
Fe^{+3}	55.85	.05372	OH^{-1}	17.0080	.05880
H^{+1}	1.0080	.99206	S^{-2}	32.066	.06237
HCO_3^{-1}	61.019	.01639	SO_4^{-2}	96.066	.02082
I^{-1}	126.91	.00788	Zn^{+2}	65.38	.03059

This unit is helpful in picturing the true chemical character of the water and is one-thousandth of the numerical value of the common chemical unit normality. As mentioned earlier, in as much as the total equivalent weights of cations and anions in a solution, must be the same; the sum of the equivalents per million can be used to check the accuracy and completeness of chemical analyses.

Data may be expressed in percentage, which is parts per hundred. For water analyses, percentage values usually would be far below unity and would involve cumbersome decimals. Some water analyses may also be reported in parts per thousand but in this study, all the units of expression have been converted to parts per million.

Some water analyses are also expressed in grains per gallon; this is particularly true for the United States and Britain. In this connection a specification of the gallon used must be given.

In considering the quality of irrigation water, the unit, tons per acre foot is commonly applied. The term here used is 2,000 pounds. For moving streams, the dissolved-solids load may be reported in terms of tons per day.

Equations showing the relations between the various units of measure, given by Todd (1959) and Davis and De Weist (1966), are shown below.

(i) $$\text{Parts per million} = \frac{\text{milligrams per liter}}{\text{specific gravity of the water.}}$$

(ii) One part per hundred (percentage) = 10,000 ppm.

(iii) One grain per U.S. gallon = 17.12 milligrams per liter.

(iv) One grain per Imperial gallon = 14.3 milligrams per liter.

(v) One tag = 735 parts per million.

(vi) One milliequivalent per liter = One milligram per liter
= One equivalent per million.

(vii) One milliequivalent per liter of ion = $\frac{\text{Parts per million of Ion}}{\text{Equivalent weight of Ion}}$

(viii) One milliequivalent per liter of Cations = $100 \, EC^{2} X 10^{6}$[1]

(ix) One part per million = $1.56 \, EC \; X \; 10^{6}$

[1] Approximations for most natural waters in the range of 100 to 5000 mho/cm at $20^{\circ}C$.

[2] Electric conductance.

In conclusion, units of expression will be dictated by the techniques adopted in the final interpretation and study of water and the precision required.

Rock chemistry analyses in this study are expressed in percantages, precipitation in inches and temperature in degrees Centigrade.

4. ANALYTICAL TECHNIQUES

Examination of water for its dissolved components is part of the work done by a large number of chemical laboratories. Some of these have methods and equipment for making certain tests of water in the field as well as in the laboratory.

(a) Field testing of water -

Before discussing field testing of water, it is appropriate to give a brief note as to the nature of the containers and precautions necessary for handling water samples. Factors that are pertinent in selecting containers used to collect and store water samples are resistant to solution and breakage, efficiency of closure, size, shape, availability and cost.

Examination of water in the field to determine its approximate chemical character, is often useful. The procedures range from the determination of specific conductance in wells, boreholes and other water bodies, to rather extensive chemical analyses made with a semi-portable laboratory equipment. Some of these are reviewed briefly below:-

(i) Probably the most useful instrument for field studies of water quality is the fully portable wheatstone bridge for measurements of conductivity. These units are sturdy and useful but of lower accuracy.

(ii) Portable conductivity meters are useful in the field as a means of checking quality of water in the field during drilling processes and location of groundwater inflows to surface streams.

(iii) Portable laboratory kits containing all the necessary glassware and solutions for simple chemical tests such as for chloride, hardness, temperature and alkalinity.

(iv) Electric logs are highly useful indicators of the location of saline water in aquifers for resistivity obtained is computed for conductivity.

In conclusion as Hem (1969) has noted the greatest utility of the field analysis is probably for the determination of constituents which change rapidly after the sample is obtained and which, therefore, require undue and perhaps impossible speed in transportation to the central laboratory.

(b) Laboratory techniques

Water analysis may be termed "Microchemistry with microvolumes, Rainwater and Thatcher (1960), because all the determinations require the quantitative determinations of either milligrams or microgram quantities or fractions thereof."

Techniques by which water analysis is made, which are briefly reviewed below include, gravimetric analysis, volumetric analysis, spectrophotometric analysis and flamephotometric analysis.

(i) Gravimetric analysis

Gravimetric techniques in water analysis are generally tedious and time consuming because of the usual necessity for precipitation, filtration, washing ignition and weighing.

(ii) Volumetric analysis

Volumetric analysis is usually more rapid than gravimetric analysis if the titrant reagent is specific for the constituent. The sensitivity and or precision may also exceed that of a gravimetric analysis for some determinations.

(iii) Spectrophotometric analysis

Colorimetric determinations based on visual estimation of colour have long been used in water analyses by the use of colorimeters. By comparing colours of the solutions whose concentrations are not known with the already prepared standard solutions whose concentration is known, the unknown concentration can be determined. The widespread application of colorimetric analysis in the refined form of instrumental spectrophotometry is a relatively new development. Spectrophotometers are well suited for water analysis because often the determinations of small quantities of substances can often be detected readily and accurately and the difference in techniques of individual analysts are also minimized.

(iv) Flame-photometric analysis

By use of a Flame-photometer or the modified Flame-spectrophotometer, the determination of particular elements in the water, especially the alkali metals (these metals have characteristic flame colouration) can be achieved. The intensity of the colouration of a given metal is determined. The intensity of colouration is proportional to the concentration of the particular element in solution.

In conclusion, other instrumental analysis, such as Turbidimetry, Polarimetry and Chromatographic analysis are also useful in various water chemistry determinations.

5. COMPUTERIZED ANALYSIS

The computer is essentially an information processing system which, by its principal advantages over manual systems of speed of operation, compactness of storage, accuracy of operation and automatic mode of working, had to be employed in this research that was otherwise hampered in development by the sheer volume of information which needed processing.

The proceeding paragraphs cover the areas considered in the reorganisation of the 7,000 water chemistry analyses to enable:

(a) The determination of correlation coefficients between various cations/anions and total dissolved solids for specific geologic units.

(b) The sketching of scatter diagrams for given total dissolved solids and respective cations and anions in given geologic units.

(c) The production of distribution maps, showing the spatial concentration of total dissolved solids, Fluoride, Magnesium, Calcium, Sulphate and Bicarbonate in Kenya's groundwater resources.

The system is developed in three phases, namely:-

Phase (1), to provide a tape-based system with data available on cards.

Phase (2), to provide a tape-based system with data available on a magnetic tape.

Phase (3), to combine master files resulting from phases (1) and (2) for the interpretation and analysis of water chemistry data.

All the programmes have been written in the 1900 FØRTRAN language and the flowcharting illustrated in Figures 2-1, 2-2 and 2-3 is in accordance with the International Computers Limited (ICL). The programmes have been run on the 1902A, I.C.L., Nairobi University computer.

Phase 1

The data source comprising 3-cards record was input for batching into a master file. Due to a lot of incorrectly punched data, a subfile had to be created and transfer of corrected input records to the master file effected. The following programmes have been run:-

a. # M20A Creation of subfile

b. # M20B Listing of cations and anions

c. # M20E Updating of master file.

The flow chart for this phase is illustrated in Figure 2-1.

List 'GBC' was used to check whether or not the batched input records are correct. List 'GBF' was the final printout of the cations and anions from the master file.

Phase 2

The source data comprising 3-cards record was batched to a new master file (in this paragraph referred to as ("phase 2 master file") from an I.C.L. magnetic tape. For access to the information available on this tape, it had to be converted from STANDARD to FØRTRAN form. Phase 2

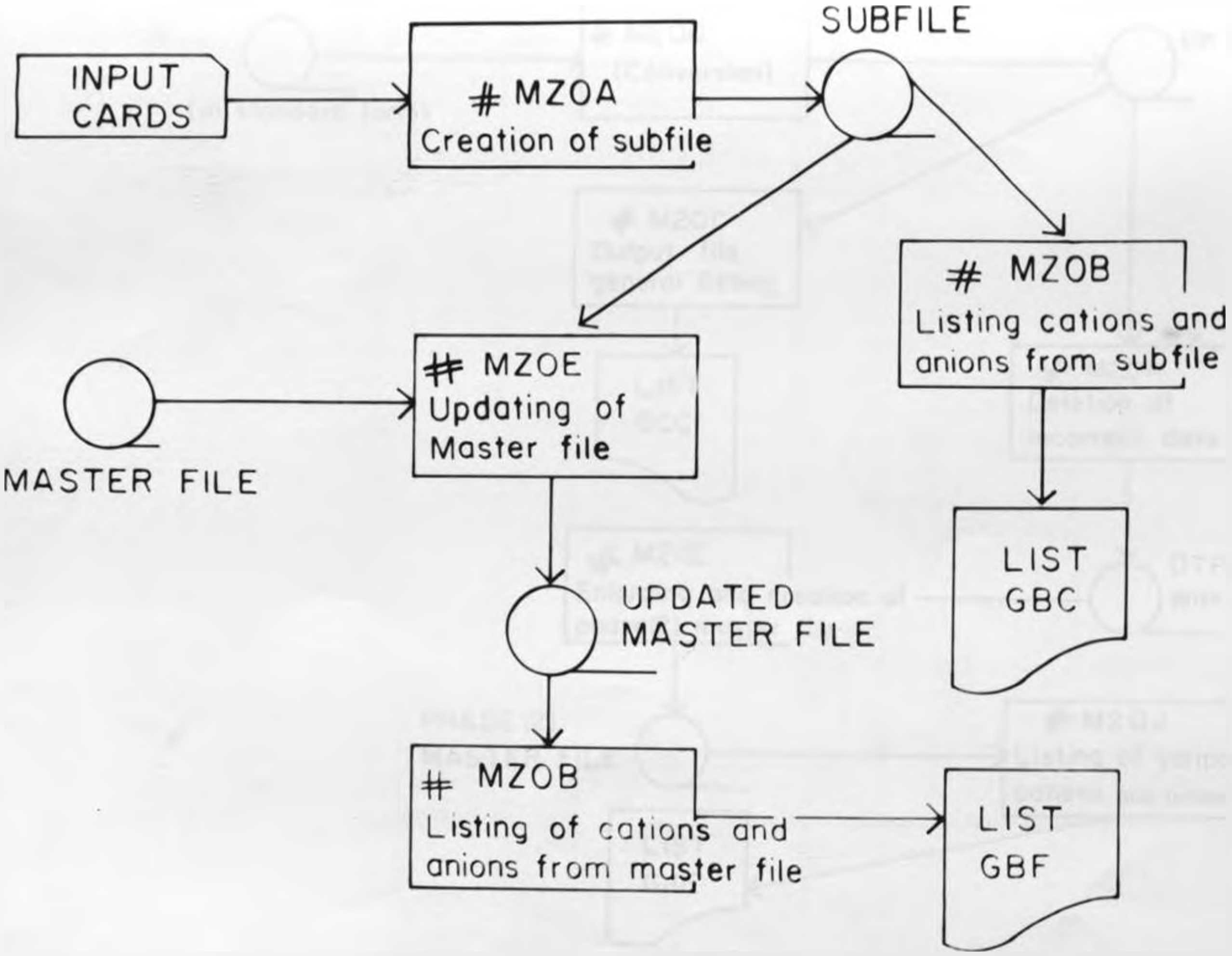


FIG 2 1 FLOW CHART FOR PHASE (I) PROGRAMS

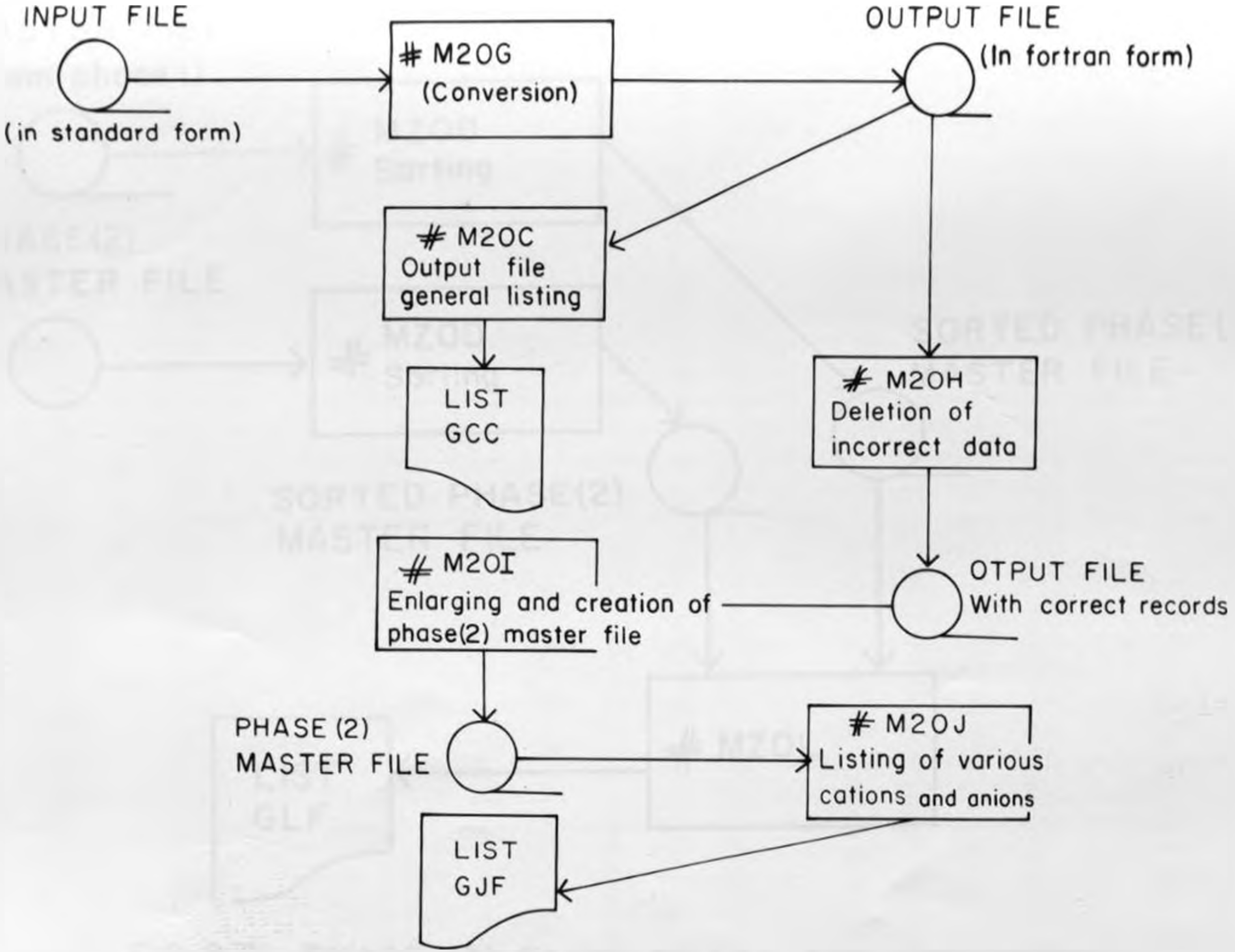


FIG 2 2 PHASE (2) FLOW CHART

flow chart is illustrated in Figure 2-2 and it consists of the following programmes:-

a. # M20G Conversion of input file data from STANDARD to FØRTRAN form.

b. # M20C Listing of the batched FØRTRAN form input file.

c. # M20H Updating of the input file. This programme deleted records without geological codes, records with less than 3-cards and records with some foreign elements.

d. # M20I Creation of phase (2) master file.

e. # M20J Listing of necessary cations and anions.

List 'GCC' is the general listing of the input file content used to check on the records to be deleted. List 'GJF' is printout of the various cations and anions from phase (2) master file.

Phase 3

The sorted master file from phases (1) and (2) were combined for:-

(i) the production of frequency distribution for various cations and anions.

(ii) The determination of correlation coefficients of various cations/anions and total dissolved solids.

(iii) The drawing of scatter diagrams on logarithmic scaled axes.

The flow chart for this phase is illustrated in Figure 2-3, 2-4 and 2-5. The programmes run in this phase include:

a. # M20D Sorting, on geological codes, geographical coordinates and sources.
b. # M20K Drawing of scatter diagrams.
c. # M20L Frequency distributions.
d. # M20N Correlation coefficients determination.

List 'GLF' represents the frequency distribution for the following cations and anions:- Calcium, Magnesium, Fluoride, Chloride, Silica, Sulphate, Carbonate, Bicarbonate and total dissolved solids.

List 'GNS' represents the correlation coefficient determination tables for the specific geologic units.

List 'GKS' represents the values used to draw up the output scatter diagrams using the graph plotter peripheral.

Before proceeding on to the conclusions that can be made from the various outputs of this section, there are two major setbacks that have been encountered while developing the programmes. Firstly, the 1902A, I.C.L. Central Processor has a core storage of approximately 16,000 locations. Exceeding of this core storage means failure to execute the loaded programme. The larger the core storage a central processor is, the more compact the programme will be and the lesser the compilation time and consequently less expenses. The programmes could be rewritten and rerun on another central processor of higher core

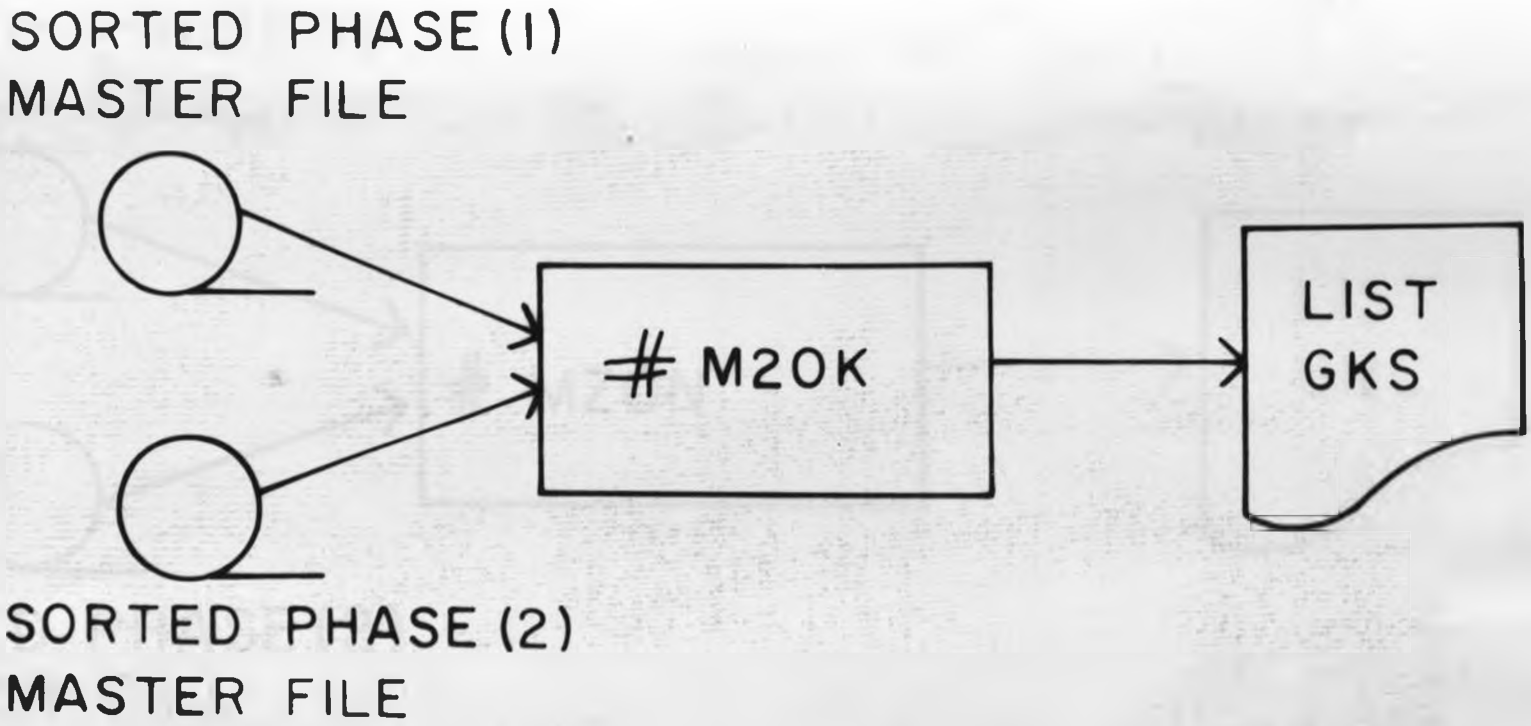


FIG. 2.4 PHASE (3) FLOW CHART FOR DRAWING SCATTER DIAGRAMS.

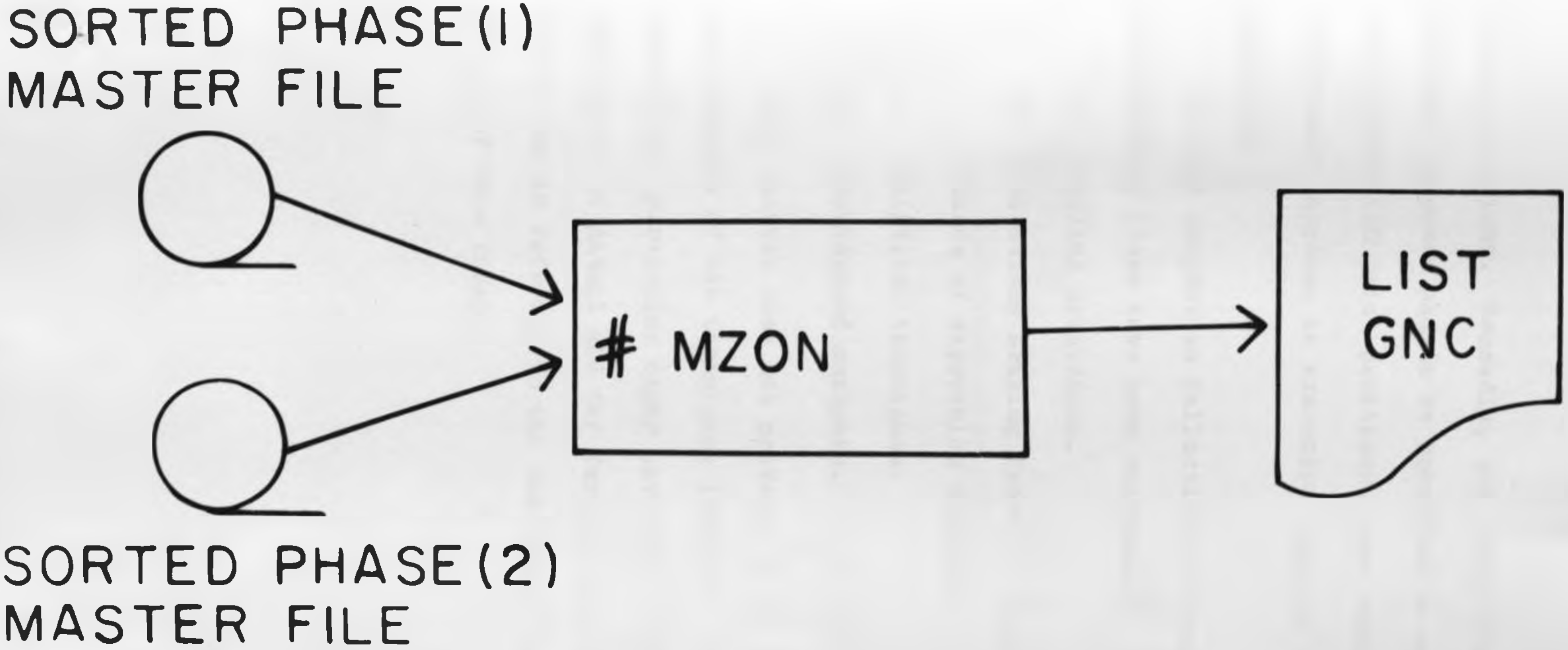


FIG. 2.5 PHASE (3) FLOW CHART FOR DETERMINING CORRELATION COEFFICIENTS.

storage locations. Secondly, the lists of output for different purposes had to be specified in content and order within 120 print-positions, thus causing some unnecessary increase in execution computer time.

CONCLUSION

In this chapter on Collection and Analysis of Data, the following items have been examined:

1. Sampling procedures.
2. Limitations arising from the data available.
3. Methods of expressing analyses.
4. Analytical techniques.
5. Computerized analysis.

This chapter does not pretend to be exhaustive in its treatment of the techniques involved. Items that concern this particular study have been touched in more or less degree of detail and for further examination of these methods one is referred to the respective texts given at the end of this thesis.

SECTION II

3. GEOMORPHOLOGY AND GEOLOGY.

4. SOILS.

5. CLIMATE AND SURFACE WATER HYDROLOGY.

CHAPTER III

GEOMORPHOLOGY AND GEOLOGY

The first part of this chapter examines the geomorphology of Kenya while the second part will discuss the geology of the country.

1. GEOMORPHOLOGY

In many parts of East Africa, especially Kenya and Tanzania, the first stage of quantitative geomorphological investigations has hardly begun. In Uganda, too, there are still many problems to be investigated. In the absence of relevant quantitative geomorphological data, the following items will be discussed in this section:-

(a) Denudation Chronology of Kenya.
(b) Drainage evolution in Kenya.
(c) Landform distribution in Kenya.

(a) Denudation chronology

Deciphering of the erosion history of Kenya is often met with many problems. These problems are a result of the geological processes that have been acting upon the landscape, and particularly so since the beginning of the Tertiary period. Among the major problems of erosion history is the lack of fossil evidence, necessary for dating a given erosion surface. This problem is being overcome by the use of isotopic age determinations but the story is not yet completed because of the sparse nature of these determinations. These complications are particularly true for the Precambrian formations and the younger

Post-Tertiary volcanics. Another method, which has been greatly used, is the correlation of erosion surfaces by the corresponding heights above sea level. These have to be used with care, taking into account the effects of faulting and volcanic activity.

Many scholars of the geomorphology of Kenya, notably, Dixey (1938, 1948, 1956); Pulfrey (1960), Saggerson and Baker (1965) and King (1948), agree that a standard cycle of pediplanation in landscape evolution applies to the determination/Of erosion history of the country. It must be noted, however, that the literature on denudational history of Kenya is scarce and often scattered.

Kenya has many places where erosion surfaces are well preserved or may be reconstructed. Some of the extensive volcanics of the Tertiary period rest upon, and thus preserve, earlier landscapes. The volcanics may be dated isotopically or by use of the intercalated Tertiary fossiliferous deposits. Baker (1970) has suggested a number of previously existing surfaces in Western Kenya and has given their respective ages. These are shown in Table III-1.

In the northern districts of Kenya, Dixey (1948), has indicated that possibly the oldest erosion surface recognized in Kenya is the Jurassic surface, whose precise age of development is not precisely established in the country, but has been well-documented in the neighbouring countries. He (1948) has shown that this surface underlies

TABLE III-1

PREVIOUSLY SUGGESTED AGES OF EROSION SURFACES IN WESTERN KENYA

	North Kenya (Dixey, 1948)	Kitale-Cherangani (Searle, 1952, Miller, 1956)	East Uganda (Bishop & Trendall, 1967)	Sekerr (McCall, 1964); S.W. Kenya (Shackleton 1951)
MID-MESOZOIC	10,000 ft peneplain	Cherangani plateau	Cherangani 10,000 ft. surface	Cherangani high level surface
		Lelon surface		
END MESOZOIC EARLY TERTIARY	6,200 ft peneplain	6,700 ft surface	Kitale surface	Cherangani surface
	5,000 ft peneplain	Kitale plain		
MID-TERTIARY	Buganda surface	W. Suk lowland (Amudat) surface	Kyoga surface	sub-Miocene, sub-Elgon & Kitale surfaces
END-TERTIARY	end-Tertiary surface (Turkana & Karamoja plains)		Karamoja plain	Masol, Amudat, W. Suk lowland surfaces

the Jurassic sediments of northern Kenya. He continues to envisage that, as seen along the Takabba-Derkali scarp, this surface was one on which planation, if effected at all, was only of local importance. There is good evidence to show that over large areas, it was a very unevenly eroded surface. The surface is well preserved on the mountains of Machakos district where the Mua, Kenzalu, Mbooni and Kilungu hills exhibit coplanar summit ridges at elevations of about 7,000 feet. According to Saggerson and Baker (1965), they appear from a distance as a well-marked tableland. The surface is also well preserved in parts of Kisii highlands (Huddleston, 1951). Mathews range and Larogi plateau are also believed to be part of this surface.

The Kitale surface, well preserved in the Kitale area, forms part of the Pre-Miocene 6,200 feet erosion surface of Trans Nzoia (Dixey, 1948). It has a slight southerly tilt, with the principal drainage system towards L. Victoria. The maximum elevation of this surface appears to lie along an East-West line corresponding to latitude 1ON, which forms a watershed between the Nyanza and Lake Rudolf drainage areas. This surface is well preserved in Nanyuki at 6,200 feet, Nzoia plateau at 6,600 feet and Machakos hills at 6000feet. It is possible that it corresponds to the Gondwana Cycle of King, (1967), Ankole Surface of McConnel (1955), Jurassic Surface of Dixey (1956) and the PI surface of Wayland (1922).

Matherson (1966), has indicated that the lower peaks of Lemilebbu and Ngoragaish hills are remnants of the Late-Cretaceous surface which correspond to the foothills of Machakos hills, (Saggerson and Baker, 1965). This has been termed the Kajiado surface. It may correspond to the Post-Gondwana Cycle of King, (1967), Cretaceous Surface of Dixey (1956) and Koki Surface of McConnel (1955).

The sub-Miocene erosion surface stands at about 1,200 feet below the Late-Cretaceous surface over many parts of Kenya. It is on this well-documented Mid-Tertiary erosion surface that much of the interpretation of the denudation chronology of Kenya is based. The subsequent deformations have determined its present altitude. The reliable dating of the surface by the overlying fossiliferous sedimentary deposits of Lower-Miocene age and the relationship of some of the Tertiary lavas to these deposits, provide a positive means of identifying this surface over much of Kenya. The surface as mapped and described by Pulfrey (1960), is shown in Figure 3-1.

A revision of Pulfrey's work concerning parts of eastern Kenya was done by Saggerson and Baker (1965). The Sub-Miocene erosion surface is recognized primarily at or near the base of the Tertiary volcanics on the eastern shoulders of the Rift Valley, particularly near Baragoi, Maralal, Sagana, Kajiado and most conspicuously along the Yatta plateau. It is also well preserved in areas south of Kisumu Gulf and in parts of the Kericho District. It is an extensive surface ranging in elevation from 4,000 to 4,500 feet above sea level. It is possible that this

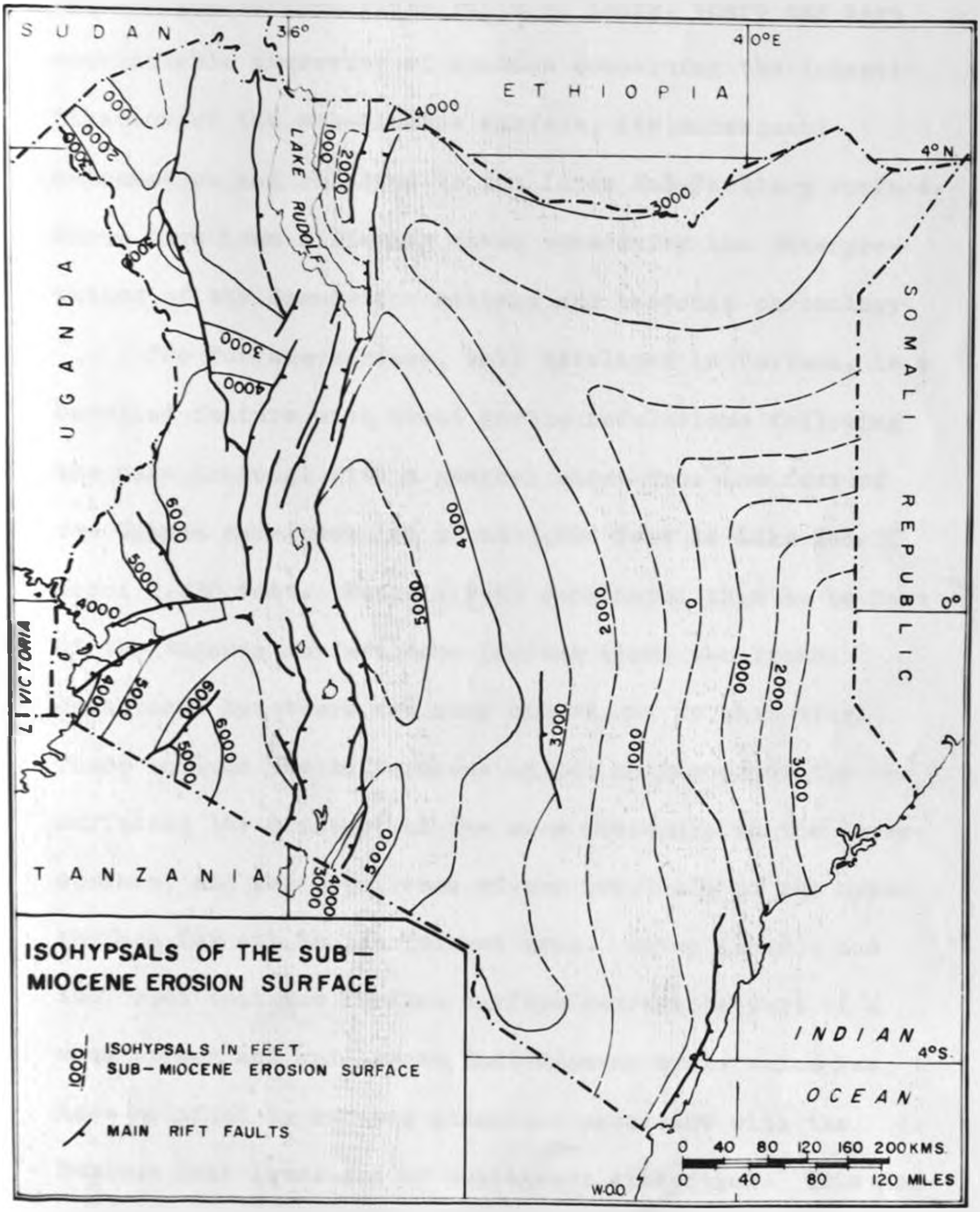

SUDAN
36°
40°E
ETHIOPIA
4°N
UGANDA
LAKE RUDOLF
SOMALI REPUBLIC
0°
L. VICTORIA
TANZANIA
INDIAN OCEAN
4°S
W.O.O.
1000
2000
3000
4000
5000
6000
0
ISOHYPSALS OF THE SUB-MIOCENE EROSION SURFACE
1000 ISOHYPSALS IN FEET SUB-MIOCENE EROSION SURFACE
MAIN RIFT FAULTS
0 40 80 120 160 200 KMS.
0 40 80 120 MILES

FIG 3 1

corresponds to the African Cycle of King (1967), Mid-Tertiary Surface of Dixey (1956), Buganda Surface of McConnel (1955) and the PII Surface of Wayland (1922). In western and north-western parts of Kenya, there has been considerable diversity of opinion concerning the indentification of the sub-Miocene surface, its subsequent deformation and relation to the later End-Tertiary surface. There have been differing views concerning the interpretation of the denudation history and tectonic chronology.

The Turkana surface, well developed in Turkana, is a bevelled feature with broad gentle undulations following the main drainage with a general slope from the foot of the Uganda escarpment at about 3,000 feet to Lake Rudolf about 1,230 feet. Fuchs (1939) considered this to be part of the Buganda surface down faulted along the Uganda escarpment but there are many objections to this view. These include the differences in the character of the two surfaces, the presence of far more residuals on the lower surface, and the occurrence of the residuals of the upper surface far out in the Turkana area. Dixey (1948), has indicated that the Turkana surface represents part of a wide spread and well known Post-Miocene cycle which has been modified by renewed planation accordant with the maximum lake level and by subsequent dissection. This End-Tertiary erosion surface is well developed in the eastern half of Kenya. It passes beneath the preserved Quaternary terrestrial and marine sediments in the lower Tana basin. It forms a fringe of well preserved plain lands adjoining the dissected remnants of the sub-miocene surface and was never continous across the central part of the country. The surface developed in eastern Kenya during Early-Pliocene times is overlain in eastern Kenya by Late-Pliocene and Quaternary lacustrine and terrestrial deposits. At the Coast, both Caswell (1953, 1956) and Thompson (1956), postulated that the surface is overlain by Upper Pliocene Magarini Sands and Marafa Beds. The extent and present elevation of this surface in Kenya, according to Baker (1970), is shown in Figure 3-2. Its occurrence in eastern Kenya has been described by Saggerson and Baker (1965). In general its elevation ranges from about 3,500 feet to 3,800 feet above sea level. It has been correlated with PIII surface of Central Uganda of Wayland (1930), Tanganyika surface of McConnel (1955), Kyoga and Kasubi surface of Bishop and Trendall (1967), End-Tertiary of Dixey (1956) and the Victoria cycle of King (1967).

The present day surface is marked by the presence of river valley terraces and beaches. This is correlated with the latest cycle of King (1967).

(b) Drainage Evolution

Faulting accompanied by volcanic eruptions, during the Tertiary period greatly interrupted the Pre-Tertiary drainage pattern. From the reconstruction of the sub-Miocene topography, illustrated in Figure 3-1, Pulfrey (1960), has shown that a topographical low existed along the present Rift Valley in Kenya. Gevaerts (1957), Ojany (1971) and Baker and Saggerson (1965) have confirmed this.

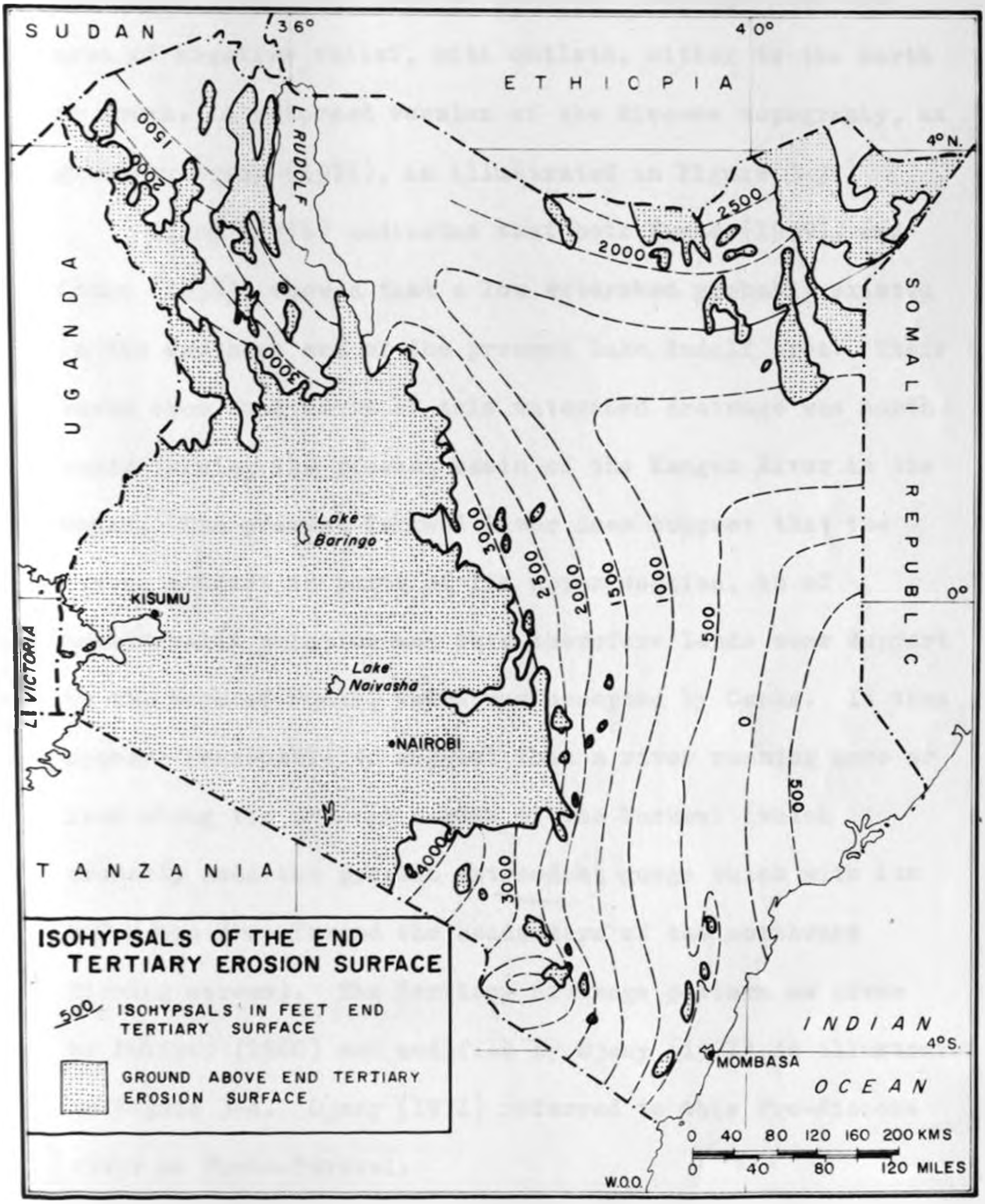

SUDAN
36°
40°
ETHIOPIA
4°N.
L. RUDOLF
1500
2000
3000
2500
2000
UGANDA
SOMALI REPUBLIC
Lake Baringo
3000
2500
2000
1500
1000
500
0
500
KISUMU
0°
L. VICTORIA
Lake Naivasha
NAIROBI
TANZANIA
4000
3000
ISOHYPSALS OF THE END TERTIARY EROSION SURFACE
500 ISOHYPSALS IN FEET END TERTIARY SURFACE
GROUND ABOVE END TERTIARY EROSION SURFACE
INDIAN OCEAN
4°S.
MOMBASA
0 40 80 120 160 200 KMS
0 40 80 120 MILES
W.O.O.

FIG 3.2

Their investigations have indicated that this topographical low was flanked by old upland massifs of more or less the same elevation as at present. Such conclusions would naturally favour the idea of internal drainage into the area of negative relief, with outlets, either to the north or south. A reformed version of the Miocene topography, as given by Ojany (1971), is illustrated in Figure 3-3.

Ojany (1971) indicates that both Fuchs (1939), and Cooke (1958), showed that a low watershed probably existed in the southern end of the present Lake Rudolf area. Their works show that north of this watershed drainage was northwards joining the present basin of the Kangen River in the Sudan. The present Turkwel River does suggest that the river, at least in parts of its upper section, is of considerable duration and this therefore lends some support to the work of Fuchs, which was accepted by Cooke. It thus appears reasonable to suggest that a river running more or less along the present course of the Turkwel (which probably used the present antecedent gorge which with its 607 metre drop formed the headwaters of the northward flowing stream). The Tertiary drainage pattern as given by Pulfrey (1960) and modified by Ojany (1971) is illustrated in Figure 3-4. Ojany (1971) referred to this Pre-Miocene river as Proto-Turkwel.

The situation south of Proto-Turkwel watershed has been examined by a number of workers and their conclusions that this area formed part of the Ruvu (Pangani) drainage

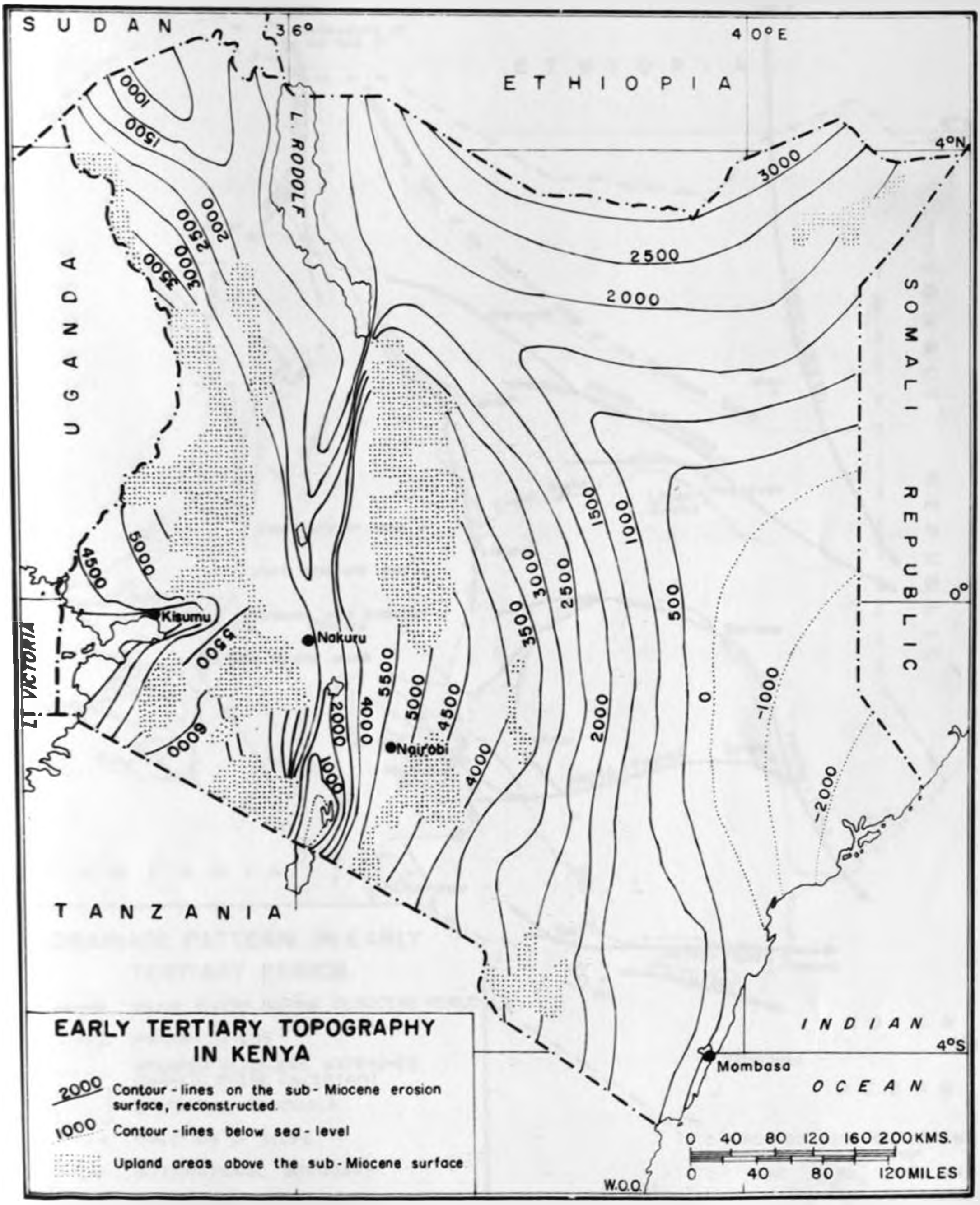
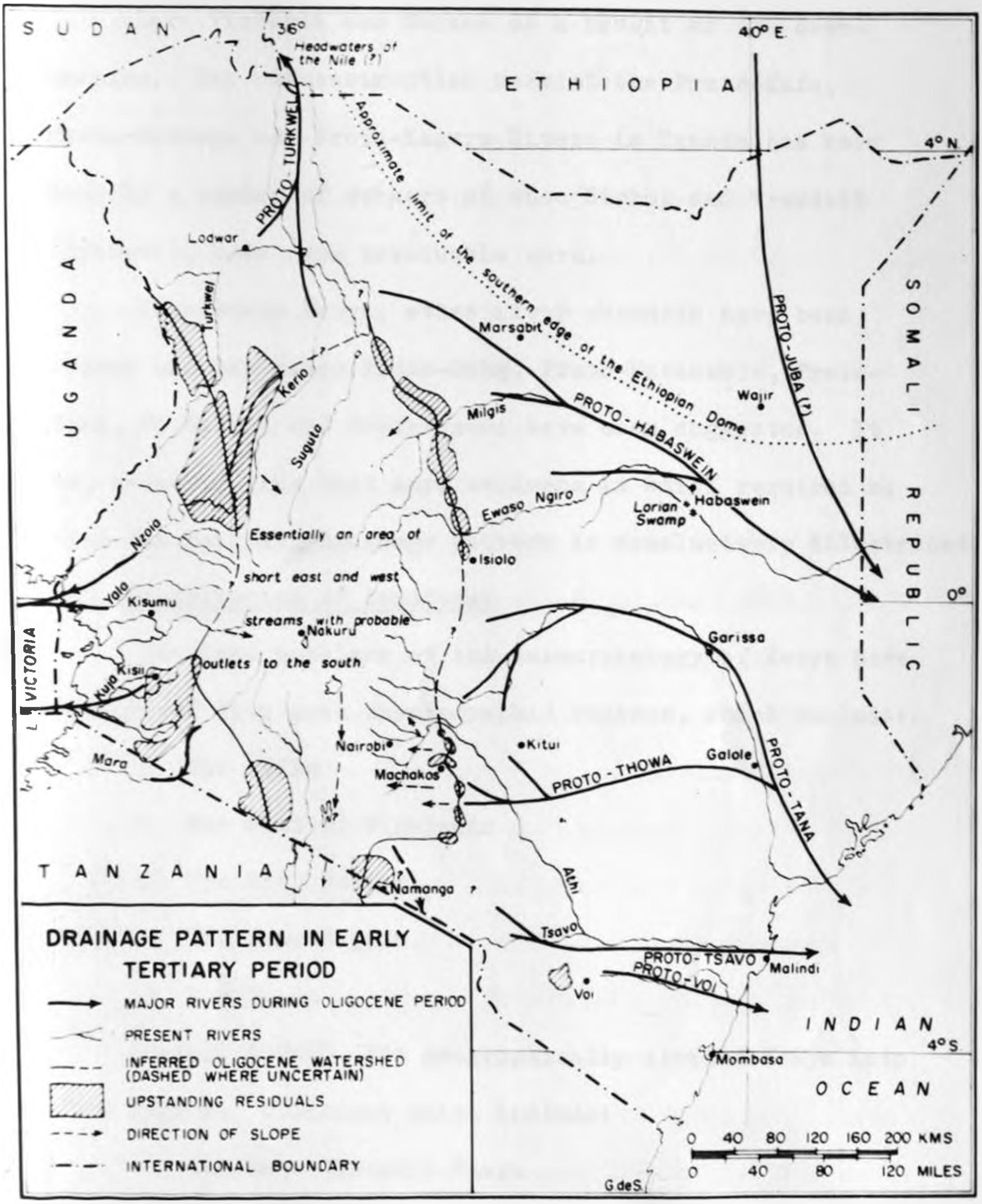

EARLY TERTIARY TOPOGRAPHY IN KENYA
2000 Contour-lines on the sub-Miocene erosion surface, reconstructed.
1000 Contour-lines below sea-level
Upland areas above the sub-Miocene surface
SUDAN
ETHIOPIA
UGANDA
SOMALI REPUBLIC
TANZANIA
L. RODOLF
L. VICTORIA
Kisumu
Nakuru
Nairobi
Mombasa
INDIAN OCEAN
36°
40°E
4°N
0°
4°S
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
500
0
-1000
-2000
0 40 80 120 160 200 KMS.
0 40 80 120 MILES
W.O.O.

FIG. 3 3



SOURCE Studies in East African Geography of Development, 1971

FIG 3.4

have been confirmed by Ojany (1971). He has further undertaken renconstruction of the drainage channels of the Proto-Ruvu in the Kajiado-Namanga area.

Lake Victoria was formed as a result of the down-warping. The renconstruction work of the Proto-Kafu, Proto-Katonga and Proto-Kagera Rivers in Uganda has been done by a number of workers of whom Bishop and Trendall (1966-67), have done invaluable work.

In eastern Kenya, other river channels have been traced and the names Proto-Juba, Proto-Habaswein, Proto-Tana, Proto-Voi and Proto-Tsavo have been suggested. It is, however, true that more evidence is still required so that the Tertiary drainage pattern is conclusively illustrated.

(c) Distribution of landforms

Previous scholars of the Geomorphology of Kenya have recognized five main physiographic regions, which include:-

i The Nyika
ii The Central Highlands
iii The Rift Valley
iv The Lake Region
v The Coast

Ominde (1968), has geographically divided Kenya into five regional divisions which include:

i The Lake Victoria Basin
ii The Central Rift and Associated Highlands
iii The Eastern Plateau Foreland
iv The Coast Region
v The Semi-arid Northern, North-eastern and Southern Kenya.

On the whole these subdivisions are based on environmental factors and not on genetic factors. The genetic approach to landform classification enables the evolution of the landform to be understood. Ojany (1966), basing his studies on the Davisian Concepts of Landscape Evolution, divided Kenya into fourteen physiographic units. Baker (1970), on a morphogenetic basis, recognized the following broad types of landforms in Kenya which are shown in Figure 3-5:-

(A) Volcanic landforms
(B) Tectonic landforms
(C) Erosional landforms

(A) Volcanic landforms

The Tertiary and Post-Tertiary volcanic activity has given rise to the most spectacular topographic features. Forming part of the main topographic features are the central volcanoes which, on the basis of their form of eruption, are grouped into four types:-

(i) Vesuvian types: These have one principal centre of eruption and include Kilimanjaro, Kenya and Elgon. Others of this type are the Kisingiri volcano of South Nyanza, Meru, Ol Donyo Lengai, Shombole and Tinderet. These volcanoes are predominantly of nephelinitic and phonolitic composition with a high proportion of pyroclastics. The Abedare volcanoes form a sub-type of this type of volcanoes.

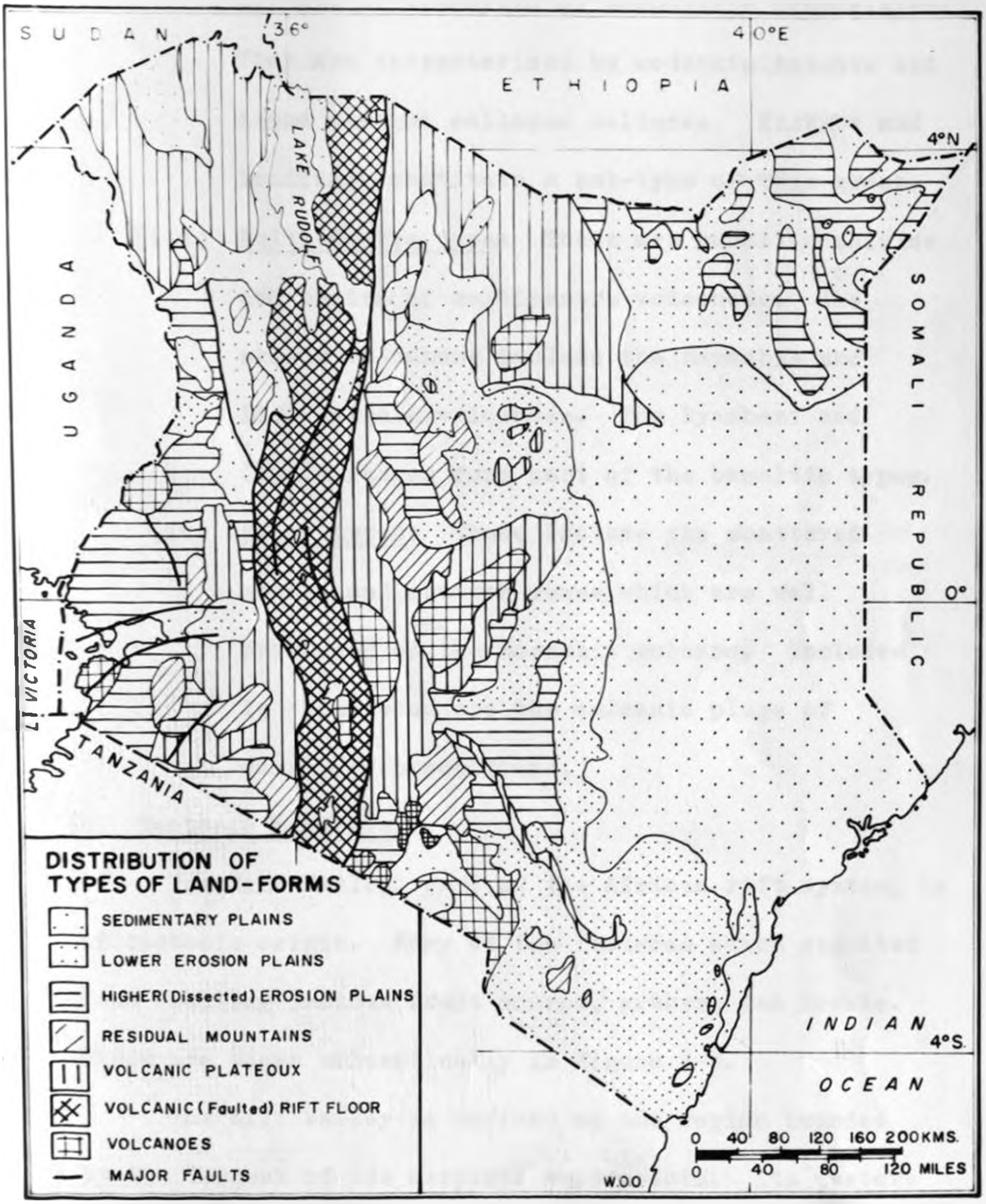

SUDAN
36°
40°E
ETHIOPIA
4°N
LAKE RUDOLF
UGANDA
SOMALI REPUBLIC
0°
L. VICTORIA
TANZANIA
INDIAN OCEAN
4°S.
DISTRIBUTION OF TYPES OF LAND-FORMS
SEDIMENTARY PLAINS
LOWER EROSION PLAINS
HIGHER (Dissected) EROSION PLAINS
RESIDUAL MOUNTAINS
VOLCANIC PLATEOUX
VOLCANIC (Faulted) RIFT FLOOR
VOLCANOES
MAJOR FAULTS
0 40 80 120 160 200 KMS.
0 40 80 120 MILES
W.OO.

FIG. 3.5

(ii) Shield-Caldera types: These are mainly situated in the Rift Valley floor and include the volcanoes of Suswa, Menengai, Peka and Karossa. All are of trachytic or phonolitic composition. They are characterized by moderate heights and broad central collapse calderas. Kilembe and Londiani constitute a sub-type of this group.

(iii) Multi-Centre types These are basaltic shields and chains of multicentre volcanoes. The shield volcanoes include the Marsabit and Dida Galgalu volcanoes. The Nyambeni and Chyulu ranges form part of the basaltic types.

(iv) Minor types: These include the scattered scoria and spatter cones which are well preserved on the Marsabit volcano. Included in this group are the volcanic plugs of variable compositions.

(B) Tectonic Landforms

The Rift Valley, part of the African rift system, is of tectonic origin. Many of the features which resulted from faulting include fault scarps, grabens and horsts. These are shown schematically in Figure 3-6.

The Rift Valley is defined as the region bounded by the largest of its marginal escarpments. Its western margin lies along the Nguruman, Elgeyio, Turkwel and Turkana escarpments, and the Nyanza rift valley is a westward trending branch of the main Rift Valley. The eastern margin occurs on the Turoka, Ngong, Sattima and

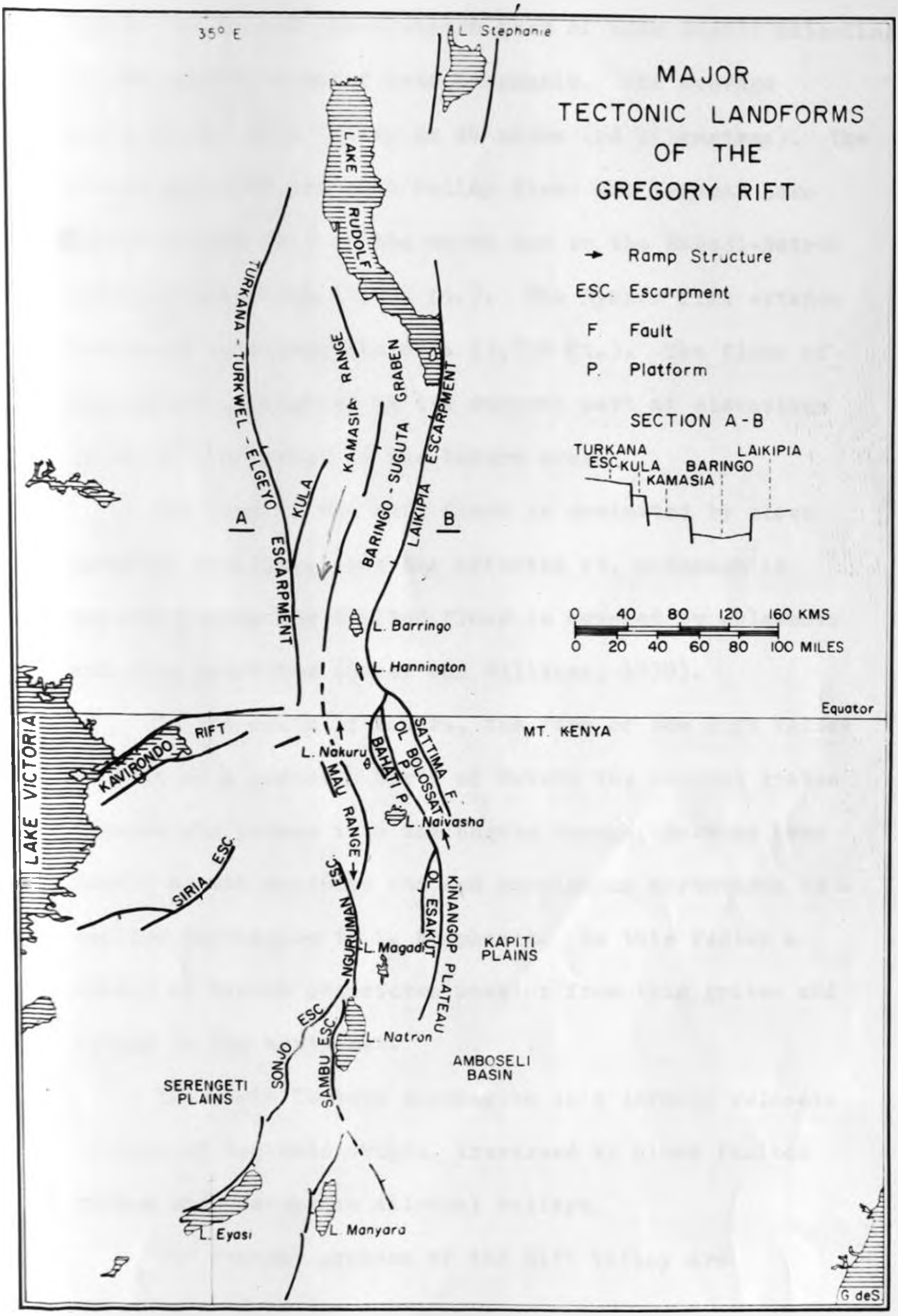

35° E
L. Stephanie
MAJOR
TECTONIC LANDFORMS
OF THE
GREGORY RIFT
Ramp Structure
ESC. Escarpment
F. Fault
P. Platform
SECTION A-B
TURKANA
ESC
KULA
KAMASIA
BARINGO
LAIKIPIA
0 40 80 120 160 KMS
0 20 40 60 80 100 MILES
LAKE RUDOLF
TURKANA - TURKWEL - ELGEYO ESCARPMENT
KULA
KAMASIA RANGE
BARINGO - SUGUTA GRABEN
LAIKIPIA ESCARPMENT
A
B
L. Barringo
L. Hannington
Equator
MT. KENYA
LAKE VICTORIA
KAVIRONDO RIFT
L. Nakuru
MAU RANGE
BAHATI P.
OL BOLOSSAT P
SATTIMA F.
L. Naivasha
SIRIA ESC
NGURUMAN ESC.
OL ESAKUT
KINANGOP PLATEAU
KAPITI PLAINS
L. Magadi
SONJO ESC
SAMBU ESC.
L. Natron
AMBOSELI BASIN
SERENGETI PLAINS
L. Eyasi
L. Manyara
G deS.

FIG 3.6

Laikipia escarpments, along the eastern side of the Suguta Valley and the southern part of Lake Rudolf extending to the eastern side of Lake Stephanie. The average width of the Rift Valley is 40 miles (64 kilometres). The lowest parts of the Rift Valley floor are beneath Lake Rudolf (1,230 ft.) in the north and in the Magadi-Natron basin in the south (1,975 ft.). The Nyanza rift extends westwards into Lake Victoria (3,718 ft.). The floor of the valley is highest in its central part at elevations of about 6,000 feet in the Nakuru area.

The form of the rift floor is dominated by close parallel faulting, that has affected it, although in several places the faulted floor is covered by volcanoes and thin eruptives (Baker and Williams, 1970).

To the south of Nakuru, the form of the Rift Valley is that of a graben. North of Nakuru the central graben narrows and passes into the Suguta trough, forming Lake Rudolf at the southern end and continuing northwards as a shallow depression to L. Stephanie. In this region a number of branch structures develop from this graben and extend to the northwest.

The north Turkana depression is a largely volcanic lowland of tectonic origin, traversed by block faulted ridges with extensive alluvial valleys.

The central grabens of the Rift Valley are characterized by the occurrence of a series of volcanoes along its centre which have been mentioned earlier.

The principal escarpments, for example, the Elgeyo and Nguruman, are caused by faulting. The trough of the valley is occupied by various lakes.

Since erosional landforms have been discussed in the denudation chronology of the country, no further examination is now attempted.

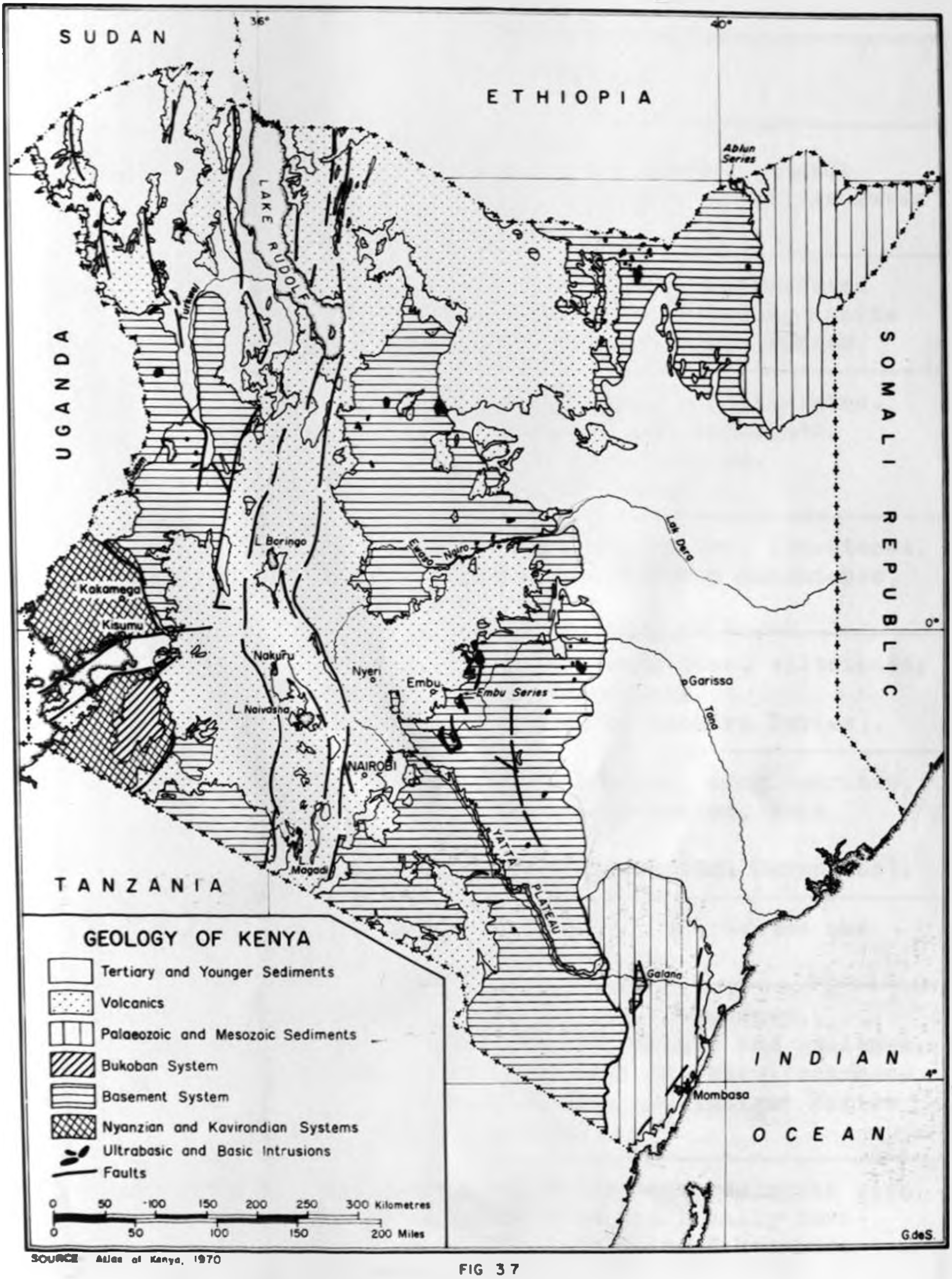
2. GEOLOGY

The geology of Kenya has been very much complicated by the tectonic and metamorphic processes that have not only altered the mineralogy of the rocks but the rock structure as well.

The lack of fossil evidence and adequate isotropic age determinations have made the study of the structural and stratigraphic relationship of the rocks quite difficult. Until recently, for example, rocks of the Basement System in eastern Kenya, were regarded as the oldest in the country, but further work by scholars of the geology of Kenya, and notably the work of Holmes (1951), has revealed that in fact rocks of the Nyanzian system of western Kenya are the oldest in the country. The Geology of Kenya as given in the Kenya National Atlas (1970), is illustrated in Figure 3-7 and the succession geochronological succession is given in Table III-2. The tectonic history of the country is summarized in Table III-3. The information in both the tables is from the Geological Survey of Kenya.

PRECAMBRIAN

The Precambrian formations occur in what have been termed two main structural regions (Baker, 1968), the Nyanza



SOURCE Atlas of Kenya, 1970

FIG 37

TABLE III-2

GEOCHRONOLOGICAL SUCCESSION

SYSTEM	LITHOLOGY
RECENT	Soils, alluvials, beach sands. Magadi soda lake, spring deposits. Alkaline lavas and pyroclastics
PLEISTOCENE	Coral reefs and sandstones, terrestrial limestones and sediments including lignite beds. Alkaline lavas and pyroclastics.
TERTIARY	Clays, sands, sandstones, conglomerates. Terrestrial limestones and sediments. Alkaline lavas and pyroclastics. (Simbara and Samburu Series).
CRETACEOUS	Sandstones, siltstones, shales, limestones. (Freretown Limestone, Marehan Sandstones, Danissa Beds).
JURASSIC	Limestones, shales, sandstones, siltstones, mudstones, typsiferous beds. (Daua Limestone Series, Mandera Series).
KARROO	Tillite, grits, sandstones, conglomerates, siltstones, carbonaceous shales, thin limestones. (Duruma Sandstones; Mansa Guda Formation).
BUKOBAN	Acid to basic volcanics, quartzites and sediments. (Kisii Series).
BASEMENT	Quartzites, crystalline limestones, garnetiferous pelitic schists and gneisses, graphitic schists, acid gneisses, charnockites. (Turoka, Kurase and Kasigau Series and Sobo Formation).
KAVIRONDIAN	Argillaceous and arenaceous sediments with boulder conglomerates and locally hornblende andesites (including Kaksingiri Schists).
NYANZIAN	Conglomerates, sandstones, quartzties, phyllites and limestones (Ablun Series). Sandstones, limestones coglomerates, pelites (Embu Series) Basic to acid volcanics, banded ironstones and sediments of Nyanza (including Samia Hills Series).

TECTONIC HISTORY OF KENYA

PERIOD		NATURE OF TECTONIC ACTIVITY
KAINOZOIC	QUATERNARY	Eustatic changes in sea level. Some vulcanicity. Minor faulting. Cutting of marine platform Grid faulting, development of major volcanoes. East and Kavirondo Rift faulting and vulcanicity
	TERTIARY	
		Faulting, warping, vulcanicity and early development of East Rift Zone (Gregory Rift)
		Sub-miocene surface with subsequent warping and development of Lake Victoria basin
		Regional uplift (2,000 ft. in central Kenya)
MESOZOIC	CRETACEOUS	Maturation of end-Cretaceous peneplain Jurassic peneplain and erosion, deposition and peneplanation during Cretaceous times
PALAEOZOIC	JURASSIC	Slight warping, tilting and faulting of Mesozoic sediments of N.E. Kenya
	KARROO	Gentle eastward tilting, warping and faulting of Duruma Sandstones and Mesozoic Sediments at the coast
		Deposition, erosion and peneplanation. No records in East Africa
PRE-CAMBRIAN	BUKOBAN	Gentle warping and minor faulting
	BASEMENT SYSTEM	Third period of N.E.-trending folds of N. Province Open and isoclinal folds of Mozambiquian trend, generally between N.S. and N.W.-S.E. Early recumbent folds, trend N.E. to N. of Southern Kenya
	NYANZIAN-KAVIRONDIAN	Isoclinal folds with N.E. and S.E. trending axis Slight metamorphism. Granite intrusion. E-trending folds of Ablun Series

TABLE III - 3

Shield and Mozambique Belt. The Nyanza Shield comprises the old Precambrian sediments, volcanics and granites in western Kenya. The Mozambique Belt consists of metamorphosed sediments and intrusives contained in an orogenic belt of Late Precambrian age, running through eastern Kenya into eastern parts of the Tanzanian mainland. Rocks of the Mozambique Belt were formally classified in the Basement System, a term frequently used by the Mines and Geological Department's Publications.

Nyanza Shield

Three of the four major systems that comprise the Kenya Precambrian are found in the western and southwestern parts of the country. As suggested above, structural and geochronological evidence suggests that these rocks are older than those of the Mozambique Belt. The three major systems of the Nyanza Shield include:

(I) Nyanzian System
(II) Kavirondian System
(III) Kisii Series (Bukoban System)

(I) Nyanzian System

The Nyanzian System is mainly composed of lavas and pyroclastics with sediments and banded ironstones. A Potassium-Rubidium-Strontium isotropic age determination taken for a rhyolite from R. Owadi along Sondu-Oyugis Road, 0° 29' S and 34° 35' E, reveals an age of between 2015 ± 300 million years.

The Nyanzian System is composed of three main rock

B
Basalt
[illegible]
Granite

groups whose exact stratigraphic positions in various parts of the area is not very clear. These rock groups are shown below.

KISUMU	MIGORI	MARAGOLI-KAVIRONDO* GULF
4. Rhyolites and Tuffs	Rhyolite Group	Basalts,** Tuffs, Agglomerates
3. Banded Ironstones and Andesites	Slaty and Andesitic Group	Andesites and Andestic Agglomerates
2. -	Greywacke Group	-
1. Basalts, Ironstones and Tuffs	Basic Volcanic Group	Samia*** Series-Rhyolites, Tuffs and Banded Ironstones

* The name Kavirondo is going out of use and instead the name Winam is coming into use.

** It has been suggested that the Basalts, Tuffs and Agglomerates are older and should come down to the Samia Series, ***, such that the Samia Series form an equivalent of the Yonger Rhyolite Group of (4) above.

The four main groups of this system to be examined briefly below include:-

(i) Basaltic Group

(ii) Banded Ironstone Group

(iii) Andesitic Group

(iv) Rhyolite Group

(i) Basaltic Group

This group is composed mainly of pillow-basalts interbedded with thin basaltic tuffs and lenses of ironstones and greywackes. A metabasalt from this group from North Ruri in South Nyanza on chemical analysis revealed the following composition:-

SiO_2	50.14%
Al_2O_3	15.85%
Fe_2O_3	2.71%
FeO	8.94%
MgO	4.07%
CaO	11.21%
Na_2O	2.67%
K_2O	0.70%
H_2O^+	1.08%
H_2O^-	
TiO_2	0.96%
P_2O_5	0.05%
MnO	0.26%
Stet	0.57%

(ii) Banded Ironstone Group

These are essentially magnetite-haematite rich rocks which show strong banding and at depth are enriched with Silica and Siderite. The chemical analysis of a banded ironstone from South Nyanza showed the following composition:

SiO_2	21.00%
Al_2O_3	-
Fe_2O_3	64.72%
TiO_2	Tr
P_2O_5	0.17
S	0.09%
Fe	-
MgO	-
CaO	-
Na_2O	-
K_2O	-
$H2O^+$	-
H_2O^-	-

(iii) Andesitic Group

These consist mainly of andesitic flows with some tuffs and agglomerates but in South Nyanza and Migori area the andesites are associated with slates. An andesite from South Nyanza, on chemical analysis, gave the following composition:

SiO_2	50.32%
Al_2O_3	14.18%
Fe_2O_3	1.71%
FeO	6.85%
MgO	5.07%
CaO	5.73%
Na_2O	1.17%
K_2O	2.57%
H_2O^+)) H_2O^-)	3.72%
TiO_2	1.00%
P_2O_5	0.28%
MnO	0.15%
CO_2	7.14%
F	Nil
S	0.04%
Loss on Ignition	-
Less O Equivalent	0.02%

(iv) Rhyolite Group

These are mainly rhyolites, dacites with associated ironstones. These acidic volcanics, by far, form the greatest proportion of the Nyanzian rocks in the south-western part of the country and the assemblage is more closely comparable with the representatives of the system in both North and Central Nyanza.

Post-Nyanzian Intrusives

These are essentially altered and sheared basic igenous rocks mainly epidiorites. After the intrusion of these rocks, a number of granites and granodiorites were emplaced. Important graniodioritic intrusions are those of Migori and Oyugis and the granitic one of Asembo.

After the deposition of the Nyanzian rocks and the intrusive activity, there was a localized Post-Nyanzian orogeny which gave rise to the mineralization of the Nyanzian System and led to the consequent deposition of the Kavirondian System.

(II) Kavirondian System

The rocks of the Kavirondian System are not only spatially but also stratigraphically closely associated with the Nyanzian System and the two have generally been folded and faulted together.

An unconformable relationship of the Kavirondian to the underlying Nyanzian System is noticeable where they occur together. A period of crustal deformation clearly separated the deposition of the rocks of two systems.

Members of both systems were also folded after the deposition of the Kavirondian rocks. The fold axes striking approximately North-East and South-West and North-West and South-East are common for the Post-Nyanzian and Pre-Kavirondian deformation while fold axes striking nearly East-West are characteristic of the Post-Kavirondian deformation.

The Kavirondian rocks consist mainly of gritty and muddy sediments with Conglomerates which have been shown to have been derived from rocks of the underlying Nyanzian System. A mudstone of this system from Butere revealed the following chemical composition.

SiO_2	57.71%
Al_2O_3	23.86%
Fe_2O_3 FeO	5.66%
MgO	Tr
CaO	0.50%
Na_2O	1.28%
K_2O	2.67%
TiO_2	2.37%
Loss on Ignition	6.01%

Although folding is locally intense and shearing is common, the regional metamorphism grade of both the Nyanzian and Kavirondian rocks is comparatively low and corresponds to that of the greenschist facies.

It is believed that the Nyzanian and Kavirondian rocks were deposited in an epicontinental environment, of a rigid continental mass, the Kavirondian being considered as a molasse assemblage derived from the Nyanzian System.

(III) Kisii Series (Bukoban System)

The Kisii Series is regarded as a representative of the Bukoban System of Tanzania. It forms a flat lying Curasse on older systems in the Gusii District but its stratigraphic relationship to the other formations is not clearly understood and it has been suggested that it is possible that it could as well be of Early Paleozoic age but no concrete evidence has been found to support this suggestion.

Huddleston (1951) proposed the following succession for the Kisii Series:-

UPPER GROUP	3. Rhyolites, Tuffs and Sandstones and Conglomerates of Eastern Kisii and Sotik. 2. Andesites and Dacites. 1. Felsites
MIDDLE GROUP	2. Ferrusinous Siltstones and Cherts. 1. Quartzites and Pebble Beds.
LOWER GROUP	3. Kisii Soapstone. 2. Non-Porphyritic Basalts. 1. Porphyritic Basalts.

From the succession given above, it is evident that the Kisii Series are of three-fold, with an upper and lower division of acidic and basic lavas respectively and a middle division of sediments.

The quartzites in the middle division in places form prominent escarpments at the plateau edges. In the western half of the District, there are often lenticle-like masses of non-magnesian "Soapstones", which are as a result of metasomatic replacement of lower lavas.

In the eastern half of the District where only the two upper groups are represented, the series have a local basal conglomerate in which gold has been found to occur. Traces of Cassiterite are found in heavy residues from some of the quartzites.

The series lie mor or less flatly with only gentle folding across the upturned edges of the gold formation. The three main groups of Kisii Series to be examined briefly below include:-

(i) Lower Group
(ii) Middle Group
(iii) Upper Group

(i) Lower Group

Porphyritic Basalts

These are well exposed at scattered pockets round the western and southern periphery of the Gusii District. They are characterized by large plagioclase phenocrysts.

Non-Porphyritic Basalts

These are overlain by quartzites throughout the area. Thin fresh dolerite dykes occassionally cut the non-porphyritic basalts and quartz-veining is not uncommon.

Kisii Soapstones

These form pockets of occurrences along the Birongo-Itumbe ridge and also on the Sameta hill. The rock consists of a mixture of Sericite and Kaolin with occassional mixture of epidote, chlorite and quartz. It is well jointed and the petrographic investigations have led to the suggestion that the soapstone may have been derived from the basalts of the Kisii Series by hydrothermal activity. On account of its refractory properties and resistance to chemical action, soapstone is widely used in furnace-linings. It can also be used for sculpting and at present a small quantity is used locally for animal carvings, ash-trays and vases.

(ii) Middle Group

Quartzites

These vary considerably in thickness up to about 250 feet along the Kisii-Manga Road.

The quartzites have given rise to good scarp faces up to 200 feet in height. The Manga Scarp is quite striking. These quartzites are of a hard fine to medium grained variety with occasional development of grit and thin pebble bands.

Cherts

These replace the quartzites in places and are essentially of two types. Those with concretionary structures and those without. They are probably a product of chemical deposition which could be equated to that one of the Nyanzian banded ironstones and cherts.

(iii) Upper Group

Porphyritic and non-porphyritic felsites

These extensively developed rocks overlie the quartzites and cherts and in places attain considerable thicknesses, well up to several thousand feet.

They are massive rocks which show few structural features and flow banding in them is not uncommon. Both the porphyritic and non-porphyritic types often contain highly vesicular bands in which vesicles range from a few millimetres to three centimetres in size. The smaller vesicles are infilled with chalcedomy or chlorite, while the large ones have a rim of coarsely crystalline quartz.

Andesites and Dacites

These form a thin lense over the felsite group. They are fine to medium-grained, purplish-blue or greenish, non-porphyritic rocks.

Rhyolites and Tuffs with Intercalated Sediments

These very fine grained and light to dark grey or grey-green rocks, weathering to pink or light-yellow slates, are well developed in the Kijaur-Kiabonyoru ridge where also the intercalated sediments are well exposed.

At the eastern margin of the Nyanza Shield there are granodiorites, migmatites, small areas of hornblende-schists, amphiboles and cataclastic derivations of these which have been involved in the later Mozambique orogeny. These rocks and the true Mozambique metasediments which occur with the older rocks in thrust slices were formally classified as part of the Basement System but are more conveniently described under the Turbo Group within the Mozambique Belt, Baker (1968).

B. MOZAMBIQUE BELT (BASEMENT SYSTEM).

The Mozambique Belt is a structural unit within which a wide variety of metasedimentary and igneous rocks are found showing a broad concordance of structural style and metamorphic history. Hitherto, the metasediments which comprise of greater part of the Mozambique Belt, have been described as the Basement System in the Geological Survey of Kenya reports.

The four fold informal subdivisions proposed by Baker (1968), differentiate rock groups of contrasting lithology structure and igneous rock content. These four subdivisions include:-

(a) Ukamba Group
(b) Turoka Group
(c) Loita Group
(d) Turbo Group

Additional subdivisions to be discussed here are:

(e) The Embu Series
(f) The Albun Series

(a) Ukamba Group

The name Ukamba Group can be applied to the migmatic, hornblendic and granitic gneisses of the axial region of the Mozambique belt, which is characterized by the occurrence of the several large basic igneous complexes and by a generally greater degree of granitisation than is found in the Turoka and Loita Groups. This group comprises the Kasigau Series, Saggerson (1957), the Galana River migmatites, Sanders (1963), the Kihari-Machakos migmatite belt, the Ingite Hills gneiss, south of Turoka, Joubert (1966) and the greater part of the Precambrian rocks of north-eastern Kenya. A member of the Kasigau Series from Simba revealed the following chemical composition:-

SiO_2	-
Al_2O_3	-
Fe_2O_3	0.32%
MgO	19.41%
CaO	31.29%
Na_2O	-
K_2O	-
H_2O^+	-
H_2O^-	-
TiO_2	-
P_2O	-
Loss on ignition	46.17%
Insoluble residue	0.82

(b) Turoka Group

The Turoka group consists of well-differentiated metasediments, which are characterized by the presence of crystalline limestones, quartzites graphite and kyanite gneisses. Substantial development of hornblendic gneisses which can be traced from Pare Mountains of north-eastern Tanzania to south-eastern part of Kenya to north-eastern

Uganda are characteristic of this group.

The group occurs in two separate zones, one in the southern and the other in western Kenya. It extends from the area south of Voi through the Namang[illegible]-Bissel area, northwards beneath the Rift Valley volcanics and reappears in the Suk and Cherengani hills in the west.

Joubert (1957), studied the group in the Bissel area. A crystalline limestone from this group in the Kajiado District revealed the following chemical composition:-

SiO_2	-
Al_2O_3	-
Fe_2O_3	-
MgO	3.72%
CaO	50.98%
Na_2O	-
K_2O	-
H_2O^+	-
H_2O^-	-
TiO_2	-
P_2O_5	-
MnO	-
CO_2	-
SO_3	-
Cl	-
F	-
S	-
Loss on Ignition	42.38%
Less O Equivalent	-
Insoluble residue	-

(c) Loita Group

These are formations of distinctive lithology and structure, occurring in the Loita-Sianna-Narok and Sotik areas which were formely included in the Basement System. The group is characterized by the dominance of ortho-quartzite, pelitic schists, Kyanite biotite and hornblende gneisses.

The quartzites occassionally retain cross-bedding, fine stratification, sun-cracks and ripple marks and also there are areas of intense recrystallisation. Granitasitation is evident in the few pelitic parts of the succession but is mild. The quartzites were clearly deposited, under deltaic, littoral and shelf facies, their great thicknesses suggesting shelf deposition at the margin of the geosyncline.

(d) Turbo-Kitale Group

These rocks are thrust in a broad zone of thrust faults through a cover of metasediments which are the western most representatives of the Turoka Group.

The rocks of these group are largely graniodioritic in composition and include the Broderick Falls granodiorite which is cut by the Nandi thrust. Elsewhere, these rocks vary from migmatites with biotitic schlieren and traces of metasedimentary lamination and the granite gneiss which are probably the deformed parts of the Kitosh batholith of the adjacent Nyanza shield.

(e) The Embu Series

These consist of low grade pelitic schists, a thin limestone and a conglomerate resting unconformably on the

Ukamba Group and occurring in a small area south-west of Embu.

The series have suffered only mild recrystallisation, with no granitisation and are characterized by minerals of low grade contact metamorphism. The age of these rocks is not clear but are considered younger than the other rocks of the Mozambique Belt.

(f) The Albun Series

They cover a small area in the north-eastern corner of the country, near the Ethiopia border and are composed of limestones, conglomerates, quartzites and phylittes. The rocks have undergone thermal metamorphism, giving rise to sericite and biotite.

Like the Embu Series, these rocks are considered to be younger than the other rocks of the Mozambique Belt, although their stratigraphic relationship to the other rocks is not quite clear.

(g) Post-Mozambique Intrusions

Several large basic igneous complexes are found in Ukamba Group rocks in Central Kenya and numerous smaller occurrences are situated elsewhere. In addition to these, amphibolites and plagioclase-amphibolites of igneous origin are widespread in the metasediments but are mostly found in the vicinity of the basic plutonic masses.

Batholytic granites such as are found commonly in deeply exposed orogenic belts elsewhere are entirely absent in the Mozambique Belt. Minor granitic intrusions are, however, quite common in rocks of the Ukamba Group.

PALEOZOIC

Included in this group of rocks is a series of sedimentary formations occurring in coastal Kenya. As shown in Table III-4, and as given by the Geological Survey of Kenya, they range in age from the Upper Carboniferous to Lower Permian.

(a) Taru Grits (Karroo)

The basal sediments of the Duruma Sandstone Series, which are part of the Karoo Sediments near the Coast, are the Taru Grits, which probably straddle the Upper Carboniterous and Lower Permian.

These consist of massive grey or bluish grey quartzo-feldspathic grits with subordinate bands of hard black shale. The grits are coarse, of variable texture, poorly sorted and generally current bedded. The constituent grains are of variable sizes and are generally sub-angular. They consist primarily of quartz and microcline with small proportions of sodic plagioclase, mica, hornblende and garnet and are generally cemented together by calcite. With extensive weathering, the feldspar breaks down and the rocks disintegrate to form a superficial covering of quartz sand. Specks of carbonaceous material are common throughout the succession and a block of coal has been found in them.

Towards the contact with rocks of the Mozambique Belt, the grits are faulted against these rocks and form two distinctive divisions, the lower division of sandy shales,

STRATIGAPHICAL SUCCESSION

ERA AND PERIOD				LOCAL FORMATION			LITHOLOGY AND MAX THICKNESS
CAINOZOIC	QUATER-NARY	RECENT		Alluvium, Oyster Beds and Sands			Alluvium and superficial sands, 200 ft
		PLEISTOCENE		Coral Reefs and Lagoonal Sands			Sands, coral limestones and coral sandstones; 500 ft
	TERTIARY	PLIOCENE		Magarini or Marafa Beds			Sands and gravels; 400 ft
		MIOCENE		Baratumu Beds			Marls, limestones, clays and sands, 1500 ft
		OLIGOCENE					
		EOCENE					
MESOZOIC		CRETACEOUS	U				
			L	Freretown Limestone			Limestone and shales; ?
		JURASSIC	U	Changamwe Shale Coroa Mombasa Limestone and Shale Rabai Shale Miritini Shale			Shales, limestones, sandy limestones; 6000 ft
			M	Kibiongoni Beds Kambe Limestone			
			L				
		TRIASSIC	U	Shimba Grits Mazeras Sandstone	U	DURUMA SANDSTONES KARROO	Sandstones and grits with shales and clays; 1000 ft
			L	Mariakani Sandstone Maji-ya-Chumvi Beds	M		Sandstones, mudstones and shales w. limestones; 10,000 ft
PALAEOZOIC		PERMIAN	U	Taru Grits	L		Grits and arkosic sandstones, 500 ft
			L				
		CARBONI-FEROUS	U				
			L				
		DEVONIAN					
		SILURIAN					
		ORDOVICIAN					
		CAMBRIAN					
ARCHAEAN		PRE-CAMBRIAN		Basement System			Gneisses and schists

TABLE III -4

arkoses and conglomerates which are faulted against the Mozambique Belt rocks and an upper division of well-bedded yellow sandstones and arkoses with interbedded conglomerate lenticles.

The Taru Grits have a gentle dip to the east-south-east, with an east-west anticlinal axis separating the basins around Maruvess and Kigutu.

MESOZOIC

Mesozoic rocks occur in two separate areas, in the north-east and along the coast. The stratigraphy and fauna of these two areas is distinct, and it is likely that the two basins of deposition were not connected.

Coastal Mesozoic Sediments

A continuous strip of sediments of Mesozoic age, about 30 miles in width, is exposed near the coast stretching from the Tanzania border to the region of River Sabaki. These sediments, as shown in Table III-4, range in age from Triassic to Cretaceous and include part of the Jurassic System.

Maji Ya Jumvi Beds

Approximately 1,300 metres of thin bedded sandstones, Estheria and plant-bearing shales, Calcareous flags, siltstones and nodular limestones with subsidiary marine shales and reef limestones lie unconformably on the Taru Grits.

The upper part of the formation is of Triassic age. Ripple marks and mud-cracks are common in many of the beds, which often contain an appreciable percentage of precipitated salts and is reflected by high salinities in groundwater obtained from them (1,500-5,000 ppm, Sanders, 1962).

A limestone from Kisusu belonging to this formation, on chemical analysis, revealed the following composition:

$CaCO_3$	95.00%
$MgCO_3$	0.80%
SiO_2	2.12%

Mariakani Sandstones

The Mariakani sandstones contain beds which are often mottled with white spots (Miller, 1952). In the Kilifi area, Caswell (1956), separated the sandstones into two divisions, namely, an upper division of dark grey or yellowish-brown sandstones, siltstones and shales and a lower division of high greenish-grey mottled sandstones and siltstones.

Thompson (1956), found that the mottled sandstones are not present in the Malindi area, except near the northern margin of the Kilifi area. He likewise described the series as consisting of the two divisions mentioned above.

Mazeras Sandstones

The Mazeras sandstones consist of sandstones with rare thin shale beds. A bed containing fossil tree trunks is widespread and in the upper part of the formation thick beds of gritty sandstones occur.

Caswell and Thompson (1956), have shown that the Upper Duruma Sandstones rest unconformably on the Mariakani sandstones. Caswell (1956), discarded the term "Shimba Grit" as a stratigraphical name , considering the fact that the grits occur as bands in the Mazeras Sandstones and Thompson (1956), agrees to this suggestion.

Jurassic Beds

The junction between the Jurassic beds and the Duruma Sandstone Series is often a faulted contact but in the Mwachi Valley an unconformity has been proved, Caswell (1956). The stratigraphical succession of these rocks is shown in Table III-4.

(i) Kambe Limestone Series

The oldest Jurassic rocks of Coastal Kenya are the Kambe Limestone Series of Bajocian-Bathonian age, consisting of a basal Conglomerate, overlain by interbedded limestone and shales of some 1,500 feet in maximum thickness. The chemical analysis of a Kambe limestone showed the following chemical composition:-

SiO_2	4.04%
Al_2O_3	0.72%
Fe_2O_3	0.29%
MgO	0.07%
CaO	50.74%
Na_2O)) K_2O)	0.27%
SO_3	0.15%
P_2O_5	-
Cl	-
F	-
Loss on Ignition	41.88%

(ii) Kibiongoni Beds

These shales and sandstones overlying the Kambe Limestones are considered by Caswell (1956), as probably a local lateral variation of limestones. A shale from these beds showed the following chemical composition on analysis:-

SiO_2	44.74%
Al_2O_3	13.58%
Fe_2O_3	9.20%
MgO	9.09%
CaO	5.88%
Na_2O	1.88%
K_2O	0.18%
H_2O^+	2.54%
H_2O^-	0.68%
TiO_2	0.46%
P_2O_5	0.24%
MnO	0.28%
CO_2	10.82%
SO_3	-

(iii) Miritini and Rabai Shales

Overlying the Kibiongoni beds are the Miritini and Rabai shales which are difficult to distinguish and embrace the Callovian and Oxfordian stages. A Miritin shale taken from Mile 11 along the Mombasa-Nairobi railway gave the following chemical composition after being analyzed:-

SiO_2	44.74%
Al_2O_3	13.58%

Fe_2O_3	9.20%
MgO	9.09%
CaO	5.88%
Na_2O	1.88%
K_2O	0.18%
H_2O^+	2.54%
H_2O^-	0.68%
TiO_2	0.46%
P_2O_5	0.24%
MnO	0.28%
CO_2	10.82%
SO_3	Nil
BaO	-
Loss on Ignition	-

(iv) Changamwe and Coroa Mombasa Limestone and Shale

The Kimmerdgian Stage is represented by the Changamwe Shales, containing the Mombasa Coroa Limestones at the base. The formation is mostly composed of Calcareous Shales with well-bedded muddy and siliceous limestones which occur in a strip of faulted shales.

A shale from the Changamwe Shales showed the following chemical composition:

SiO_2	57.25%
Al_2O_3	13.22%
Fe_2O_3	5.81%
MgO	2.32%
CaO	3.91%
Na_2O	0.82%
K_2O	3.32%

H_2O^+	-
H_2O^-	-
TiO_2	1.4%
P_2O_5	0.30%
MnO	0.74%
CO_2	-
SO_3	0.24%
BaO	-
Loss on Ignition	10.89%

Cretaceous Rocks

Freretown Limestone

The representatives of the Cretaceous in Coastal Kenya are the small outcrops of well-bedded, compact, slightly siliceous muddy limestones of Freretown near Mombasa.

Post Cretaceous Intrusions

Among the intrusives, small bosses and dykes in the Sabaki Valley, the Jombo intrusives, which include ijolites, melteigites and nepheline syenites and the nearby Mrima Carbonatites are the only known intrusives occurring among the coastal sediments.

Mesozoic Rocks of North-Eastern Kenya

Rocks of Triassic-Cretaceous age are exposed over an area of 10,000 square miles in the north-eastern corner of the country. These cannot, however, be directly correlated with those of coastal Kenya. Succession of these rocks is given in Table III-5, as indicated in the Geological reports cf the Geological Survey of Kenya.

Table III-5

SUCCESSION OF MESOZOIC SEDIMENTS IN NORTH-EAST KENYA

System	Stage	Representative	
Cretaceous	Wealdan	Marehan Series (Marehan Sandstone (Danissa Beds	
	unconformity		
Jurassic	Tithonian	Mandera Series	
	Kimmeridgian	Dakacha Limestones	Daua Limestone Series
		Herori Shales	
		Seir Limestone	
	Oxfordian	Rahma Shales	
		Muddo Erri Limestones	
	Callovian	Rukesa Shales:	
		Asaharbito Beds	
	Bathonian		
	Callovian	Murri Limestones	
		Didimtu Beds	
	unconformity		
Trias (?)		Mansa Guda Formation	
	unconformity		
Precambrian		Precambrian	

(a) Triassic Rocks

(i) Mansa Guda Formation

Thompson (1958) and Dodson (1958), have shown that this formation expands from a thickness of less than 20 feet near Didimtu to about 2,000 feet near Tarbaj.

In addition to the characteristic sandstones and Conglomerates, lenses of fine grained shely rocks and a band of quartzite are also found in the formation.

No certain evidence on its age has been discovered but it underlies the Liassic Didimtu beds and hence it is regarded provisionally as Triassic in age.

(b) Jurassic Rocks

(i) Daua Limestone Series

These series comprise all the Jurassic beds ranging from the Lias to Kimmerdgian known to occur in this part of the country. The various local names that have been given to the different parts of the series are shown in Table III-5.

The rocks belonging to this series consist of a variety of limestones and shales. A shelly limestone from this series revealed the following chemical composition:

SiO_2	1.44%
R_2O_3	0.17%
MgO	0.12%
CaO	55.00%
P_2O_5	0.20%
Loss on Ignition	42.65%

A calcite mudstone from the Didimtu Beds has been shown to consist 0.98% MgO and 51.12% CaO.

(c) Cretaceous

The Cretaceous rocks of North-Eastern Kenya, forming the Maheran Series, rest unconformably on the Jurassic. A lower group referred to as the Danissa Beds consists of about 380 feet of sandstones, variegated siltstones, marlstones and porcellaneous limestones that form the slopes of hills capped by the Maheran Sandstones, while the upper group consists mainly of sandstones and siltstones with a thickness of less than 400 feet in the northern areas.

Cenozoic

(a) Miocene sediments

The Baratumu Beds of Coastal Kenya rest unconformably on the Mesczoic formations of the Coastal plain and comprise the Early Miocene littoral sandy marls, limestones and sands. Also included in the group are the Fundi Isa Limestones.

The Baratumu Beds consist of variety of marls ranging from the nodular marly limestones with Gastropods, yellow foraminiferous marls and grey-dirty white marls with many fossil fragments.

The Fundi Isa Limestones are calcareous throughout ranging from yellowish limestones, which are frequently foraminiferous to calcareous sandstones and fine-grained calcareous conglomerates with allogenic minerals being quartz and feldspar.

Early Miocene fossiliferous beds are found intercalated in the pyroclastics of Rusinga and Mfanganu Islands of the Winam Gulf. Sub-volcanic sediments named the Turkana Grits, (Baker, 1968) are composed of grits, sands, conglomerates and tuffs are found beneath the phonolites in several localities in Turkana. A magnesiam limestone from the southern Turkana had the following chemical composition:-

SiO_2	n.d.
Al_2O_3	0.92%
Fe_2O_3	1.95%
MgO	18.70%
CaO	27.92%
P_2O_5	0.02%
CO_2	n.d.

In the eastern part of the Nyanza Rift Valley, fossiliferous limestones and tuffs, the Koru Beds, occur in the lower part of the Tinderet Volcanics and are regarded as of Early Miocene age. A limestone from these beds on chemical analysis gave the following results:

SiO_2	0.58%
Al_2O_3	0.23%
Fe_2O_3	0.22%
MgO	0.83%
CaO	54.58%
Na_2O	-
K_2O	-
H_2O	0.04%
TiO_2	0.02%
P_2O_5	1.62%
MnO	0.14%
SO_3	-
F	-
Loss on Ignition	41.82%
Less O Equivalent	-

(b) Pliocene Sediments

The Miocene Beds in the Coast are overlain with slight unconformity by a series of littoral and continental sediments of Pliocene-Pleistocene age comprising the continental Magarini Sands in the south, the subaqueous Marafa Beds of the Malindi area and Midadoni Beds of the Fundi Isa area containing fossiliferous Calcareous sandstones, clays, sands and soils.

The Magarini Sands when fresh are creamy-white in colour but are often bright-red at the surface owing to the concretions of the ferric oxide.

The Marafa Beds, consist of white to creamy-white, with occasional lenticular bands of red and purple sands and clays. The sands, clays and pebble beds are false bedded and are essentially non-calcareous in composition.

(c) Pleistocene Sediments

Rocks of Pleistocene age occur along or near the present Coastline and consist of a range of sediments laid down during the fluctuations of the sea above and below the present level, when a total of about 500 feet of lagoonal sands, coral reefs and coquinas were deposited.

Analysing a coral reef limestone from a borehole at Bamburi yielded the following results:

SiO_2	2.0%
Al_2O_3	0.4%
Fe_2O_3	0.5%
MgO	0.5%
CaO	53.6%

H_2O^+	-
NaCl	-
Loss on Ignition	43.3%

Inland Pleistocene sediments are more extensively developed in the Rift Valley where they are represented by thick deposits of lacustrine and fluviatile sediments, among which diatomite beds are commonly found intercalated. The dating of these has given rise to the pluvial periods.

A chemical analysis of a Diatomite from Kariandusi gave the following results:

SiO_2	89.91%
Al_2O_3	5.65%
Fe_2O_3	2.15%
MgO	0.51%
CaO	0.80%
Na_2O	n.d.
K_2O	n.d.
TiO_2	-
MnO	-

Recent Deposits

These deposits are largely soils and alluvial accumulations. The desiccation of lakes has led to the accumulation of salts, particularly at Lake Magadi which at the surface consists of solid trona with interstited mother liquor fed and maintained by saline springs.

Tertiary and Quaternary Volcanics

The volcanic rocks cover the whole of the central and northern parts of the country, occurring in the flow of the Rift Valley and on the volcanic plateaux. The oldest of these volcanics are of Early Miocene age and comprise the eroded nephilinite lava and pyroclastic piles of the southern shores of Winam Gulf.

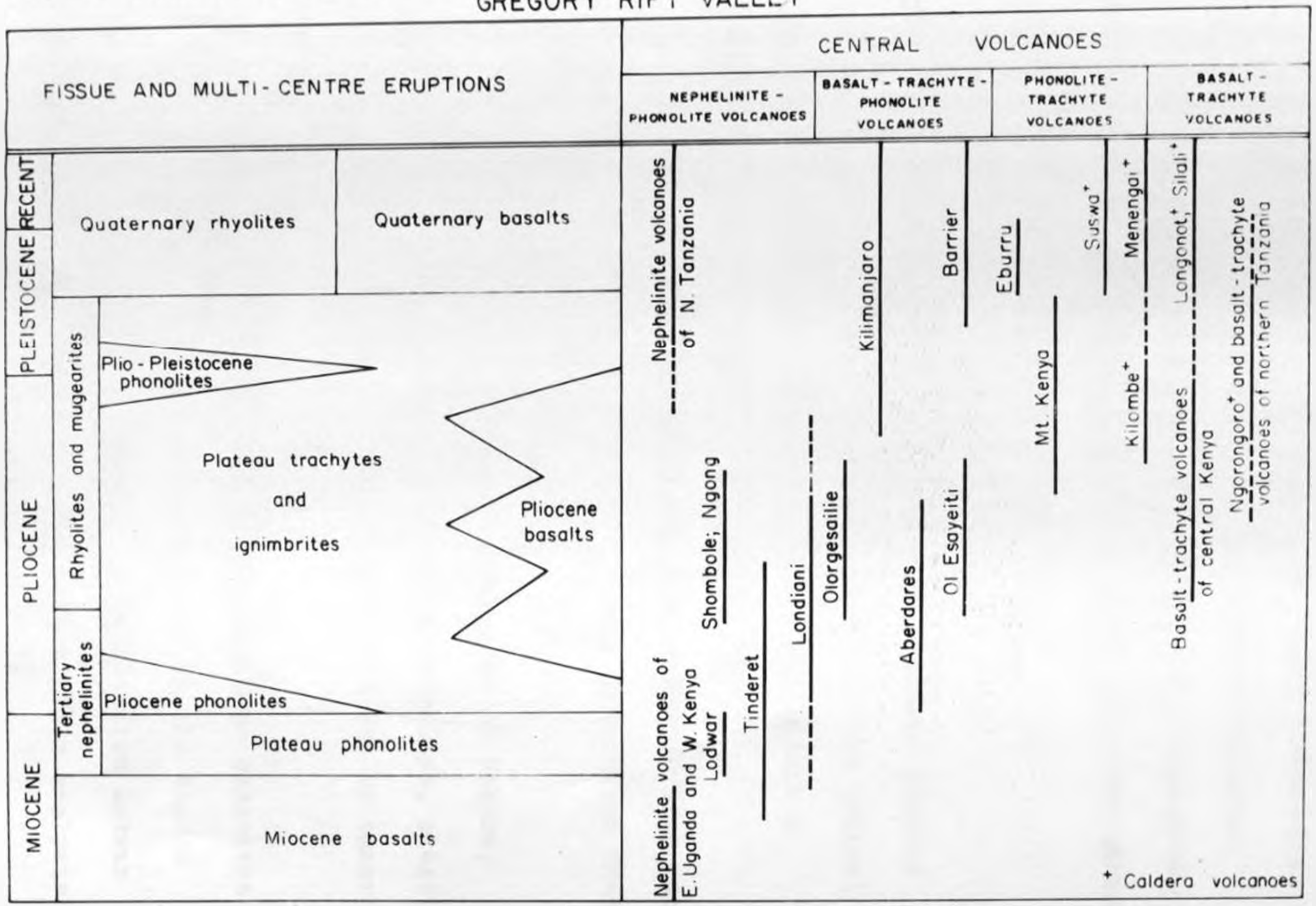
Extensive erosion of these volcanics have exposed a series of Igneous complexes aligned along the Nyanza Rift Valley. These contain the Usaki Ijolitic complex, the Nyamaji phonolite complex, the Sokolo Carbonatite, Ruri Carbonatite complexes and the Rangwa complex.

The summary of the stratigraphy of Miocene to Recent Volcanics in the Gregory Rift Valley, as given by Williams (1970), is shown in Figure 3-8.

Williams (1969), devised a number of petrological groups to summarize the compositions of the volcanics in Kenya on a stratigraphical basis and in 1970, he defined the chief volcanic associations in the Gregory Rift Valley, noting that certain associations are encountered only among the products of fissure and multi-centre eruptions from the major central volcanoes.

The formations considered to have been originated by fissure and multi-centre eruptions, are separated from the products of major Central Volcanoes, for it has been shown that these two environments are characterized by distinct volcanic associations (Williams, 1969). The Plateau Volcanics are readily subdivided for descriptive purposes on age and composition basis.

THE STRATIGRAPHY OF THE MIOCENE TO RECENT VOLCANIC ROCKS ASSOCIATED WITH GREGORY RIFT VALLEY



Source Bulletin Volcanologique Tome XXXIV-2, 1970.

FIG. 3.8

Fissure and Multi-Centre Eruptions

The main volcanic associations reported by Williams (1969a), among the products of fissure eruptions and closely related multicentre fields are, basalt-basanite, phonolite-phonolitic trachyte and trachyte-phonolitic trachyte. Basalt-phonolitic-melanephelinite, comendite-pantellerite, Mugearite-trachyte-rhyolite and nephelinite-phonolite associations occur locally.

(a) Miocene Basalts

These include the Samburu Series, Samburu Basalts and Elgeyo Basalts and are the oldest basalts in the central and northern parts of the Kenya Rift. They attain a thickness of about 1,000 in the Samburu area.

In the eastern and western scarps defining this part of the Rift, the basalts underlie plateau phonolites that are confidently referred to the Late Miocene.

In the Laikipia escarpment north-east of Nakuru, porphyritic olivine basalts, analcime ankaramites, picrite basalts and augite-rich picrite basalts are cut by numerous basaltic dykes.

Porphyritic Olivine basalts and analcime basanites (the Elgeyo Basalts) underlie phonolites in the Elgeyo escarpment, north-west of Nakuru. A basalt from Lodwar showed the following chemical composition after analysis:-

SiO_2	42.94%
Al_2O_3	11.47%
Fe_2O_3	7.22%
FeO	7.93%

MgO	6.58%
CaO	11.36%
Na_2O	2.83%
K_2O	1.32%
H_2O^+	2.24%
H_2O^-	0.55%
TiO_2	4.78%
P_2O_5	0.57%
MnO	0.12%
CO_2	-
SO_3	Tr
F	-
S	-
SrO	-
Cl	0.05%
Less O Equivalent	0.01%

(b) Plateau Phonolites (Late Miocene)

Uasin Gishu Phonolites, Rumuruti Phonolites, Kericho Phonolites, Mau Phonolites, Kapiti Phonolites and Yatta Phonolites are members of this group.

In Late Miocene times, flood phonolites that probably attain a maximum thickness of about 1,000 metres, were erupted from fissures along the crest of a region of repeated Upwarping ("Kenya dome") which is now bisected by the Rift Valley.

The Phonolites are typical porphyritic lavas with conspicuous phenocrysts of nepheline and potash-feldspar and small biotite phenocrysts are often visible. Most of the phonolites are analcime bearing with mainly ferro-magnesian minerals of soda-pyroxenes, aenigmatite, alkali-amphiboles and biotite. A phonolite from the Kapiti plains gave the following chemical composition on analysis:-

SiC_2	54.58%
Al_2O_3	19.42%
Fe_2O_3	1.87%
FeO	3.17%
MgO	1.42%
CaO	1.53%
Na_2O	5.00%
H_2O^+	2.95%
H_2O^-	0.64%
TiO_2	0.80%
P_2O_5	0.33%
MnO	0.23%
CO_2	-
Cl	0.01%
F	0.10%
S	0.04%
Less O Equivalent	0.04%
SO_3	-
BaO	-
Loss on Ignition	-

A porphyritic phonolite from Londiani Road, north of Lumbwa showed the following chemical composition:-

SiC_2	53.54%
Al_2O_3	20.13%
Fe_2O_3	2.93%
FeO	2.32%
MgO	1.05%
CaO	2.12%
Na_2O	5.98%

K_2O	5.76%
H_2O^+	2.58%
H_2O^-	2.22%
TiO_2	0.50%
P_2O_5	0.09%
MnO	0.31%
CO_2	Nil
Cl	0.23%
F	0.07%
S	-
Less O Equivalent	0.09%
SO_3	Nil
BaO	-
Loss on Ignition	-

(c) Tertiary Nephelinites

In the southern end of the Gregory Rift on the Tanzania border, melanephelinites, Olivine-melanephelinites, ankaratrites, nephelinites and rare phonolitic and tephyritic lavas are accompanied by strongly porphyritic nephelinite dykes. The flows rest on the Sub-Miocene surface and are overlain by Late Miocene Plateau Phonolites.

A nephelinite from Karungu indicated to be of the following chemical composition:-

SiO_2	37.53%
Al_2O_3	8.35%
Fe_2O_3	13.81%
FeO	5.94%
CaO	10.96%
Na_2O	3.31%
K_2O	1.99%

H_2O^+	-
H_2O^-	-
TiO_2	1.96%
P_2O_5	-
MnO	1.02%
CO_2	1.00%
SO_3	-
Cl	-
F	-
BaO	-
Loss on Ignition	9.33%
Less O Equivalent	-

(d) Plateau Trachytes and Ignimbrites (Plio-Pleistocene)

Plateau Trachyte Series, Lake Hannington Phonolites, Kinangop, Bahati, Nyeri, Kerichwa Valley, Mau, Kedowa and Eldama Ravine Tuffs, Nairobi Trachytes, Mbagathi Phonolite-Trachyte and Kabarnet Trachytes are part of this group of volcanics.

As indicated above, large sections in the southern part of Kenya, large areas of the Rift floor and parts of its shoulders are covered by trachytic volcanics which show rapid variations in lithology and thicknesses. For example, the strongly acidic varieties range from the undersaturated phonolitic types containing small amounts of modal nepheline to the oversaturated quartz trachytes, while the ignimbrites range from the eutaxitic thoroughly welded tuffs to lapilli tuffs containing uncollapsed pumice fragments.

A trachyte from the Kikuyu escarpment revealed the following chemical composition:-

SiO_2	62.54%
Al_2O_3	15.85%
Fe_2O_3	3.66%
FeO	2.62%
MgO	0.36%
CaO	1.46%
Na_2O	6.12%
K_2O	5.07%
H_2O^+	0.59%
H_2O^-	0.45%
TiO_2	1.07%
P_2O_5	0.13%
MnO	-
Cl	0.04%
F	-
S	-
SO_3	0.08%
CO_2	-
Less O Equivalent	-
Loss on Ignition	-

An alkali trachyte from the northern side of Magadi had the following chemical composition:-

SiO_2	60.25%
Al_2O_3	10.87%
Fe_2O_3	5.08%
FeO	3.50%
MgO	0.83%
CaO	2.73%
Na_2O	6.29%
H_2O^+	4.77%

H_2O^+)) H_2O^-)	1.25%
TiO_2	0.88%
P_2O_5	1.62%
MnO	0.83%
CO_2	1.06%
ZrO_2	-
SO_3	0.08%
Cl	0.06%
F	-
S	-
Fe_2S_2	-
NiO	-
BaO	-
Less O Equivalent	0.02%

(e) Pliocene Basalts

Kirikiti Basalts, Singarain Basalts, Kwaibus Basalts, Keporania Basalts, Seyabei Basalts and Mbaruk Basalts are members of this group of basalts.

Distributed according to the development of the Rift Valley in the Rift floor and its shoulders, among these the macroporphyritic Olivine basalts, occurring on the Nguruman escarpment, the aphyritic olivine basalts and zeolite basanites and other basalts south of Lake Rudolf, comprise the majority of the basalts of Pliocene times.

A basalt from Oloronyi in Laikipia gave the following chemical composition:-

SiO_2	49.58%

Al_2O_3	15.34%
Fe_2O_3	6.11%
FeO	8.39%
MgO	3.98%
CaO	7.74%
Na_2O	3.35%
K_2O	1.75%
H_2O^+	1.47%
H_2O^-	0.52%
TiO_2	3.80%
P_2O_5	1.46%
MnO	0.24%
CO_2	-
SO_3	-
Cl	-
F	-
S	-
BaO	-
Less O Equivalent	-

(f) Pliocene-Pleistocene Phonolites

The Pliocene phonolites in which nepheline occurs as microphenocrysts or only interstitially in the groundmass are underlain by some of the Plateau trachytes. The Nairobi Phonolite, Mbagathi Phonolite, and the Thomson's Falls phonolites, which occupy a similar stratigraphic position between Plateau Phonolites and Trachytes are members of this group. The phonolite lavas of Lake Hannington, considered younger, are analycime trachytes and phonolites in which olivine is a rare constituent.

A phonolite from Moridjo forest in Thomson's Falls had the following chemical composition:-

SiO_2	57.29%
Al_2O_3	17.36%
Fe_2O_3	3.61%
FeO	3.16%
MgO	0.79%
CaO	1.82%
Na_2O	6.62%
K_2O	5.70%
H_2O^+	2.23%
H_2O^-	0.60%
TiO_2	0.73%
P_2O_5	0.17%
MnO	0.31%
CO_2	-
SO_3	-
Cl	-
Loss on Ignition	-
Less O Equivalent	-

(g) Pliocene Rhyolites and Mugearites

These are thick sheets of acid volcanics mainly occurring in north-western part of Kenya, where flows attain thicknesses of 900M and overlie Miocene basalts.

Ignimbrites are associated with Soda-rhyolites, rhyolitic tuffs and pantelliritic trachytes. Most of the rhyolite rocks contain amphiboles of the riebeckite-arfvedsonite group. Lavas described as andensites are intercalated in the acid succession, but from the descriptions, many of these would appear to be better classified as Mugearites and hawaiites. A pantellirite from Turkana showed the following chemical composition:-

SiO_2	69.78%
Al_2O_3	6.68%
Fe_2O_3	5.63%
FeO	2.68%
MgO	0.04%
CaO	0.68%
Na_2O	2.42%
K_2O	5.07%
H_2O^+	5.43%
H_2O^-	1.09%
TiO_2	0.56%
P_2O_5	0.00%
MnO	0.19%
Loss on Ignition	-
Less O Equivalent	0.16%

(h) Quaternary Basalts

Nyambeni Volcanic Series, Thiba Basalts and Elmentaita Basalts, are amongst the members forming this age-group of basalts. The Chyulu range, north east of Kilimanjaro is an entirely basaltic field with the main lavas being olivine-basalts and analcime basanites.

Pleistocene to Recent Olivine basalts, Mugearites and nepheline basanites form the greater part of the Nyambeni range. A basalt from the Chyulu range gave the following chemical composition:-

SiO_2	43.73%
Al_2O_3	13.40
Fe_2O_3	15.07%
FeO	-
MgC	10.21%
CaO	9.58%
Na_2O	3.70%
K_2O	1.80%
H_2O^+	-
H_2O^-	-
TiO_2	3.01%
P_2O_5	-
MnO	0.20%
CO_2	-
SO_3	-
Cl	-
F	-
S	-
BaO	-
Less O Equivalent	0.02%

(i) Quaternary Rhyolites

Pleistocene to Recent Comendites, pantellirites, rhyolites, obsidi[illegible] and ignimbrites, form a north-south zone of plugs and domes in the Naivasha area. Many of the rocks of this age-group contain alkali amphiboles (chiefly riebeckite) together with the soda-pyroxenes and aenigmatite, A rhyolite-obsidien from Lake Naivasha area revealed the following chemical composition:-

SiO_2	75.55%
Al_2O_3	12.31%
Fe_2O_3	0.69%
FeO	1.17%
MgO	0.04%
CaO	0.23%
Na_2O	4.55%
K_2O	4.69%
H_2O^+	0.15%
H_2O^-	Nil
TiO_2	0.13%
P_2O_5	0.01%
MnO	0.04%
Cl	0.21%
F	0.28%
S	0.01%
Less O Equivalent	0.16%
Loss on Ignition	-

A vitreous pantellirite from the same area showed the following chemical composition:-

SiO_2	70.61%
Al_2O_3	8.59%
FeO	5.96%
MgO	0.07%
CaO	0.61%
Na_2O	6.77%
K_2O	4.46%

H_2O^+)) H_2O^-)	0.10%
TiO_2	0.15%
P_2O_5	-
MnO	0.34%
Cl	-
F	-
S	-
Less O Equivalent	-
Loss on Ignition	-

A comendite from the Njorogwa Gorge revealed the following chemical composition:-

SiO_2	73.30%
Al_2O_3	11.56%
Fe_2O_3	1.68%
FeO	2.41%
MgO	0.24%
CaO	0.78%
Na_2O	4.84%
K_2O	3.96%
H_2O^+	0.40%
H_2O^-	0.30%
TiO_2	0.33%
P_2O_5	0.03%
MnO	-
Cl	-
F	-
S	-
Less O Equivalent	-
Loss on Ignition	-

CENTRAL VOLCANOES

The approximate range in time of the activity at the more important Central Volcanoes is indicated in Figure 3-8. For descriptive purposes, the centres are divided into four major groups.

(a) Nephelinite-Phonolite Volcanoes

Included in this group are the nephelinite-melilite suite volcanoes of Kisingiri, Tinderet, Londiani, Ngong and Shombole.

(b) Basalt-Trachyte-Phonolite Volcanoes

Basaltic volcano of Aberdare, the Mugearite Olivine basalts, basanites, trachy-basalts-trachyandesites and phonolitic volcano of Kilimanjaro, and the basalt and trachybasalt centre of Ol Esayeti and the Olorgesaillie centres of alkaline-nephelinite-phonolite are among the representatives of this group.

(c) Trachyte-Phonolite Volcanoes

The Mount Kenya volcano, mainly composed of phonolites rhomb porphyries and Kenytes, together with Olivine-Zeolites and quartz-bearing trachytes and Eburru volcano chiefly characterized by trachytic and phonolitic products are included in this group.

(d) Caldera Volcanoes

The basalt-trachyte centre of Longonot, the phonolite and subordinate trachyte volcano of Suswa, the trachyte Caldera of Menengai and Lenderunt, a Pliocene volcano close to the Tanzania border is apparently composed only of basanites, tephyrites and andesites.

CONCLUSION

In the first section of this chapter, the denudation chronology of Kenya and the drainage evolution have been outlined. With much more isotopic age determinations, structural and stratigraphical analysis of the country, the erosion history of Kenya will be much more understood and the results will be of value in applied earth sciences. The tectono-volcanic features have been briefly examined, emphasizing the fact that the main Rift Valley and its associated features are a result of prolonged geological processes. It may be appreciated that the different landforms will respond differently to the agencies of weathering and finally the hydrogeochemical processes in any one given environment.

The second section of this chapter has shown that the geology of Kenya is mainly composed of metamorphosed rocks, the volcanics occupying the eastern and central parts of the country respectively and the sedimentaries lying to the coastal and north-eastern parts of the country.

Such a diversity not only gives rise to the differences in rock lithology, but also the chemistry of the rocks. This then means that the response of these rocks to the hydrogeochemical reactions will be equally varied. It is on this basis that chapter six examines the relationship of rock chemistry and water chemistry.

CHAPTER IV

SOILS

INTRODUCTION

The main factors contributing to soil formation include climate, living organisms, parent material, time and topography. Soils are formed largely by the weathering of rocks or parent material. Weathering is by no means uniform all over the world and soils in different climatic regions and latitudes are not similar. From the point of view of the formation of soil types, the following major climatic divisions may be recognized:-

a) Equatorial
b) Dry Desert
c) Temperate
d) Arctic

Owing to the great variations in altitude, in Kenya, there is a considerable range of climatic conditions such that all the climatic soil types enumerated above are represented in this country. The Arctic type is represented on the top of Mount Kenya. Furthermore, it must be appreciated that there is a close relationship between relief and local soil types.

In Equatorial regions, where rainfall is heavy and temperatures are high, chemical processes are very active. The decomposition of silicates is especially complete and silica is often entirely removed in solution. A characteristic product of these changes is the laterite which consists mainly of the hydrated oxides of iron. The lateritic type of weathering results in the Red Earths of the Kenya Highlands.

The desert and semi-desert areas account for more than 40% of the total land area of Kenya. As will be observed in Chapter V, the daily range of temperature in these areas is great and the effects of alternate expansion and contraction are important in the disintegration of parent rock material. Here there is little solvent action owing to lack of rain, but the rocks hold capillary water within them. Owing to the heat of the sun and drought of the atmosphere, this capillary water is drawn out and brings with it to the surface soluble salts of sodium, magnesium etc., with which many desert deposits are saturated. Chemical reactions then take place between these solutions and the constituents of the rocks, causing their decomposition. This process also leads to the colouring of desert sands, usually red or brown. Wind is an important eroding and transporting agent in deserts. It wears away the soft rock or polishes hard rock surface.

There is no solid or well defined boundary between the climatic soil types, for they merge gradually into one another. Within higher altitudes in Kenya, the temperate soil types appear where the prominent forms of weathering are by solution and to a lesser extent by chemical disintegration. On the top of Mount Kenya, the Artic type of weathering takes place with the shattering of rocks by alternate expansion and contraction of water on freezing.

In Kenya, frost action is very limited but in colder countries it plays a most important part in the disintegration of rocks. Here it is the alternation of long dry seasons and intense heat with heavy rainy periods that is the dominant factor causing disintegration of the parent material. These effects are widely distributed in the country.

SOIL CLASSIFICATION

In dealing with soil classification in Kenya, Milne (1935), provided a tentative soil classification and delineated the major soil boundaries when compiling a soil map of East Africa. The soils included in this classification are:-

(a) The Red Earths
(b) The Plains Soils
(c) The Blakc and Grey Clays
(d) Coastal Soils
(e) The Volcanic Soils

(a) The Red Earths

These soils are widespread in the Kenya Highlands and are usually classified in the "laterised group" on account of their physical properties and behaviour in tillage. They are often very homogenous in composition when derived from fine-grained lavas and tuffs. The lack of unweathered coarse particles makes them difficult to use, especially for road-making, under high rainfall (40" - 50" = 1000 -1250 mm) and free drainage. The tuffs weather deeply and there is usually over 15 feet (5m) of a bright red, very porous and friable loam without marked horizons, though scattered iron concretions in pellet form may occur near the regolith.

The top soil varies in colour from dark chocolate to dull red, depending on the preservation or depletion of the original content of organic matter. The soil reaction is variable, depending mainly on the nature of surface cover which influences the intensity of leaching. The acidity commonly increases with depth (from pH=5 in the upper 2 metres to pH=6 lower down). Laterisation is not very advanced and these are the most fertile soil types in the country.

The rather pink and more sandy soils of south-western Kenya and Ukambani are derived from metamorphic and granitic rocks. These ancient rocks in time give rise to the soils similar to those derived from the lava. However, where young lava occurs in a metamorphic area, the soils derived from it are distinguished by their tendency to stoniness. According to Cole (1950), the profile of soils derived from metamorphics and granites differs from that derived from volcanic rocks in that it is shallow, more sandy and red in colour and less resistant to erosion.

(b) <u>The Plains Soils</u>

These are a difficult group of soils to classify. A common feature of them all is that they occur on erosion surfaces.

The non-calcareous subgroup occupying the floor of the Rift Valley from Naivasha northwards towards Lake Baringo vary in colour from light grey to light brown or pinkish brown and are very variable in depth of the profile. When developed on consolidated volcanic materials, the soils are more pink in colour. On unconsolidated deposits they are greyer or light brown.

Calcareous plains soils, akin to the Chestnut-brown group of southern Russia and the Red Karroo soils of South Africa, occur in the semi-arid and arid parts of north-eastern Kenya. The soil colour is light red and there is an almost continuous pan of lime concretions in the subsoil often within the first 30 cms. Localized occurrences of this type of soil occurs under the semi-humid conditions in the neighbourhood of Nanyuki to the west of Mount Kenya. The profile shows a deep friable fawn coloured soil with columnar secondary limestone.

(c) The Black and Grey Clays

Clays develop on soil formations of even topography and poor drainage where seepage is received and cannot be parted with under gravity. These vary from the calcareous to non-calcareous black soils and then to grey soils, with a further stage having a pronounced humus top soil overlying a bleached fine textured horizon. This in turn overlies a yellowish brown iron mottled zone, often with concretionary soft "murram" just below the bleached zone.

The calcareous black clays are very extensive on the drier and flatter regions which are subject to alternation of short rainy seasons and prolonged droughts. The characteristic physical properties of the black clays, exaggerate the effects of drought for they swell and become nearly impervious when wet, thereby increasing runoff. Their marked shrinkage on drying results in the formation of broad deep cracks and then this leads to severe drought of the soil. The amount of Calcium Carbonate contained in these soils varies in space and within the soil profile.

Large continuous areas of such soils are found in level regions at about 6,000 feet (1800 metres) throughout Laikipia and areas north of Nyeri. These extend northwards from the foothills of the Aberdare mountains and Mount Kenya towards the Ewaso Ngiro River and to the Athi and Kapiti plains south of Nairobi. Soils of less Calcareous nature have been develcped on the sedimentary deposits in the relatively warm regions of south-western Kenya. In Ukambani, the soil types become catenary with the calcareous black clays occupying the more level country and the red earths the more elevated ground. Both the soil types have been derived from gneisses and related metamorphic rocks.

There is no sharp division between the calcareous and non-calcareous black clays. The latter passes suddenly to the greyish-black and grey types to those that have podsolic characters.

The non-calcareous black or grey clays are well established in the Kinangop Plateau. The soil has impeded drainage and is very acid in reaction. Usually a greyish bleached and mottled top overlies a yellowish-brown compact subsoil containing iron concretions. In the elevated high rainfall mountain district of Lumbwa there is an arid black soil containing bleached stones, overlying a stiff greyish brown clay.

Shackleton (1956), has observed that the distribution of red and black soils depends on slope, which controls drainage and consequently oxygenation or aeration rather than the nature of the bedrock.

(d) The Coastal Soils

The prevailing soil in the narrow Coastal strip is a loose sand but locally with soils of the black or grey clay group on low-lying flats and sandy red earths on ridges. Further inland the soil enters into the group of plains soils with a predominantly red colour.

Within the Coastal soils, a subgroup of "lithosols" and Recent alluvium need to be mentioned. Many of the "lithosols" are derived from the Recent volcanics. Areas covered by alluvial soils lie along the main rivers and lakes. In the Tana River area they extend to more than 30 miles from the sea. In the upper reaches is a great depth of dark-coloured, badly drained heavy soils which is subject to flooding during certain times of the year.

In the lower reaches, the soils vary markedly in texture from place to place, but have the common property in that they are very sticky and have a very high content of salt, especially in the deeper subsoil. On the Lake Victoria coast alluvial soils are shown at the estuaries of rivers Sondu, Nzoia, Yala and Nyando. Their profile is variable but there is usually a good depth of greyish to light brown material with fair natural drainage, though they are flooded during heavy rains.

(e) Volcanic Soils

Youthful volcanic soils overlie Recent lavas and tuffs. They are mainly found in the Rift Valley, south of Naivasha and in a small area around Nakuru. They also occur as skeletal soils in areas north-east of Mount Kenya. Those occurring on the unconsolidated volcanic ash are very coarse in texture and contain the primary minerals almost unaltered. Locally glistering crystals of sanidine are very prominent.

OTHER SOIL CLASSIFICATION AND NOMENCLATURE

In discussing the units of classification and mapping of East African soils, Milne (1935), noted that there is no generally accepted usage in soil classification in regard to the definations and names of categories falling between the great soil group at one extreme and the series at the other. In allowing for latitude in defining a soil series, a form of grouping of allied series is described under the name fasc, specifically for soils in East Africa.

The series included in a fasc are parallel in their development. They have undergone the same kind of intensity of climatic weathering, have similar conditions of drainage and the genetic factors due to the parent material have similar effect. They, however, differ in the degree of maturity, in the effects of changes of vegetation, effects of man's intervention or in the sum total of small effects due to their being geographically distant in occurrence.

A unit of mapping termed "Catena" has been found necessary for the East African soils. The Catena is a grouping of soils which, while they fall widely apart in a natural system of classification on account of fundamental genetic and morphological difference, are yet linked in their occurrence by conditions of topography and are repeated in the same relationship to each other wherever the same conditions are met (Milne, 1935).

Jones (1935), described thirty-three soil series occurring in Kenya. Five of those are stated to be lateritic pedalfers, five are typical pedocals and the others are intrazonal. He has further developed twenty textural classes with further classes for the highly organic soils for soil durvey purposes in Kenya.

Jones and Scott (1962) have grouped Kenya soils systematically, the first separation being on drainage basis as follows:

(A) Well drained soils.
(B) Soils with slightly impeded drainage.
(C) Seasonally water-logged soils.
(D) Soils with impeded drainage.
(E) Poorly drained soils.
(F) A category of lithosols and regosols.

The well-drained soils have been sub-divided on the basis of climatic regions as follows:-

(i) Humid regions with rainfall of 40 inches and over.
(ii) Sub-humid regions with a rainfall range of between 30-40 inches.

(iii) The semi-arid regions with rainfall between 20-30 inches.

(iv) Arid regions with rainfall below 20 inches.

Nyandat (1968), has indicated that the major distribution of soils may be considered to follow a vertical zonation following the sequence given below, starting at the highest altitudes.

(1) Strongly acidic humus rich moor soils found at altitudes above 9,500 feet.

(2) Brown or nearly Black humus rich soils found at altitudes between 5,000 - 10,000 feet.

(3) Deep red soils found at altitudes between 3,000 - 7,000 feet.

(4) Yellowish and Greyish soils with laterite found at altitudes of between 1,000 - 4,000 feet.

(5) Vlei soils (Grey soils, Planosols, Grumosols) found at altitudes of upto 7,000 feet.

(6) Saline and Alkaline soils found in low-lying bottom lands, at altitudes of upto 2,500 feet.

(7) Alluvial soils found in River plains.

(8) Coastal sands and coral rag found at sea level.

Jones and Scott (1962), have further sub-divided the given soils (sub-divided on drainage and climatic basis) into thirty eight individual soil associations and or as catena mainly on the basis of physical and chemical properties, altitude and rainfall.

A (i) Well drained soils of humid regions of Kenya

Included in these group of soils are a variety of ando-like soils, podsolic soils and latosolic soils. In all six of them are recognized.

The ando-like soils consist of two sub-types, i.e. the strongly acidic brown loams derived from the volcanic material and the dark brown loams derived from the volcanic tuff.

The podsolic soils consist mainly of dark brown sandy loams derived from the sedimentary and basement complex materials.

Included in the latosolic soils are a variety of three sub-types, namely the pinkish-red sandy loams, derived from the metamorphosed sediments of the Basement Complex, the dark red friable clays with deep humic topsoils derived mainly from the volcanic and metamorphic rocks and the red friable clays.

A(ii) Well drained soils of sub-humid regions of Kenya

Included in this group are a variety of latosolic and podsolic soils. The latosolic variety consists of red friable clays which are derived from the volcanic and Basement complex materials, the dark red loamy sands which are derived from the coastal sediments and the yellow to red loamy rocks of granitic composition.

The podsolic soil type consits mainly of yellow to red loamy sands with parent material of volcanic and Basement rocks.

A (iii) Well drained soils of semi-arid regions

Here the chestnut, rendzinic and latosolic subtypes are included. The chestnut variety consists mainly of brown calcareous loams derived from volcanic ash.

The rendzinic subtype consists of a variety of dark grey brown calcareous loams derived from the Post Jurassic lacustrine sedimentary deposits.

The dark red sandy loams derived from Basement and volcanic rocks form the latosolic subtype.

A (iv) Well drained soils of arid regions

The desert and red desert soils are included in this group. The desert soils derived from aeolian deposits consist mainly of brown calcareous loamy sands and dunes, while the dark reddish-brown calcareous sandy loams derived from the sedimentary and Basement complex rocks from the Red Desert variety.

B Soils with slight seasonal impeded drainage

There are five sub-types of soils in this group and they include the very dark brown clay loams derived mainly from volcanic ash and found on steep slopes; the dark brown loams; the red strong brown friable clays with a laterite horizon associated with the Sub-Miocene erosion surface and the brownish-yellow loamy sands with a laterite borizon occurring as a catenary component on middle and low slopes.

C. Seasonally waterlogged soils

Included in this group are a variety of very pale brown mottled loamy sands with groundwater laterite horizons which form a catenary component on the lower and bottom slopes.

of undulating land. They are derived from colluvial and transported material.

D. Soils with impeded drainage

These are a variety of grumosolic soils consisting of black clays commonly known as Black Cotton soils. These include the calcareous and non-calcareous variants derived from colluvium, dark brown claysloams derived from colluvium in low-lying bottom bands, and brown clays derived from sediments in the coastal areas.

E. Poorly drained soils

In this group the following sub-types are recognized:

(i) Alpine Meadow Sub-type.
(ii) Gley Soils.
(iii) Solodized Solonetzic Soils.
(iv) Planosolic Soils
(v) Solanchak.
(vi) Soils of the Peaty Swamps.

The dark peaty loams derived from the Basement and volcanic rocks occurring on smooth rolling land comprise the Alpine Meadow sub-type.

In the Gley soils the grey mottled clays derived from colluvium dominate this soil type. Grey compacted loamy sands with deflocculated clay and gritty sands mainly form the solodized solonetzic sub-type.

The dark brown clays with light textures topsoils form the plenosolic soils that occur on both level and sloping land. The solanchak variety consists of saline and alkaline clays derived from colluvium in low-lying landforms of upto 2,500 feet in height above sea level. The peaty swamps sub-type are peaty soils subjected to the fluctuations of the seasonal water table.

F. Lithosols and Regosols

Included in this group may be the coastal sands, coral rag, alluvium and Recent lacustrine deposits, ash and pumiceous soils and shallow stony soils with frequent rock exposures.

CONCLUSION

It has been observed in this chapter that the products of weathering will be different under varying climatic and rock conditions. The classification based on mode of soil formation is largely not different from that based on mode of occurrence, although various aspects are stressed in the nature and purpose of classification.

It must be appreciated, however, that no comprehensive picture of the Kenya soils can be obtained in one chapter for the factors governing soil formation are many and equally variable. Detailed regional mapping of Kenya soils is necessary. Until this is done, valuable quantitative data on the Kenya soils will still be lacking. The East African Royal Commission Report (1955), has noted that there is not an uncommon belief that tropical soils are capable of high sustained yields at the cost of little expenditure of human effort. In actual fact, the soils of East Africa, in common with those of a large section of the tropical world, are by nature relatively poor, unproductive and fragile. There are certain exceptions, mainly the volcanic and alluvial soils which are highly friable and display an alarming tendency to erode or to become lateritic depending upon the circumstances. It is here where detailed quantitative analysis of Kenya's soils is required so as to ascertain these conclusions.

From the groundwater chemistry point of view, it is evident that these variable soils will respond differently to weathering agents and consequently in the provision of salts to groundwater. Obviously, their chemical and physical components will greatly determine the nature and amount of salts derived from them into the groundwater.

CHAPTER V

CLIMATE AND SURFACE WATER HYDROLOGY

This chapter is to examine the climate and surface water hydrology of Kenya in as far as it affects the groundwater chemistry. The first section of this chapter will survey the climatic factors, while the second and last section will discuss the surface water hydrology.

1. CLIMATE

The climate of an area as defined by Griffiths (1962), "Is the Synthesis of Weather or atmospheric conditions of that area". The climatic factor is important for it influences not only the nature of weathering of the underlying rock but also the evolution of landforms and the nature of the prevailing vegetation and soils. The two most important features of climate are rainfall and temperature.

Temperature is strongly influenced by the altitude of the landsurface and, to some extent, the same is true of rainfall, for higher areas tend to have a consistently high rainfall while the rainfall regime in the low areas ranges from very low to high. Temperature affects the rate of weathering which tends to be more rapid with higher temperatures.

is
limited
to snow
time

Rainfall affects the soil by leaching; the higher the rainfall, the greater the leaching of soluble products of weathering from the soil. Both rainfall and temperature, therefore, affect the weathering of the underlying rock. Intense weathering is closely associated with high rainfall areas. It has been noticed, for example, that in areas of Recent Volcanic ash, intensive weathering has taken place where rainfall is higher whereas less intense weathering is associated with less rainfall. Rainfall intensity is quite important in the rates of weatheing. The higher the intensity of rainfall, the greater will be the erosive power of the rain. This is particularly true of the drier areas where the vegetative cover tends to be poor. Although the total amount of rainfall may be low, appreciable erosion may occur if the intensity is high.

The effects of climate, which vary from arid to humid conditions in Kenya result in a diversity of weathering products which in turn influence the nature and amount of solutes in the water. These solutes are reflected in the water Chemistry. It must, however, be appreciated that climate has not always remained the same. The effects of past climates, although modified by the present, still persist in paleosols and old erosion surfaces occurring in arid and semi-arid areas of the Country.

(a) Pleistocene Climatic Changes

The reconstruction of the past climatic conditions is complicated by the geomorphological processes that have been modifying the landscape throughout geologic time. The study of lake levels and materials associated with them has helped to reconstruct the Pleistocene climatic history. Scholars in this field have suggested that there is geomorphological evidence to support the existence of a great lake known as Lake Kamasia before the Early Pleistocene period. According to Cole (1950), the lake is thought to have stretched from the present area of Lake Rudolf to Lake Magadi in the south. Accounting for the existence of this lake is rather difficult, because its centre, the present area of Lake Naivasha, is the highest point (6200 feet) and its north and south ends are some 4000 feet lower. Leakey (1931), thinks that the whole of the central area has been uplifted since the Middle Pleistocene period. This would then account for the fact that the Aberdares which are at present over 10,000 feet show no sign of glaciation in Early Pleistocene there whereas other East African mountains seem to have been glaciated down to 10,000 feet at this time. The summits of the Aberdares were probably much lower then but by the end of the Middle Pleistocene these mountains had been uplifted and do show traces of glaciation.

During this period, Lake Victoria stood 300 feet higher than it does to-day. This is partly proved by its raised beaches in places like Rusinga Island. Glaciers on the mountains stood at a much lower level than they do now. These phenomena of larger lakes and more extensive glaciers can be explained by the fact that the climate of Kenya in Early and Middle Pleistocene times was probably far weter and cooler than it is to-day. Cole (1950), has given a summary of the climatic changes during this period as shown in Table V-1.

The times when the lakes were high correspond to the periods of increased rainfall. Three main pluvial periods are recognized in Kenya, namely, the Kageran, Kamasian, and Gamblian pluvials, followed

TABLE V-1 CHANGES IN KENYA DURING PLEISTOCENE PERIOD

PHYSICAL REGIONS	EARLY PLEISTOCENE	END OF EARLY PLEISTOCENE AND START OF MIDDLE PLEISTOCENE	MIDDLE PLEISTOCENE	END OF MIDDLE PLEISTOCENE AND START OF LATE PLEISTOCENE	LATE PLEISTOCENE	END OF LATE PLEISTOCENE AND START OF POST-PLEISTOCENE
(1) Coast Region	Sea level low. Islands joined to mainland	Sea level high. Islands and part of coast submerged	Sea level low. Islands joined to mainland	Sea level rising to drown islands and parts of coast	Sea level low. Islands joined to mainland	Sea level dropping and aeolian deposits forming
(2) Plains 2000 to 5000 feet	Wet and most favourable areas for man and game	Too dry for human habitation	Wet and most favourable areas for man and game	Too dry for human habitation	Early wet but not so favourable as region 3	Dry. Man lives mainly by springs
(3) Highlands 5000 to 8000 feet	Too wet and cold for human habitation	Man probably moves up to these areas near mountains	Too wet and cold for human habitation	Man definitely moves up to these altitudes	The most favourable area for man	Dry. Man lives near springs
(4) 8000 to 10,000 feet	Too wet and cold for human habitation	Man probably occupies parts of this region	Too wet and cold for human habitation	Humans occasionally move into these areas	Humans occasionally move into these areas	No evidence
(5) Above 10,000 feet	Under snow and ice most of the year	Glaciers retreat	Under snow and ice most of the year	Glaciers retreat	Snow in winter. Glaciers in higher regions	Glaciers retreat
General remarks	L. Victoria very high. Greater L. Rudolf linked with the Nile	Earth movements. L. Victoria becomes a swamp. Greater L.Rudolf dries	L. Victoria 300 feet above present level. Greater L.Rudolf linked L.Kamasia and is the source of the Nile	Big earth movements. Rift Valley gets its present form. L.Victoria a swamp. Lake Kamasia dries up. L. Rudolf very low	L.Victoria 100 feet above present level. New lakes form in the Rift	Lakes shrank. Some earth movements. Big volcanic eruption

by two minor post-pluvial wet phases, the Makalian and Nakuran. It has been postulated that the increased glaciation on mountains of East Africa seem to be connected with the glacial periods in Europe and their correlation according to Cole (1950), is shown in Table V-2.

One theory advanced to explain the cause of these major climatic changes is the connection of pluvial periods with the times of greater solar radiation. More heat from the sun causes greater evaporation from the earth's surface. This in turn means more rain and snow fall. Conversely the interpluvials and interglacials correspond to periods of diminished solar heat.

The Kageran and Kamasian pluvials showed high rainfall with a break of a dry period which was followed by the Gamblian pluvial during which, Lake Victoria developed into a swamp. Lakes Nakuru, Elmentaita and Naivasha were all connected to form one big lake. At the end of the Gamblian pluvial there was another period of extreme aridity when the lakes dried up.

(b) Rainfall

The climatic factor of greatest economic significance is rainfall. From the agricultural point of view, the amount of rain, its variation in space and time, its reliability and its intensity are the rainfall elements which are most important to the farmer. These same elements are also of great importance in weathering and consequent provision of the chemical solutes in groundwater.

TABLE V-2 Correlation of East African Pluvials with European Glacial Periods

GEOLOGICAL PERIOD	EUROPEAN CHRONOLOGY	EAST AFRICAN CHRONOLOGY	HEIGHT OF LAKES ABOVE L. NAKURU	REMARKS AND DATES
Holocene or Recent		Nakuran wet phase	145 feet	Second or last post-pluvial wet phase. About 850 B.C.
Epi-Pleistocene		Makalian-Nakuran interval	Lake dried up	Desiccation and formation of aeolian deposits. About 2000 to 850 B.C.
		Makalian wet phase	375 feet	First post-pluvial wet phase. 8000 to 2000 B.C.
		Gamblian-Makalian interval	Lake dried up	Dessication and formation of aeolian deposits. 10,000 to 8000 B.C.
Late-Pleistocene	Last Glaciation	Upper Gambian	375 feet ±	75,000 to 10,000 B.C. Evidence in Naivasha area, etc. Glaciers advance on E.African mountains with each maximum of pluvial conditions
		Drier pause	250 feet ±	
		Middle Gamblian	510 feet ±	
		Drier pause	360 feet ±	
		Lower Gamblian	720 feet ±	Third Pluvial Period
Middle Pleistocene	Interglacial	Kamasian-Gamblian interval	Rift Valley lakes dried up. L.Victoria a swamp	100,000 to 75,000 B.C. Major unconformities
	Penultimate Glaciations II and I	Upper Kamasian	Pre-Rift lakes large. L.Victoria 100 feet above present level	500,000 to 100,00 B.C. Wet conditions, with advance of ice sheets on E. African mountains. Evidence at Olorgesaile and Karjera.
	Interglacial	Drier pause	Lakes shrunk	Red beds formed (e.g. at Rawi).
	Ante-Penultimate Glaciations II & I	Lower Kamasian	Pre-Rift lakes very high. L.Victoria 300 feet above present level	Very wet, with advance of ice sheets. Second Pluvial Period.
Early Pleistocene	Interglacial	Kageran-Kamasian interval	Lakes dry or shrunk	Evidence at Marsabit.
	Early Glaciation	Kageran	Lakes very high	First Pluvial Period. Evidence in W. Kenya and Uganda.

Kenya, like many other parts of East Africa, has a wide range of climatic conditions. The elevation of the ground varies from sea level to well over 19,000 feet above sea level, with the inhabited land extending to above 9,000 feet. The mean annual rainfall varies from less than 10 inches to over 100 inches per annum.

In such a wide range of climate, the elements of rainfall, relevant to hydrogeochemical reactions, show a great spatial variation. It is consequent to this that the resulting products of weathering are equally variable.

(i) Rainfall Amounts

Kenya has a mean annual rainfall of about 20 inches (510 mm). However, the annual variations are relatively large and rainfall is often erratic.

Reliability studies reveal that in four years out of five, only fifteen per cent of the country has rainfall equal or in excess of 30 inches (760 mm) per annum.

Areas receiving over 50 inches (1270 mm) of annual rainfall are small and account for only three per cent of the country. These are areas where the major rivers originate. This emphasizes the vital need for strict and organized hydrological, agricultural and foresty practices in these regions if the streams are to maintain a perennial flow. Table V-3 gives the mean annual rainfall of some selected stations in Kenya. Records from which the mean annual values have been calculated range from 70 to less than 10 years for individual stations. The mean annual rainfall in Kenya is given in Figure 5 - 1.

TABLE V-3 Mean Annual Rainfall of Selected Stations in Kenya

STATION NUMBER	STATION NAME	GEOGRAPHICAL COORDINATES		ALTITUDE		MEAN ANNUAL RAINFALL IN MM.
		Latitude	Longtitude	Feet	Metres	Millimetres
90.39/00	Garissa Meteorological Station	S00 29	E 39 38	420	128	282
89.37/03	Isiolo District Commissioner's Office	N00 21	E 37 35	3621	1104	579
91.36/25	Kabete Scott Laboratories	S01 15	E 36 46	5700	1738	910
89.34/01	Kakamega District Commissioner's Office	N00 17	E 34 45	5100	1555	1845
90.35/03	Kericho District Commissioner's Office	S00 23	E 35 17	6500	1982	1837
92.37/02	Kibwezi Dwa Plantations	S02 27	E 37 56	3000	915	598
93.39/04	Kilifi District Commissioner's Office	S03 40	E 39 51	10	3	1001
88.35/08	Kitale Agricultural Department	N01 01	E 35 01	6200	1890	1132
90.34/04	Kisumu Town	S00 06	E 34 45	3759	1146	1064
90.34/01	Kisii District Commissioner's Office	S00 41	E 34 47	5800	1768	1687
91.38/00	Kitui Agricultural Station	S01 22	E 38 01	3860	1177	996
91.36/42	Limuru Station	S01 07	E 36 38	7340	2238	1005
86.35/00	Lodwar Meteorological Station	N03 07	E 35 37	1660	506	162
91.31/10	Machakos District Commissioner's Office	S01 31	E 37 16	5400	1646	870
91.36/56	Magadi Soda Co., Magadi	S01 53	E 36 17	2010	613	384
93.40/00	Malindi District Commissioner's Office	S01 13	E 40 07	10	3	1063
90.34/02	Miwani Station	S00 05	E 34 59	4000	1219	1172
94.39/02	Mombasa Observatory	S04 03	E 39 42	53	16	1221
86.39/00	Moyale District Commissioner's Office	N03 32	E 39 03	3650	1113	669
91.36/10	Nairobi Station	S01 17	E 36 50	5450	1661	830
90.36/02	Naivasha District Commissioner's Office	S00 43	E 36 26	6234	1901	608
90.36/20	Nakuru Station	S00 17	E 36 04	6070	1851	836
91.35/01	Narok Meteorological Station	S01 08	E 35 50	6200	1890	694
91.36/13	Ngong P.C.	S01 20	E 36 40	6700	2043	751
93.38/04	Tsavo Station	S03 00	E 38 28	1525	465	350
93.38/01	Voi Meteorological Station	S03 24	E 38 34	1837	560	502

SOURCE: E.A.M.D.


ETHIOPIA
SOMALI REPUBLIC
UGANDA
TANZANIA
INDIAN OCEAN
LAKE RUDOLF
L. BARINGO
KISUMU
NAKURU
L. NAIVASHA
NAIROBI
L. MAGADI
LAKE VICTORIA
MOMBASA
KENYA
MEAN ANNUAL RAINFALL
—20—MEAN ANNUAL RAINFALL
ISOHYETS IN INCHES
Kilometres 20 0 20 40 60 80 100 120 140 KM.
Miles 20 10 0 20 40 60 90 100 ML.
34°E
36°E
38°E
40°E
4°
2°
0°
J.A.

FIG. 51

(ii) Rainfall Distribution

A rainfall distribution map of Kenya shows that there exists a relatively wet belt which extends along the Indian Ocean. Another wet belt covers parts of Western Kenya, just east of Lake Victoria. All the mountain and highland areas have high rainfall. Dry parts are mainly found in the north-eastern and north-western half of the country.

The seasonal distribution of rainfall is somewhat complicated. Broadly speaking, the area west of the Rift Valley is characterized by one long and almost continuous rainy season. Most of the rain falls from April to August. September and October are characterized by low rainfall amounts. East of the Rift Valley, two distinct rainy seasons are characteristic. These are the "long rains" from March to May, and the "short rains", from October to December.

The seasonal rains of Kenya are associated with the oscillations of the Equatorial trough of low pressure following the movement of the overhead sun and the resulting changes in patterns of air flow. Theoretically, the distribution of rainfall should be simple, two wet and two dry seasons, near the equator, where the sun passes overhead in March and September, with a tendency towards one wet and one dry season in the north, where towards the Tropics, the sun passes overhead twice but with a shorter intervening period. The two rainy seasons are not everywhere distinct even on the Equator. The rains are extremely variable, both in time and space and the result is a complicated seasonal distribution of rainfall.

Few individual years fit the average picture of monthly distribution of rainfall and some months are more variable than the others. Figures 5 - 2 and 5 - 3 indicate the seasonality of rainfall in Kenya as given by Kenworthy and Glover (1958). Figure 5 - 2 shows the probability of receiving less than 15 inches of rain while Figure 5 - 3 indicates the probability of receiving less than 20 inches of rain. One aspect which is hereby emphasized is the contrast between the area west of the Rift Valley with its shorter rains and those areas with two distinct but shorter rainy seasons. Figure 5 - 2 shows that along much of the coastal strip, only between 10 and 20 years in a hundred is the rainfall from April to June likely to be less than 15 inches. The probability of failure, however, increases rapidly inland. East of the Rift Valley, the maps show clearly how limited are the areas with reliable rainfall in the March and May season. Even at the 15 inches level the main areas with less than 30 per cent probability of failure are limited to the highlands region, from Nairobi to Mount Kenya and a little beyond. With the change to 20 inches in a season as shown in Figure 5 - 2 the areas of reliable rainfall are restricted to a much narrower belt in the Kenya Highlands.

West of the Rift Valley, the picture is more encouraging, with a five-month rainy season. The whole of the Highlands West of the Rift Valley, as shown in Figure 5 - 2, receive 15 inches during this season. The probability of failure increases rapidly north-westwards to Narok and also towards a dry zone along the shores of the Winam Gulf and other parts of the Lake

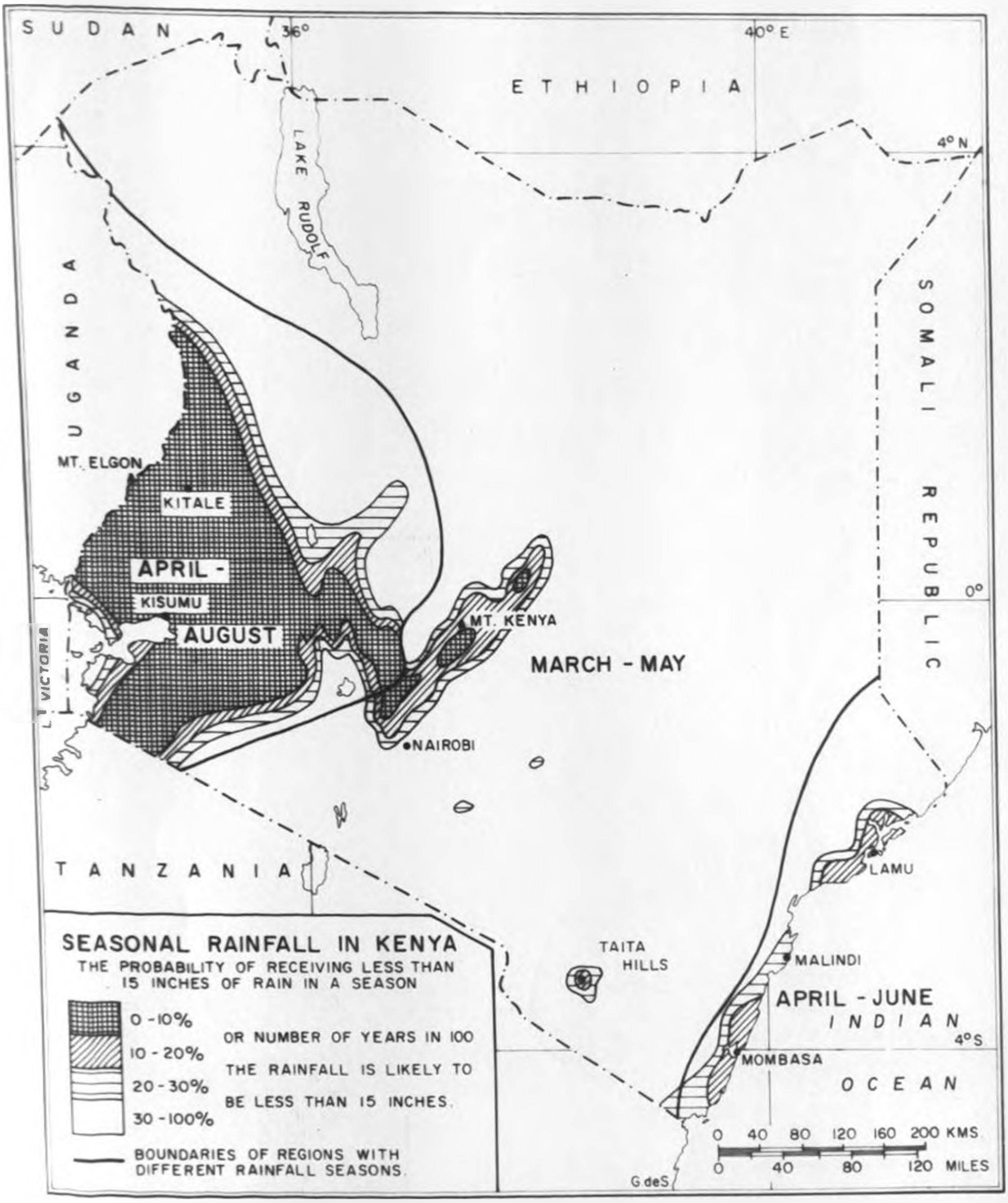

SUDAN
36°
40° E
ETHIOPIA
4° N
LAKE RUDOLF
UGANDA
SOMALI REPUBLIC
MT. ELGON
KITALE
APRIL - AUGUST
KISUMU
VICTORIA
MT. KENYA
MARCH - MAY
NAIROBI
0°
TANZANIA
LAMU
TAITA HILLS
MALINDI
APRIL - JUNE
INDIAN OCEAN
4°S
MOMBASA
SEASONAL RAINFALL IN KENYA
THE PROBABILITY OF RECEIVING LESS THAN 15 INCHES OF RAIN IN A SEASON
0 - 10%
10 - 20%
20 - 30%
30 - 100%
OR NUMBER OF YEARS IN 100 THE RAINFALL IS LIKELY TO BE LESS THAN 15 INCHES.
BOUNDARIES OF REGIONS WITH DIFFERENT RAINFALL SEASONS.
0 40 80 120 160 200 KMS.
0 40 80 120 MILES
G deS

FIG 5 2

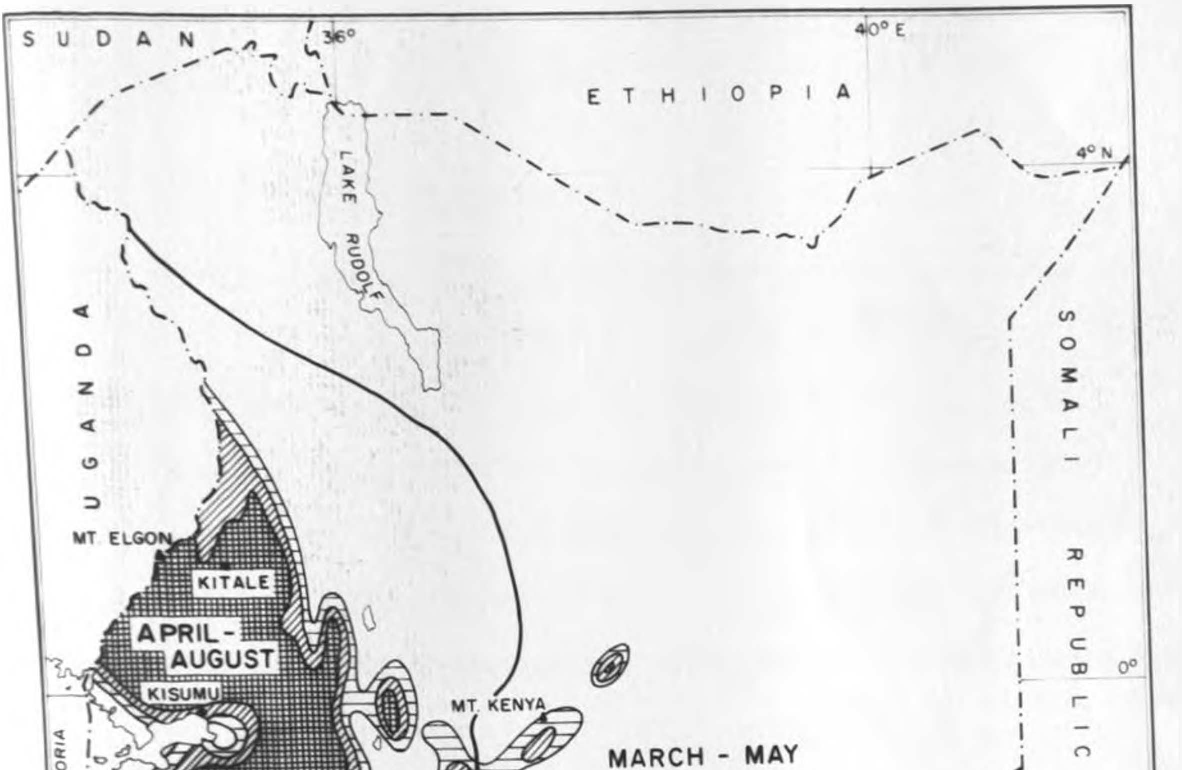

SUDAN
36°
40° E
ETHIOPIA
4° N
LAKE RUDOLF
UGANDA
SOMALI REPUBLIC
MT. ELGON
KITALE
APRIL-AUGUST
KISUMU
L. VICTORIA
0°
MT. KENYA
MARCH - MAY
NAIROBI
TANZANIA
TAITA HILLS
LAMU
MALINDI
APRIL - JUNE
INDIAN OCEAN
4° S
MOMBASA
G.deS.
0 40 80 120 160 200 KMS
0 40 80 120 MILES
SEASONAL RAINFALL IN KENYA
THE PROBABILITY OF RECEIVING LESS THAN 20 INCHES OF RAIN IN A SEASON
0 - 10%
10 - 20%
20 - 30%
30 - 100%
OR NUMBER OF YEARS IN 100 THE RAINFALL IS LIKELY TO BE LESS THAN 20 INCHES.
BOUNDARIES OF REGIONS WITH DIFFERENT RAINFALL SEASONS.

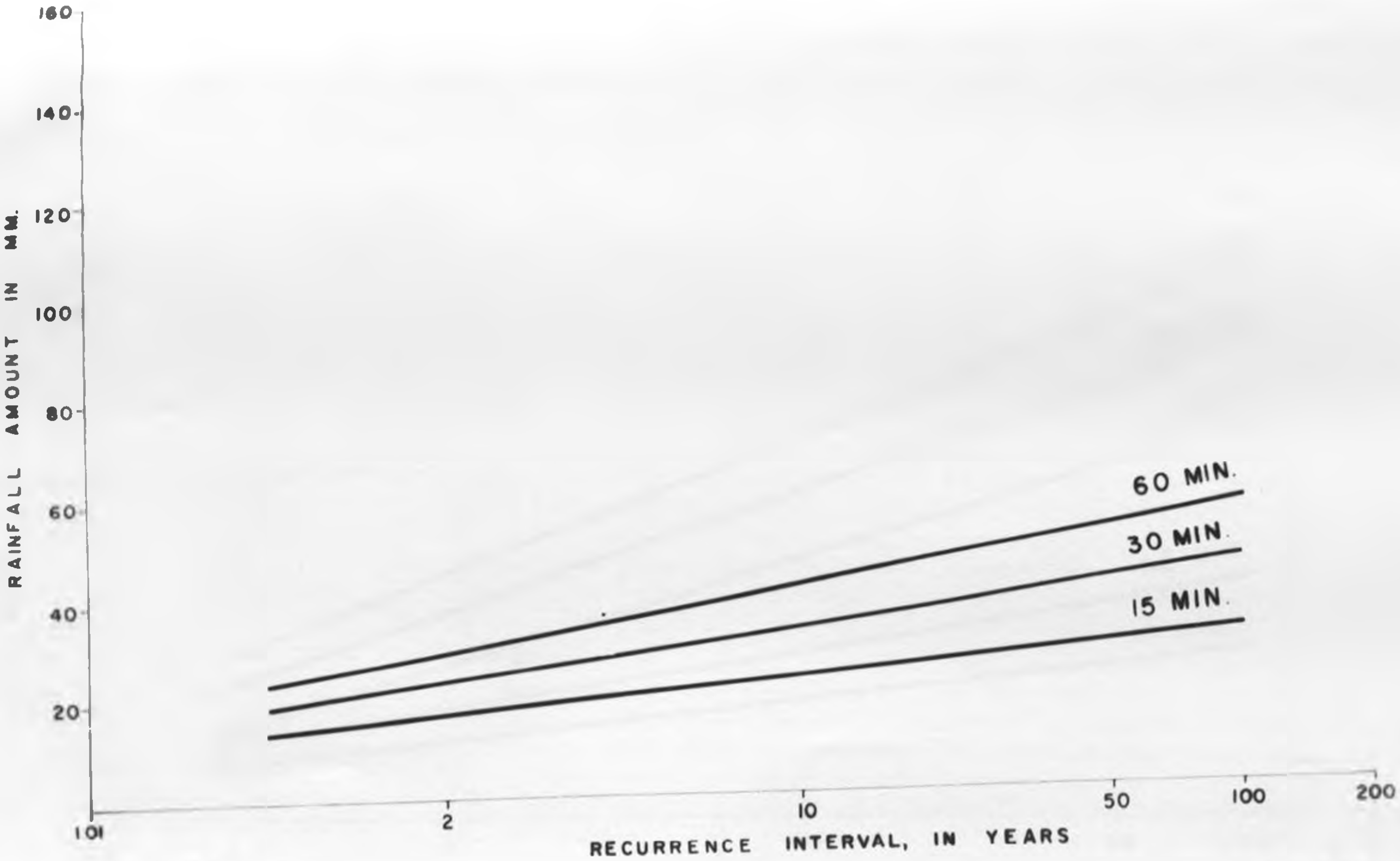
FIG 53

Victoria shore. Here the offshore prevailing winds tend to develop storms towards the Uganda side. In contrast to the eastern region, however, the wetter slopes in this area tend to be those facing the west.

(iii) Rainfall Intensity

So far, discussion of the variation of precipitation with time has been largely concerned with comparatively long-term totals of precipitation for individual years, seasons or months. Particularly in relation to surface runoff and subsequent weathering, one is concerned with the short-term variation of rainfall intensity during the course of an individual storm and with the expected frequencies and durations of given intensities of rainfall.

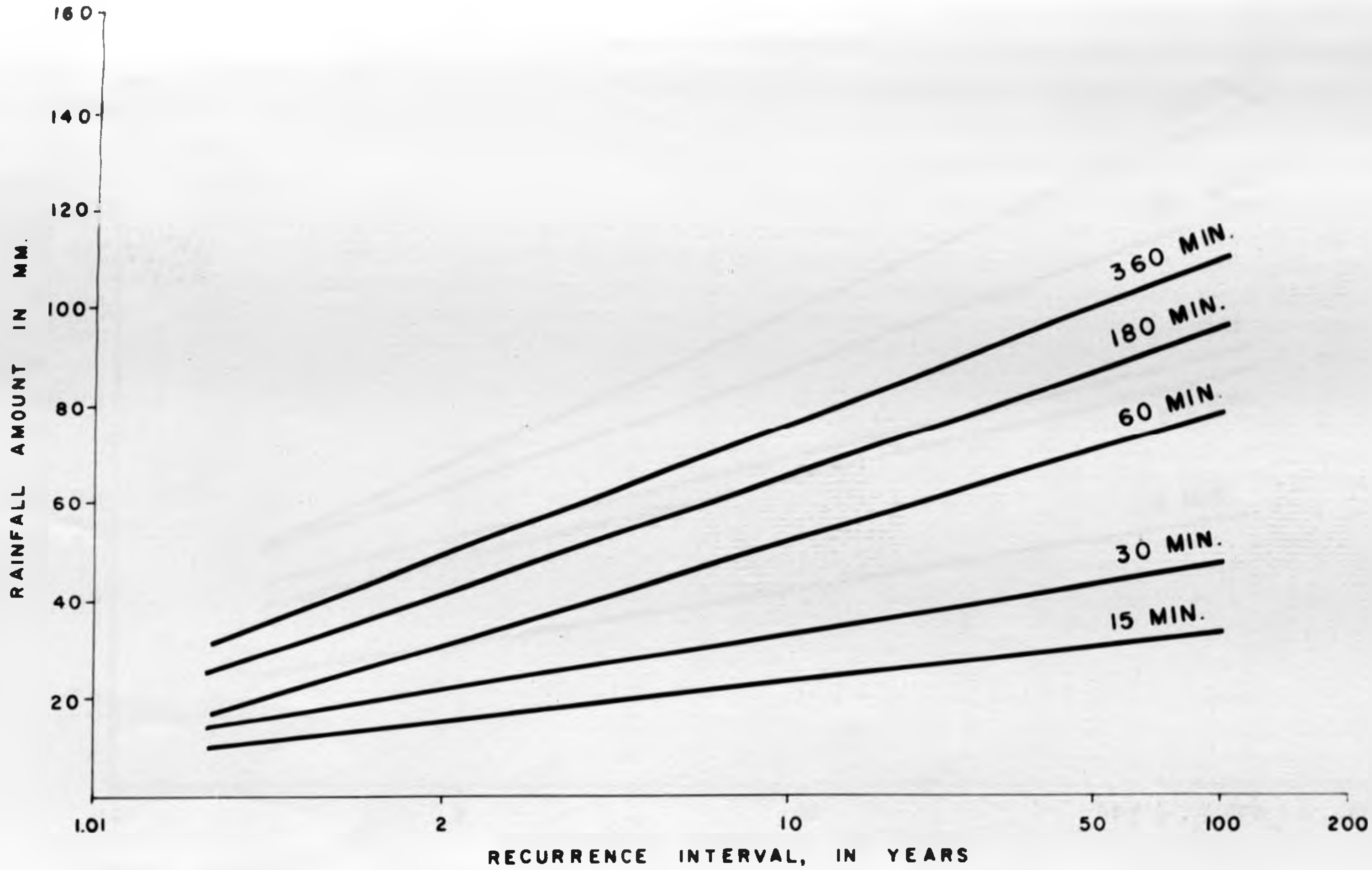
In terms of rainfall intensity, daily rainfall totals may be very misleading. Thus, for example, on each of two days when 2.4 inches of rain falls, the average intensity of 0.1 inches per hour might be fairly accurate reflection of actual conditions, if the rain falls continuously and uniformly throughout the 24 hour period. If, however, the rain on one day results from the passage of two clearly defined months, the duration of the two main periods of rainfall, may be restricted to say about 14 hours and the maximum intensity may then rise to more than 1.0 inch per hour for a brief period. The effects of these rainfalls on stream flow would differ markedly with the sudden increases in stream levels and discharge, almost certainly resulting from the higher intensity of rain. Even during storms of very short duration, for example, one or two hours, the variation of intensity may be very important. These variations may be described with the aid of intensity-duration curves in which rainfall intensity in inches per hour is plotted against the duration of rainfall. Taylor and Lawes (1971) in carrying out a rainfall-intensity-duration-frequency study of given stations in East Africa, carried out an extreme-value frequency analysis of the intensity data using the Gumbell method. Amounts of rainfall durations of 15, 30 and 60 minutes, 2 and 6 hours, expected to be equalled or exceeded in, various times or retun periods were used for periods of up to 50 years. These are drawn on probability paper and the results are shown in Figures 5-4 to 5-10 and represent such stations as Equator, Kabete, Kisumu, Kitale, Mombasa Port Reitz Airport, Nanyuki and Voi respectively. The amounts for 2, 5, 10, 20 and 50 year return periods have been read off from the probability paper and these are given in Table V-4. Table V-5(a to f), gives the frequency of occurrences of rainfall of 15, 30 and 60 minutes duration of intensity greater than 6.2 mm, 25 mm, 12.5 mm and 25 mm per hour for the rest. Table V-6(a to b) shows for a three hour period the frequency of occurrence of amounts greater than 30 mm while Table V-7(a to b) gives the frequency of occurrence of greater than 30 mm for a six hour period. Daily or 24 hour rainfall frequency amounts greater than 25 mm are shown in Table V-8(a to b). These refer to the 24 hour period and are not limited to periods of continuous rain. Figure 5-11 gives the maximum 24-hour falls recorded in Kenya in any area up to 1968 as illustrated by Taylor and Lawes (1971).



Source. E.A.M.D

Extreme value theoretical frequency lines after Gumbel for Equator (relating rainfall amount and recurrence interval in years).

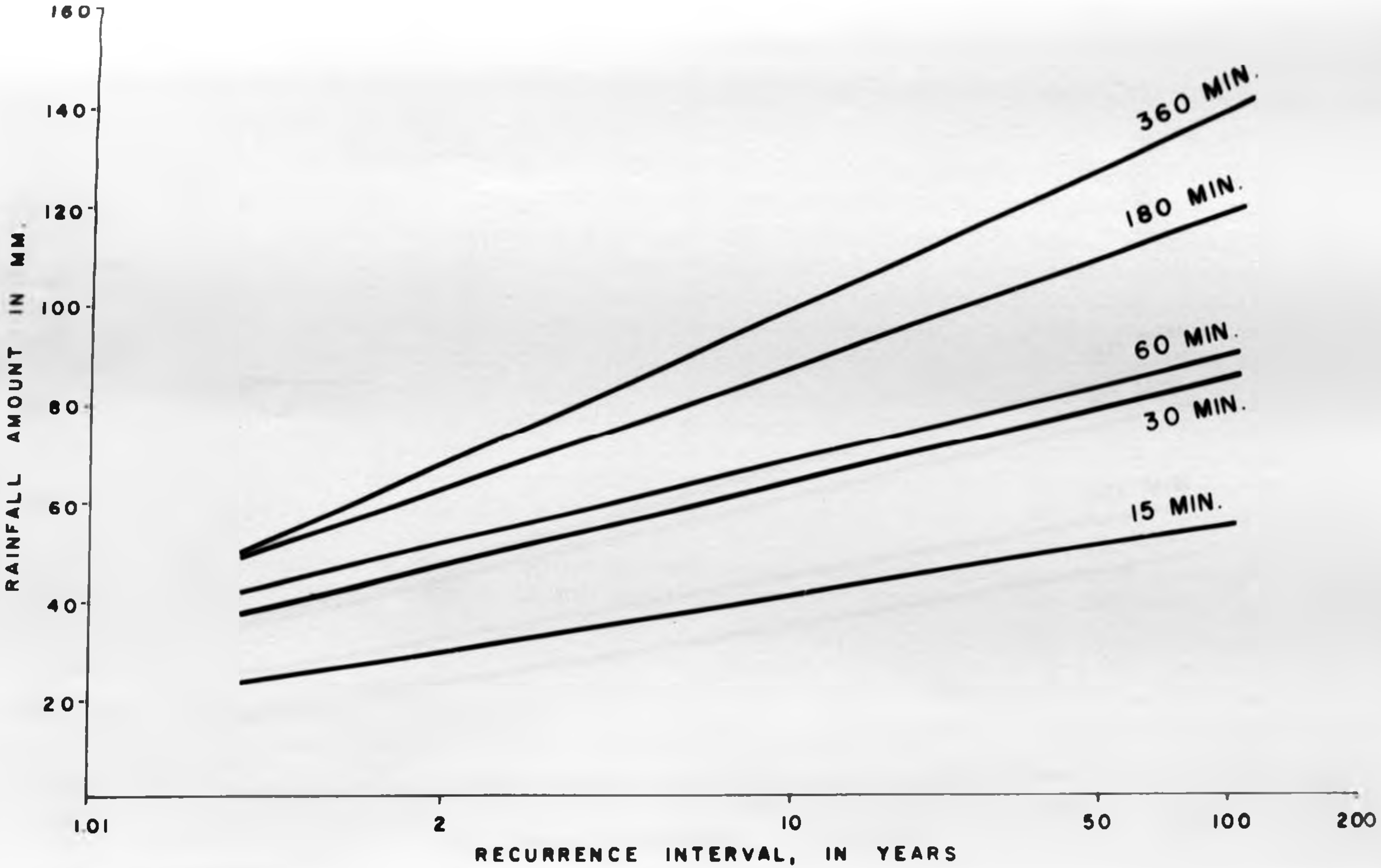
FIG 5.4



Source: E.A.M.D.

Extreme value theoretical frequency lines after Gumbel for Kabete (relating rainfall amount and recurrence interval in years).

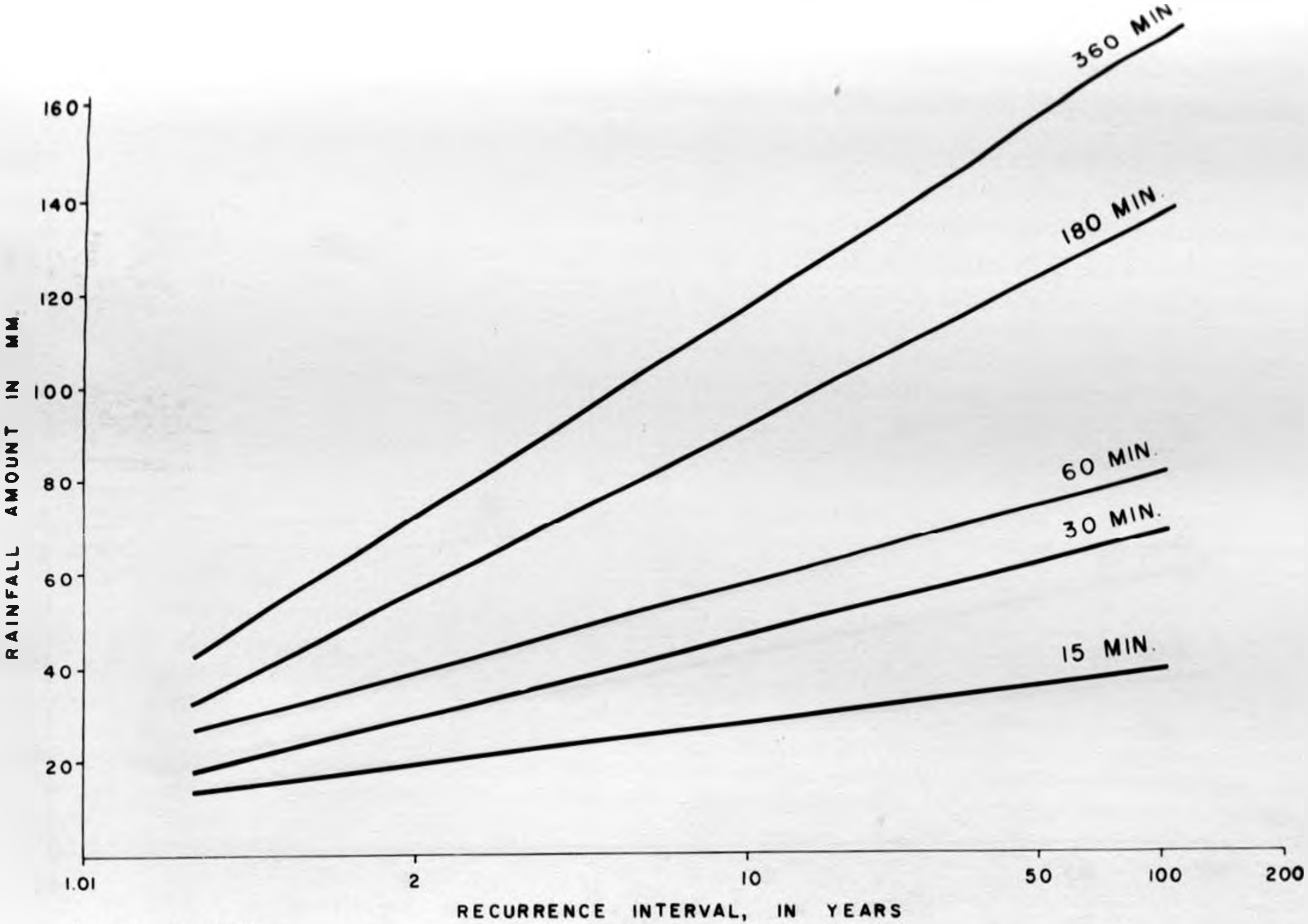
FIG 5.5



Source: E.A.M.D.

Extreme value theoretical frequency lines afrer Gumbel for Kisumu (relating rainfall amount and recurrence interval in years).

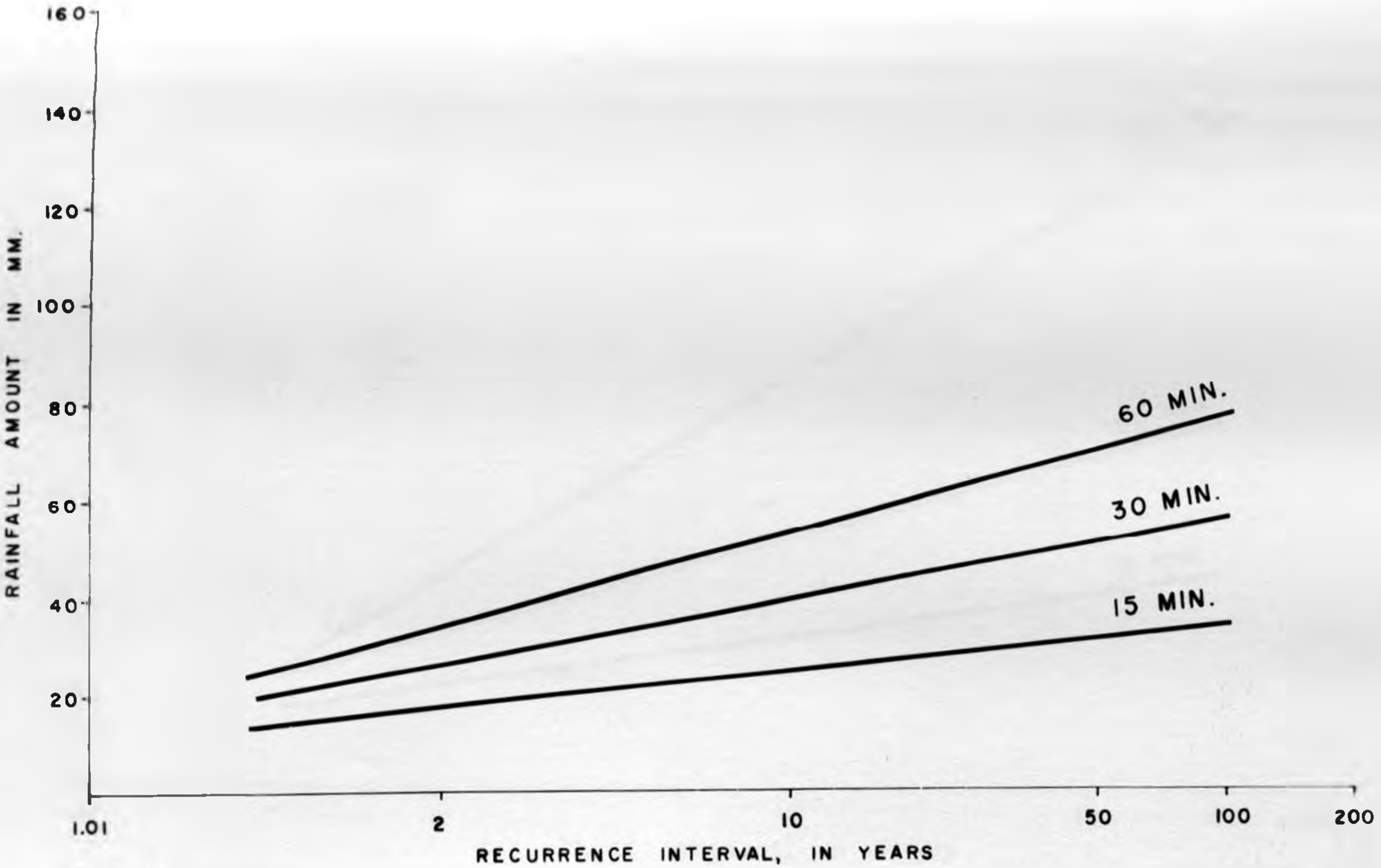
FIG 5.6



Source: E.A.M.D.

Extreme value theoretical frequency lines after Gumbel for Mombasa Port Reiz Aiport (relating rainfall amount and recurrence interval in years).

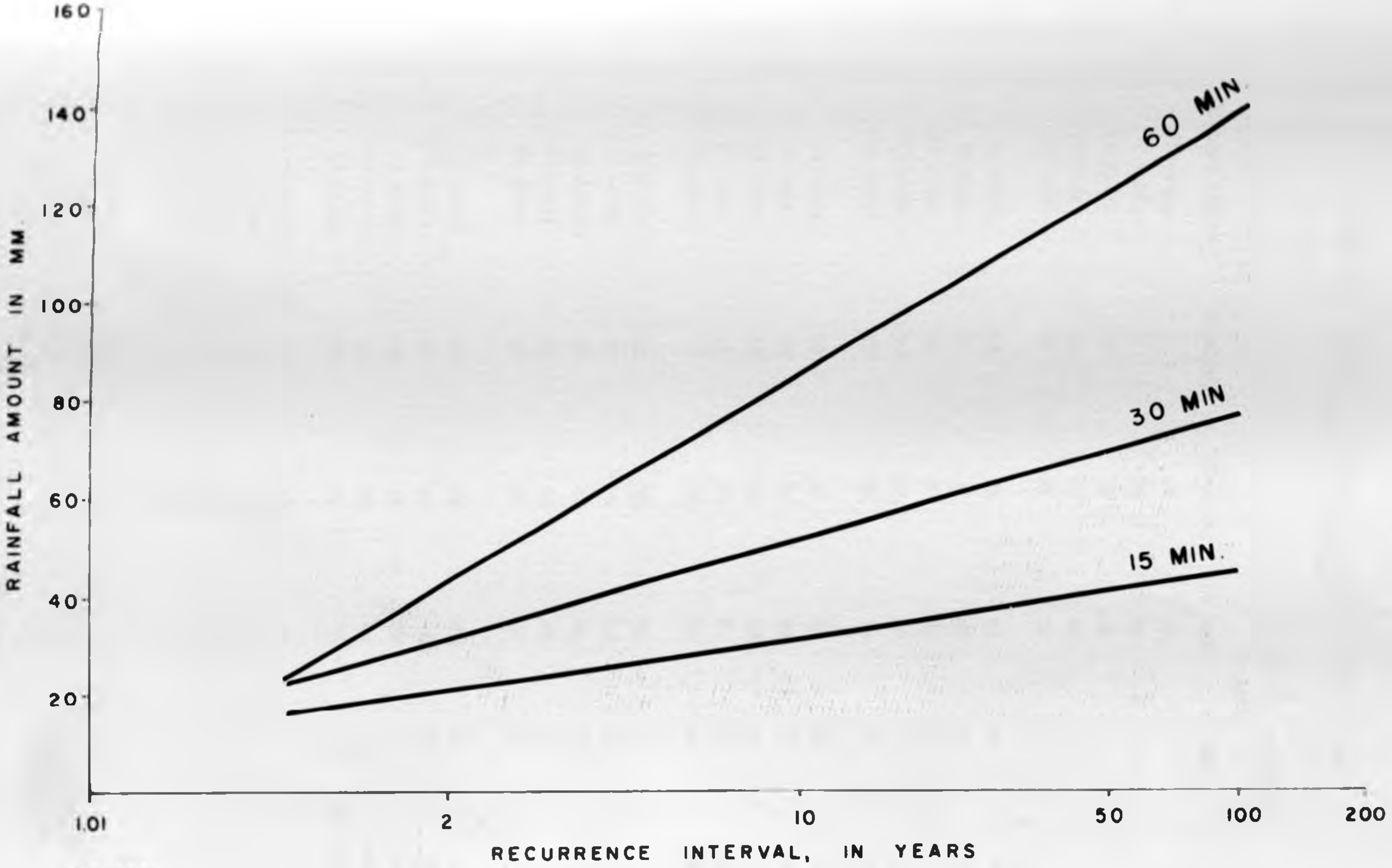
FIG 5.8



Source: E.A.M.D.

Extreme value theoretical frequency lines after Gumbel for Nanyuki (relating rainfall amount and recurrence interval in years).

FIG. 5.9



Source: E.A.M.D.

Extreme value theoretical frequency lines after Gumbel for Voi (relating rainfall amount and recurrence interval in years).

FIG. 5.10

TABLE V-4 Amount — Duration — Frequency Data for some selected Stations in Kenya

		Amounts in millimetres				
		Duration				
Station	Return Period	15 mins.	30 mins	1 hour	3 hours	6 hours
Equator	2 years	17	24	30		
	5 years	21	29	36		
	10 years	24	33	41		
	20 years	26	37	46		
	50 years	29	41	52		
Kabete	2 years	15	22	31	41	49
	5 years	20	29	43	55	65
	10 years	23	33	52	65	75
	20 years	26	37	59	74	85
	50 years	30	43	70	85	98
Kisumu	2 years	30	47	51	62	68
	5 years	36	56	61	77	86
	10 years	40	63	68	86	98
	20 years	45	69	74	95	110
	50 years	50	77	82	107	125
Kitale	2 years	21	30	41	44	
	5 years	27	36	50	54	
	10 years	31	40	56	62	
	20 years	35	44	61	68	
	50 years	39	50	68	77	
Mombasa	2 years	19	29	39	56	73
	5 years	25	40	50	77	99
	10 years	28	46	57	91	116
	20 years	31	53	64	104	133
	50 years	35	61	73	121	155
Nanyuki	2 years	18	27	34		
	5 years	22	34	45		
	10 years	25	39	52		
	20 years	29	44	60		
	50 years	31	50	69		
Voi	2 years	21	31	42		
	5 years	27	43	67		
	10 years	31	51	83		
	20 years	35	58	99		
	50 years	40	68	120		

TABLE V-5 (a to f) Frequency of Occurrence of rainfall of 15, 30 and 60 Minutes Duration for given Intensities per Hour

(a)

Frequency of occurrence of 15-minute cumulative falls greater than 6.2 mm.

Frequency of falls greater than:-		6.2	10	15	20	25	30	35	40	45 mm.
Station	No. of years	Number of occasions								
Equator	16	523	121	23	5					
Kabete	27	1004	133	28	5					
Kisumu	24	1267	630	279	121	51	21	10	2	
Kitale	17	721	316	106	36	4				
Mombasa	17	668	150	38	9	3				
Nanyuki	22	630	131	35	8	4				
Voi	21	379	188	68	18	9	2	1	1	

(b)

		Falls of intensity greater than 25 mm/hour		Highest Fall		
		Total for period	Average per year	Amount mm	Intensity mm/hour	Date
Equator	16	523	32.7	24.1	96	June 53
Kabete	27	1004	40.9	22.0	88	Apr.37
Kisumu	24	1267	52.8	43.7	175	Apr.56
Kitale	17	721	42.4	29.2	117	Feb.54
Mombasa	17	668	39.3	30.0	120	Apr.53
Nanyuki	22	630	28.6	27.9	112	Jun.43
Voi	21	379	18.0	40.6	162	Jan.44

(c)

Frequency of occurrence of 30-minute cumulative falls greater than 12.5 mm

Frequency of falls greater than:-		12.5	15	20	25	30	35	40	45	50	55	60	6'mm
Station	No. of years	Number of occasions											
Equator	16	248	72	26	9	5							
Kabete	27	334	115	43	21	4	1						
Kisumu	24	682	414	260	164	100	54	33	16	10	6	2	2
Kitale	17	334	198	99	54	30	9	3					
Mombasa	17	304	111	54	21	7	4	2	2	1	1		
Nanyuki	22	278	105	49	26	10	6	2	1				
Voi	21	170	119	64	34	16	10	8	4	3	1		

(d)

Station	No.of years	Falls of intensity greater than 25 mm/hour Total for period	Average per year	Highest Fall Amount mm	Intensity mm/hour	Date
Equator	16	248	15.5	33.0	66	Aug.55 June 56
Kabete	27	334	12.4	36.4	73	Apr.52
Kisumu	24	682	28.4	67.3	135	May 49
Kitale	17	334	19.6	43.1	86	June 43
Mombasa	17	304	17.9	56.9	114	Apr.53
Nanyuki	22	278	12.6	48.0	96	June 43
Voi	21	170	8.1	56.6	113	Feb.43

(e)

Frequency of occurrence of 60-minute cumulative falls greater than 25 mm.

Frequency greater than:-		25	30	35	40	45	50	55	60	65	70	75	80	85	90mm.
Station	No. of years	Number of occasions													
Equator	16	30	14	7	2										
Kabete	27	67	33	18	10	3	3	3							
Kisumu	24	233	159	113	73	47	28	17	8	5	1	1			
Kitale	17	77	47	31	14	7	3	2							
Mombasa	17	55	34	19	13	6	4								
Nanyuki	22	40	21	13	4	3	2	1	1	1					
Voi	21	55	38	22	13	8	7	6	5	4	4	3	2	1	1

(f)

		Falls of intensity greater than 25 mm/hour Total for period	Average per year	Highest Fall Amount mm	Intensity mm/hour	Date
Equator	16	30	1.9		41.4	May 53
Kabete	27	67	2.5		60.0	Apr.31
Kisumu	24	233	9.7		77.5	Jan.48
Kitale	17	77	4.5		55.9	Mar.41 Jul.50
Mombasa	17	55	3.2		55.0	Apr.54
Nanyuki	22	40	1.8		68.6	Jul.47
Voi	21	55	2.6		108.0	Feb.43

(a)

TABLE V-6(a to b) Frequency of occurrence of 3-hour cumulative falls greater than 30 mm.

Frequency of falls greater than:-		30	40	50	60	70	80	90	100 mm.
Station	No. of years	Number of occasions							
Equator	16	14	8						
Kabete	27	67	28	11	1	1			
Kisumu	24	113	75	41	21	11	4	1	1
Kitale	17	23	16	6	1				
Mombasa	17	74	37	17	9	4	3	1	1
Nanyuki	22	16	6	2	2	1	1		
Voi	21	21	17	13	7	4	2	2	1

(b)

		Falls of intensity greater than 25 mm/hour		Highest Fall		
		Total for period	Average per year	Amount mm	Intensity mm/hour	Date
Equator	16	14	0.9	48.0	16	Jul.46
Kabete	27	67	2.5	72.3	24	Feb.41
Kisumu	24	113	4.7	101.4	34	Aug.44
Kitale	17	23	1.4	65.2	22	Mar.58
Mombasa	17	74	4.4	105.0	35	Mar.58
Nanyuki	22	16	0.7	85.9	29	Jul.47
Voi	21	21	1.0	106.7	36	Nov.51

(a)

TABLE V-7(a-b) Frequency of occurence of 6-hour cumulative falls greater than 30 mm.

Frequency of falls greater than:-		30	40	50	60	70	80	90	100	110 mm.
Stations	No. of years	Number of occasions								
Equator	16	18	13	2						
Kabete	27	96	46	27	13	1	1	1		
Kisumu	24	103	72	43	24	13	6	3	2	1
Kitale	17	13	10	8	4	1	1	1	1	
Mombasa	17	79	51	31	19	11	9	7	4	2
Nanyuki	22	27	12	4	2	1	1			
Voi	21	3	3	3	3	2	1			

(b)

		Fall of intensity greater than 25 mm/hour		Highest Fall		
		Total for period	Average per year	Amount mm	Intensity mm/hour	Date
Equator	16	18	1.1	50.8	8	Jul.46 Mar.51
Kabete	27	96	3.6	96.6	16	Feb.41
Kisumu	24	103	4.3	115.3	19	Nov.61
Kitale	17	13	0.8	104.4	17	Mar.58
Mombasa	17	79	4.6	117.4	20	Jun.41
Nanyuki	22	27	1.2	85.9	14	Jul.47
Voi	21	3	0.1	88.1	15	Nov.62

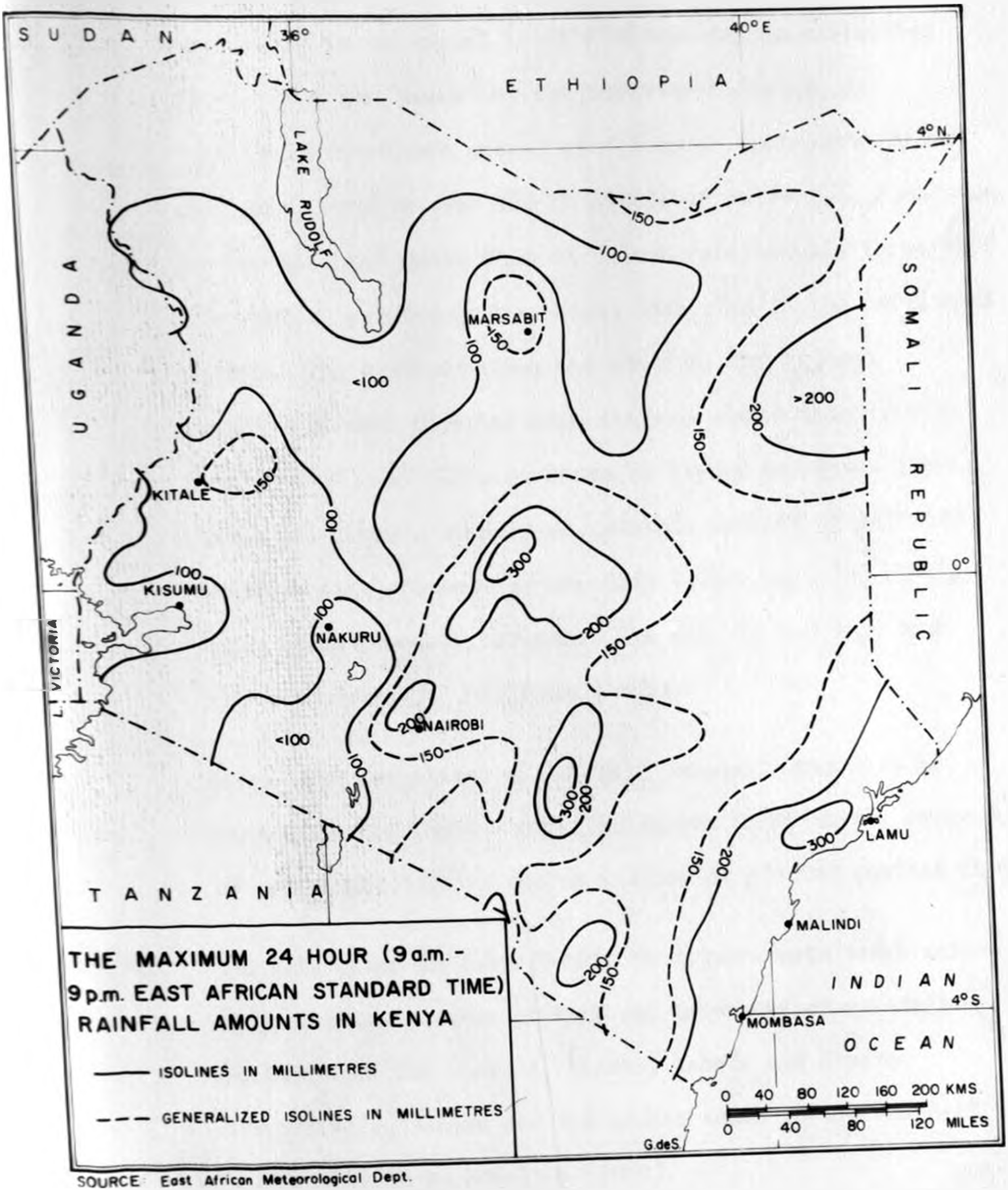
TABLE V-8 (a to b) Frequency of occurrence of 24-hour totals greater than 25 mm.

(a)

Frequency of totals greater than:-		25	40	55	70	85	100	115	130	145	160	175	230	245 mm.
Station	No. of years	Number of occasions												
Equator	16	93	21											
Kabete	27	241	92	33	1	1	1							
Kisumu	24	302	132	54	17	4	2	1						
Kitale	17	146	41	8	1	1	1							
Mombasa	17	144	74	43	23	16	11	2	2	2				
Nanyuki	22	80	21	4	1	1								
Voi	21	83	37	20	12	9	3	1						

(b)

		Amounts greater than 25 mm		Highest Fall	
		Total for period	Average per year	Amount mm	Date
Equator	16	93	5.8	52.1	Mar.51
Kabete	27	241	8.9	111.3	Feb.41
Kisumu	24	302	12.6	128.3	Nov.61
Kitale	17	146	8.6	104.4	Mar.58
Mombasa	17	144	8.5	156.0	May 47
Nanyuki	22	80	3.6	85.9	Jul.47
Voi	21	83	4.0	119.4	Feb.43



THE MAXIMUM 24 HOUR (9 a.m.- 9 p.m. EAST AFRICAN STANDARD TIME) RAINFALL AMOUNTS IN KENYA

SOURCE: East African Meteorological Dept.

FIG 5 11

In each of those tables, the frequencies of amounts greater than certain values are listed; the intensity(mm/hour) equivalent to an amount in millimetres may be calculated by dividing the amount by the duration in hours, for example, a 15-minute amount of 6.2 mm is equivalent to an average intensity over the 15 minute of $6.2 \div \frac{1}{4} \simeq 25$ mm/hour. An "occurrence" means that it rained continuously throughout the period, producing the amount indicated in the particular column. For each duration and station, the highest recorded amount together with correspondence intensity is included in each table as given by Taylor and Lawes (1971). Table V-9 gives a summary of rainfall records at selected stations east and west of the Rift Valley supplied by the Water Development Department. The data is not very much different from the foregoing tables.

Short term variations of rainfall intensity may also be represented by depth - duration curves in which the percentage of total rain falling during a storm is plotted against time.

The data given in Table V-10(a to d) show both total rainfall against time in which it fell and intensity of rainfall against time for Mombasa, Kisumu, Kabete and Equator respectively. These and the graphs shown in figures 5-12 to 5-15 are given by McCallum (1959).

The graphs for each set of data are of two types, namely, total rainfall against the period of the fall on one hand and the greatest intensity against the period on the other

TABLE V-9 Summary of Rainfall Records at Selected Stations

(All Values in inches)

A. EAST OF RIFT VALLEY

STATION		YEARLY TOTAL			OCT. + NOV. 1961		MAX. FALL IN 1 DAY		MAXIMUM INTENSITY OF RAINFALL, INCHES PER HOUR								
										MINUTES			HOURS				YEAR OF RECORDS ANALYSED
Name and Number	Period of Records Years	Average	1961	% of Average	Total 2 Months	No. of rain days 2 months	1961	Previous Max.		10	15	30	1	3	6	12	
MERU 89-3700	48	52	116	223	90	47	4.98	8.67	1961	5.28	4.40	3.60	2.00	0.87	0.44	0.22	1952-57
									Previous Max.	4.68	4.00	2.10	1.14	0.52	2.29	0.5	
EMBU 90.3708	54	41	77	188	49	47	4.28	5.98	1961	2.28	2.04	1.48	1.21	0.63	0.50	0.32	1952-57
									Previous Max.	7.88	7.30	6.72	4.89	2.06	1.12	0.56	
FORT HALL 90.3707	59	46	70	152	42	45	3.10	8.40	1961	4.26	4.04	2.72	1.43	0.61	0.38	0.19	1951-57
									Previous Max.			3.07	2.77	1.85	1.04	0.55	
THIKA 91.3718	32	31	43	139	25	30	2.40	4.00	1961	2.76	2.48	1.76	1.12	0.42	0.21	0.10	1951-61
									Previous Max.	4.92	4.44	3.22	2.30	0.85	0.45	0.22	
NYERI 90.3617	57	36	64	176	34	50	4.27	4.10	1961	4.08	2.96	1.70	1.16	0.68	0.40	0.27	1953-57
									Previous Max.	4.37	3.42	1.98	1.04	0.65	0.36	0.18	
NANYUKI 89.3722	22	28	45	161	21	47	2.36	3.50	1961		2.44	1.72	1.29	0.55	0.36		1941-62
									Previous Max.		4.40	3.78	2.70	1.13	0.58	0.29	
LARI F. STA. 91.3622	55	54	74	137	35	51	2.23	4.80	1961	2.88	2.48	1.62	1.04	0.38	0.20	0.10	1951-57 (Sasuma Dam)
									Previous Max.	3.48	2.96	2.36	1.23	0.41	0.21	0.10	
THOMSON'S FALLS 09.3615	24	37	63	170	21	49	6.43	3.56	1961	NO RECORDS							
									Previous Max.								

B. WEST OF RIFT VALLEY

STATION		ANNUAL RAINFALL				TOTAL FOR 2 MONTHS 1961 OCT. +NOV.1962 APR.+ MAY	NO.OF RAIN DAYS 2 MONTHS 1961 OCT. +NOV.1962 APR.+ MAY	MAX.FALL IN 1 DAY		MAXIMUM INTENSITY BY RAINFALL, INCHES PER HOUR								
Name and Number	Period of Records Years	Average	Year	Total	% of Average				Previous Max.		MINUTES			HOURS				YEAR OF RECORDS ANALYSED
											10	15	30	1	3	6	12	
KITALE 89.3408	45	50	1961	67	134	20	34	2.30	3.82	1961	5.28	4.00	2.42	1.24	0.51	0.31	0.16	1941-62 (Agri.Dept.)
			1962	59	118	19	30	2.25		1962	4.50	3.20	2.54	1.50	0.60	0.30	0.15	
										Prev. Max.		4.60	3.40	2.20	0.86	0.69		
ELDORET 89.3586 89.3526	52	41	1961	51	124	13	45	1.69	4.40	1961								
			1962	49	120	16	35	2.60		1962		NO	RECORDS					
										Prev. Max.								
KISUMU 90.3404	58	44	1961	59	134	22	33	5.05	5.00	1961		4.48	3.04	2.17	1.08	0.76		1939-62
			1962	55	125	23	31	3.92		1962		4.76	3.50	2.10	0.74			
										Prev. Max.		6.88	5.30	3.05	1.33	0.67		
KERICHO 90.3503			1961	104	144	31	57	2.21	3.32	1961	4.08	3.24	2.00	1.48	0.54	0.27	0.14	1951-56
			1962	89	124	28	52	3.20		1962	4.56	3.76	3.58	1.96	0.71	0.35	0.17	
										Prev. Max.	6.00	4.40	2.44	1.40	0.56	0.37	0.21	
LONDIANI FOREST STA. 90.3502	54	44	1961	62	141	20	46	1.60	3.30	1961								
			1962	53	120	13	45	1.85		1962		NO	RECORDS					
										Prev. Max.								
KAKAMEGA 89.3401			1961	108	146	30	50	4.21	4.65	1961								
			1962	98	132	29	53	2.98		1962		NO	RECORDS					
										Prev. Max.								

TABLE V-10 (a to d) Rainfall amounts and Intensity in Inches per hour for selected Stations in Kenya for given years.

Mombasa 1946-1955

(a)

t	½	1	2	3	6	24
R	1.90	2.24	2.52	3.20	1.09	8.11
I	3.80	2.24	1.26	1.07	0.68	0.34

Kisumu 1930-1955

(b)

t	½	1	2	6	12	24
R	2.36	3.35	4.00	4.00	4.00	5.18
I	4.72	3.35	2.00	0.67	0.33	0.22

Kabete 1942-1955

(c)

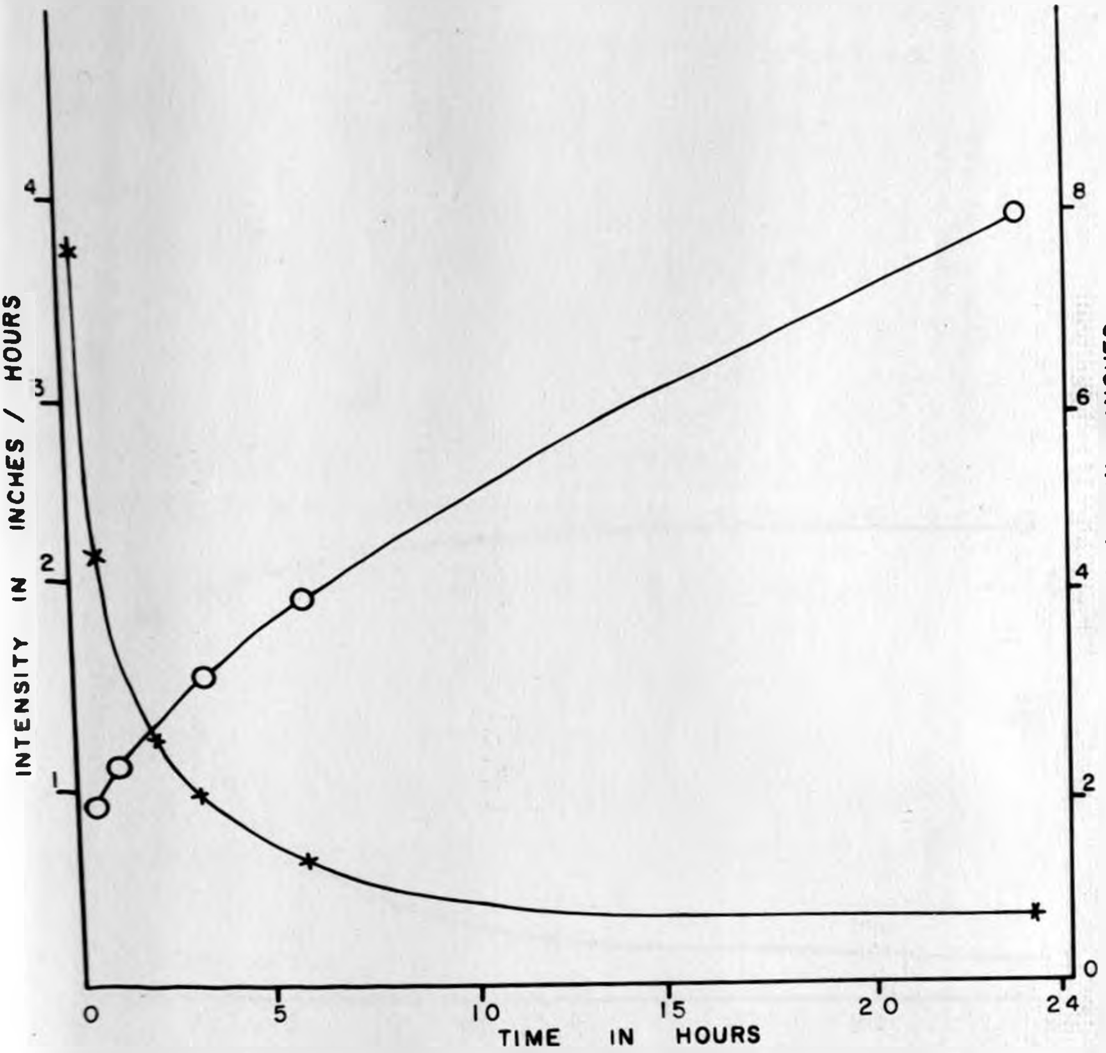
t	1	3	6	12	24
R	2.52	3.07	3.41	4.36	4.45
I	2.52	1.02	0.57	0.36	0.19

Equator 1941-1955

(d)

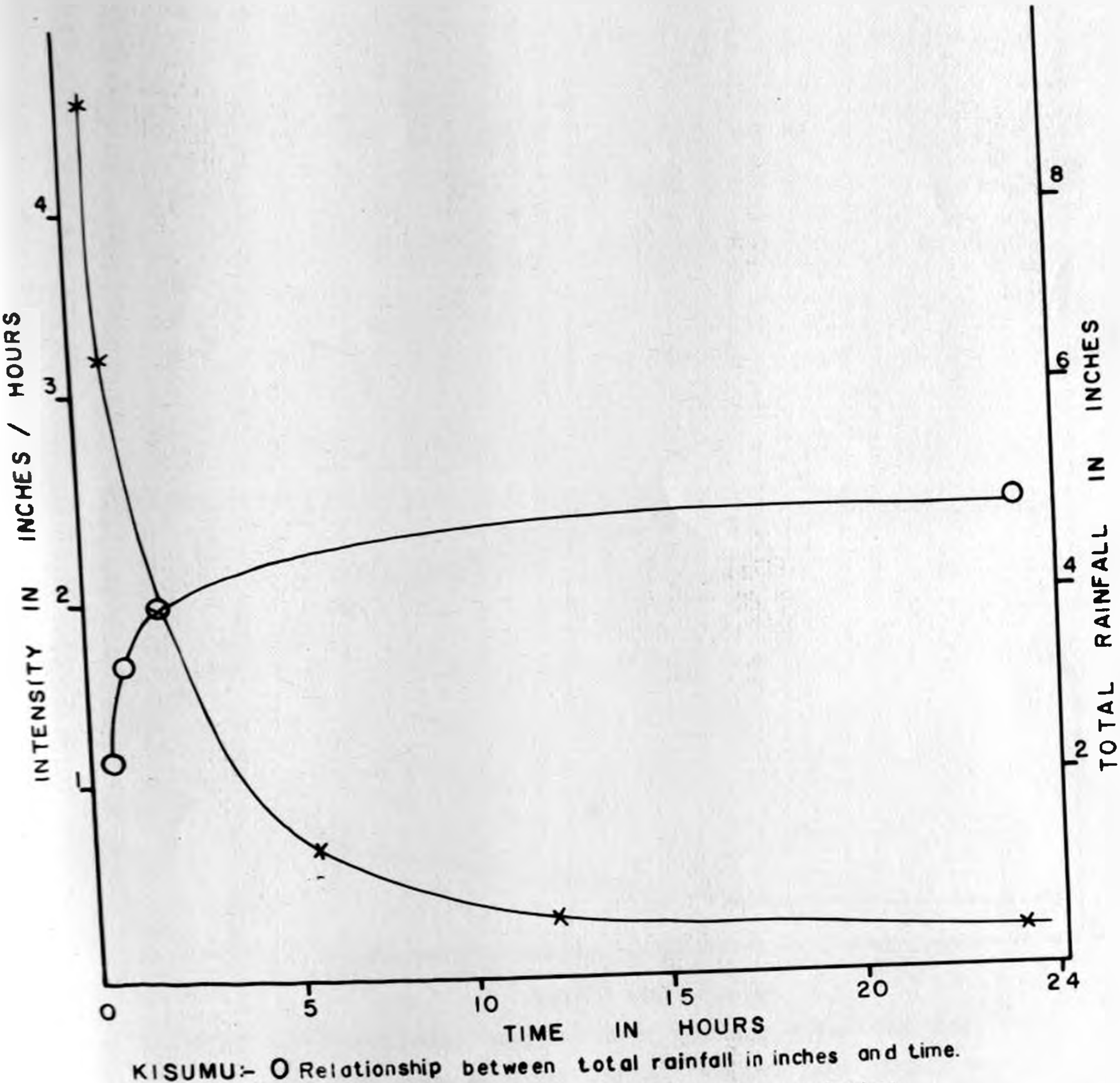
t	1	3	6	12	24
R	1.50	1.89	1.89	2.24	2.58
I	1.50	0.63	0.37	0.19	0.11

t = time in hours
R = rainfall in ins.
I = intensity in ins/hr.



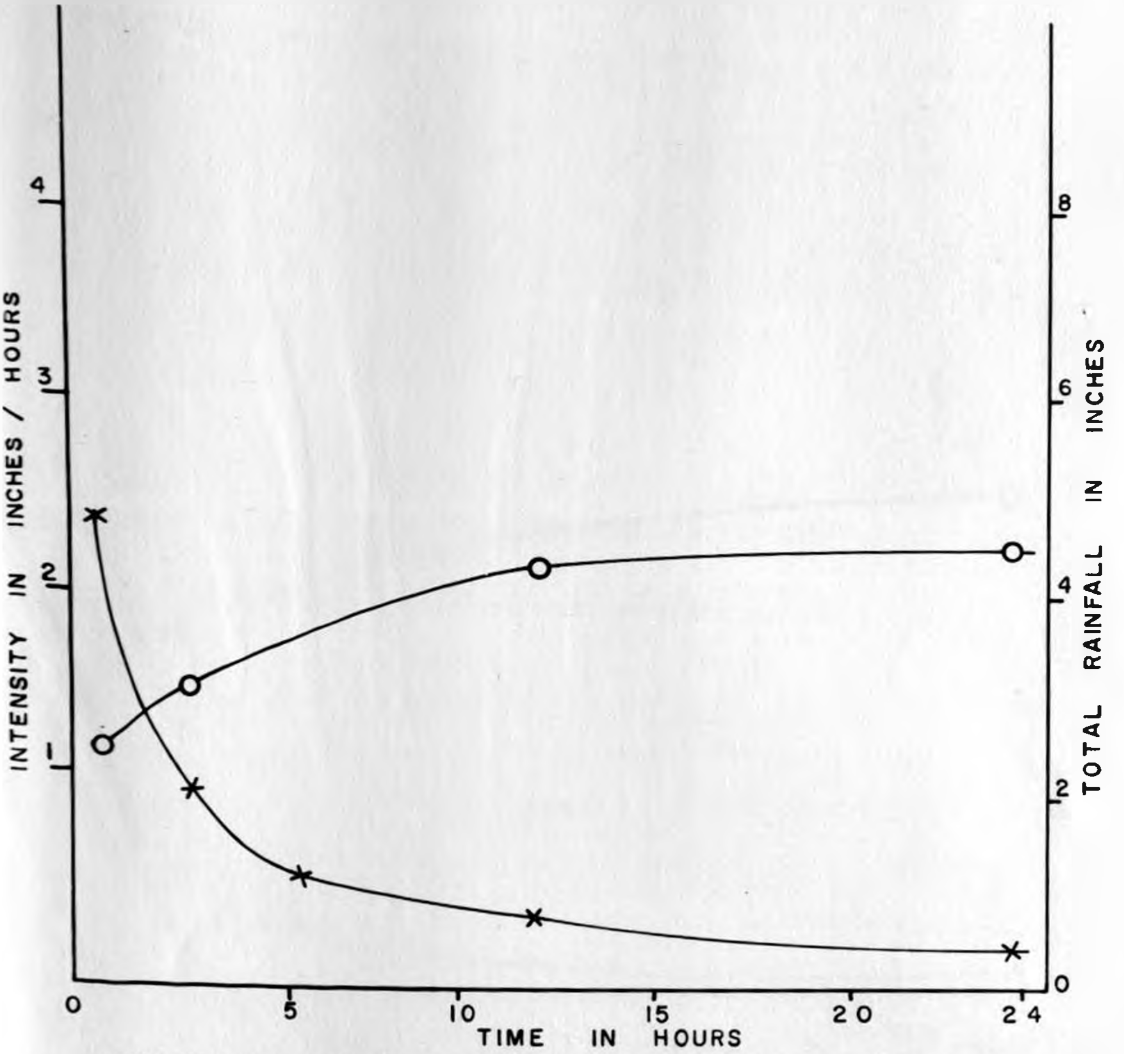
MOMBASA-O Relationship between total rainfall in inches and time.
X Relationship between rainfall intensity and time.

FIG. 5.12



KISUMU:- O Relationship between total rainfall in inches and time.
X Relationship between rainfall intensity and time.

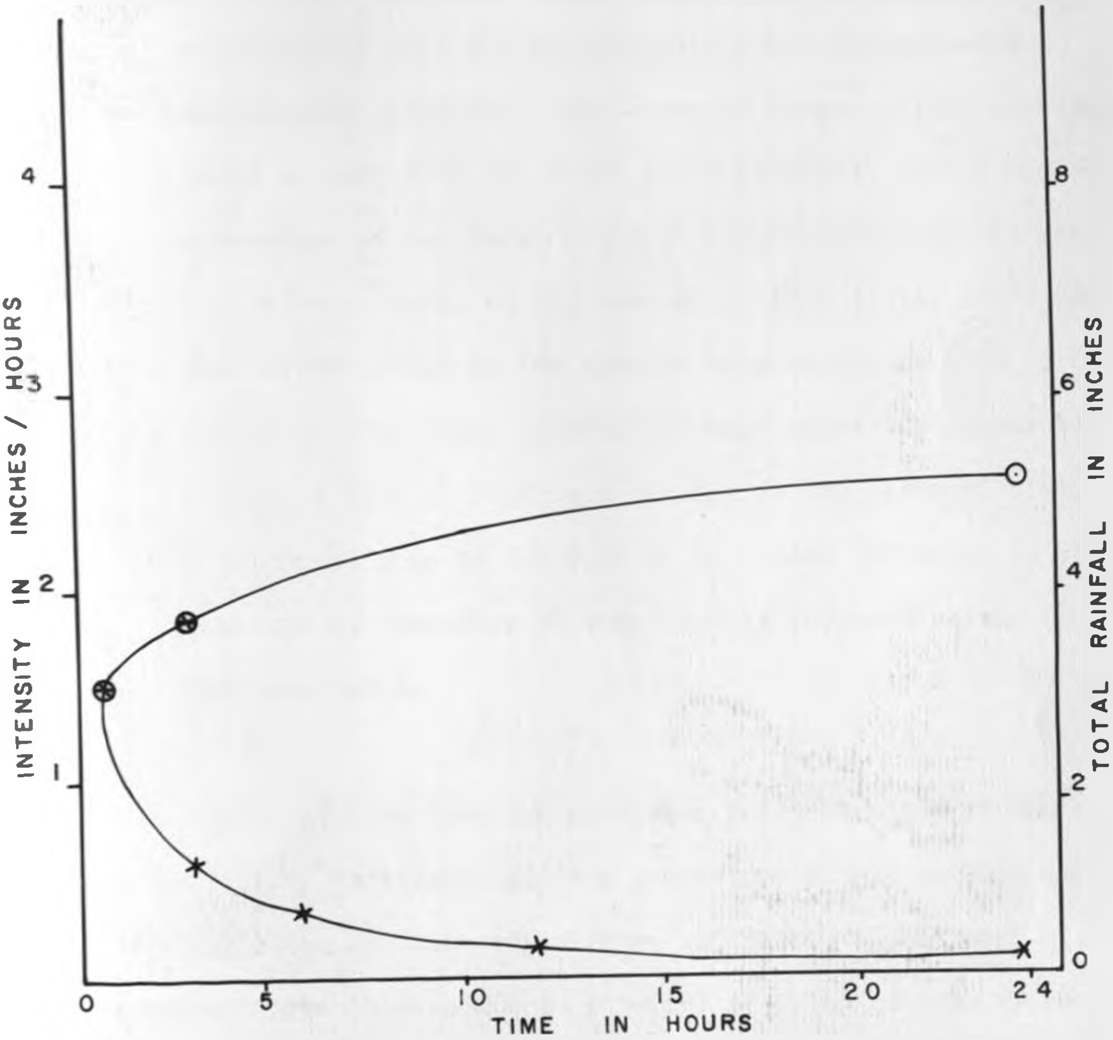
FIG. 5.13



KABETE : O Relationship between total rainfall in inches and time.

X Relationship between rainfall intensity and time.

FIG. 5.14



EQUATOR: ○ Relationship between total rainfall in inches and time.
X Relationship between rainfall intensity and time

FIG 5.15

hand. These graphs were drawn on the same chart for each station but using different vertical scales. The intensity - time graphs were all remarkably smooth curves as can be seen, although the total rainfall-time graphs were not quite impressive. From the form of the intensity-time graphs, it would appear that the relationship could be that of a rectangular hyperbola. The shape of these curves, however, tends to vary with the total storm rainfall, with a higher percentage of the total rainfall occurring during the early part of the storm, in the case of lighter falls, and a more even distribution in the case of heavier falls. The frequency with which rainfall of high intensity occurs is likely to have an important bearing on the susceptibility of a catchment area to flooding or to sudden increases in stream flow and is therefore of considerable interest to the hydrogeologist.

Water soaking into the ground or being absorbed by the rock or soil (i.e. infiltration), has a profound effect on the chemistry of the surface and subsurface water and varies widely over a catchment area in response to a number of often closely related factors such as rainfall intensity,amount and rain chemistry. It has been observed that if the rainfall intensity is lower than the infiltration capacity of a soil or rock, all the falling rain not held on surface storage, will infiltrate into the soil or rock. This then means that, there will be a direct relationship between the rate of infiltration and the intensity of the rainfall. When, however, rainfall intensity exceeds the infiltration capacity, the foregoing relationship breaks down and may indeed be replaced by an inverse relationship between infiltration and rainfall intensity. This is normally the case when an increase in rainfall intensity is reflected in an increase in rain drop size and consequently in an increase in their compacting force as the drops strike the ground surface.

Falling raindrops may compact the surface of the soil such that infiltration is rapidly and effectively reduced. This effect is more noticeable in clay soils which can be rendered virtually impermeable than on clear sandy soils which are much less susceptible to rain compaction. Fine particles carried in suspension by infiltrating water may clog pores in the soil surface and so lower the infiltration rates. The rate of infiltration might be expected to vary with the depth of standing water, particularly during the early stages of the infiltration process when only a thin layer of surface soil has been saturated so that the resistance to infiltrating water is comparatively low.

It may now become clear that one of the main factors governing the magnitude of infiltration is the time available for infiltration process so that infiltration is generally greatest in conditions which slow down the movement of water over the ground surface. The nature of the surface is, thus very important in this respect.

Water quality is another factor whose influence on infiltration is difficult to delimit quantitatively. Most water passing through the soil surface collects fine clay and silt particles and carries these suspensions into the soil profile, where blocking of smaller pore spaces may occur. Infiltration rates have also been found to vary when the infiltrating water is contaminated by salts, particularly in very alkaline soils because the salts affect not only the viscosity of the water but also the rate of swelling colloids.

Since the viscosity of the water and therefore the ease with which it may move through the soil pore spaces, varies with water temperature, the latter will tend to exert some influence upon infiltration rates. Scarcely any evidence exists, however, which definitively illustrates this relationship, although it is known that infiltration rates for given precipitation conditions are generally higher during periods of higher temperatures than during lower temperature seasons.

(c) Temperature

Since air and water temperatures are largely dependent upon solar radiation, a fairly close correlation between them and the rate of evaporation can be expected. The temperature of the water surface is important in that it governs the rate at which water molecules leave the ground and enter the overlying air. A change on water surface temperature may therefore have a profound short-term effect upon the rate of evaporation. Ultimately, however, it is the net movement of water vapour molecules, and the way on which the molecules leaving the water surface are redistributed within the lower layers of the overlying air, which largely conditions the evaporation process. Apart from this chain of reactions, temperatures are important in weathering processes as they are largely responsible for contraction and expansion of rocks which lead to the physical breakdown of a rock mass into relatively ~~large~~ ~~Small~~ ~~Large~~ ~~Small~~? Small fragments.

It has been shown, for example, that evaporation decreases by about one per cent for every one per cent increase in salinity, so that evaporation from the sea water with an average salinity of about 3.5 per cent is in some cases two or three per cent less than evaporation from other surface water. This reduction is brought about by the reduced vapour pressure of the saline water. However, in cases of non-marine water, salinity values are normally so small that they can be discounted when comparing evaporation rates of different water bodies.

The effect of water depth upon the rate of evaporation may be quite considerable. The seasonal temperature regime of a shallow water body, for example, a small lake, will normally approximate closely to the seasonal air temperature regime. This means that maximum rates of evaporation from a shallow water body will be experienced during warm seasons and minimum during cold seasons.

Kenya, like other parts of East Africa, is a low-latitude region, where variation in mean monthly bulb temperature is very small and, according to Griffiths (1962), being generally of the order of 6 to 8 degrees fahrenheit. The mean annual maximum and minimum temperatures are expected to vary closely with the elevation of the ground. The annual mean temperature of a station without a thermometer reading, as given in the Kenya

National Atlas (1970), can be obtained from the relationship $T = 30.2 - 6.5 \times E (^{\circ}C)$, where E, is the elevation of the ground in thousands of metres or kilometers. Table V-11 gives the mean annual temperatures of selected stations in Kenya, while Table V-12 gives the highest maximum temperatures recorded at given stations in Kenya. The data given in both the tables is from the East African Meteorological Department. The mean annual maximum temperature of Kenya, as given in the Kenya National Atlas (1970), is shown in Figure 5-16. This map shows that the highest temperatures are experienced in the arid and semi-arid areas of Kenya. These largely comprise the north-western and north-eastern parts of the country. Relatively moderate temperatures, are experienced in the highland and mountainous parts of the country.

Annual temperature variations are generally small (less than 5°C) throughout Kenya. The hourly temperatures, however, differ considerably between day and night. The temperature ranges between maximum and minimum vary from 6°C at the coast to 16°C in the highlands. Such a variation will have a profound effect on weathering and consequently on groundwater chemistry in Kenya.

(d) Regional Climatic Zones

So far, the discussion has been centred on the broad aspects of climatic parameters that ultimately have a major role to play in the weathering of rocks and soils and which finally influence the nature of water quality. It should be appreciated

TABLE V-11 Mean Annual T° of Selected Stations in Kenya

STATION NUMBER	STATION NAME	GEOGRAPHICAL COORDINATES		ALTITUDE	MEAN ANNUAL T°C	
		Latitude	Lontitude	Feet	Maximum	Minimum
86.35/000	Lodwar Meteorological Station	N03 07	E 35 37	1690	34.7	23.7
86.39/000	Moyale District Commissioner's Office	N03 32	E 39 03	3650	27.0	17.5
86.41/100	Mandera Meteorological Station	N03 57	E 41 52	758	34.3	23.3
88.35/001	Kitale District Commissioner's Office	N01 01	E 35 00	6200	25.0	12.0
89.35/026	Eldoret District Commissioner's Office	N00 32	E 35 16	6863	24.2	9.4
89.35/046	Ainabkoi	N00 08	E 35 31	8750	18.9	7.6
89.37/003	Isiolo District Commissioner's Office	N00 22	E 37 35	3750	30.2	16.6
89.37/022	Nanyuki Meteorological Station	N00 01	E 37 04	6386	23.5	8.5
90.34/004	Kisumu, P.C.	S00 06	E 34 45	3759	28.7	18.3
90.34/030	Kisii Seed Farm	S00 41	E 34 47	5600	26.2	13.6
90.35/001	Kericho Jamji Estate	S00 29	E 35 11	6000	27.1	9.1
90.35/069	Equator Meteorological Station	S00 01	E 35 32	9062	18.4	8.0
90.36/002	Naivasha	S00 43	E 36 26	6350	25.1	9.4
90.36/021	Nakuru, D.C.	S00 17	E 36 04	6275	26.4	10.0
90.37/007	Fort Hall, D.C.	S00 43	E 37 10	4200	26.3	13.0
90.37/112	Mwea Tebere Experimental Station	S00 38	E 37 22	3800	27.8	15.4
90.39/000	Garissa Meteorological Station	S00 29	E 39 38	420	34.3	22.5
91.35/001	Narok Meteorological Station	S01 08	E 35 50	6200	24.5	8.5
91.36/010	Nairobi Railway Station	S01 17	E 36 49	5450	24.9	13.3
91.36/018	Kiambu Dondu Estate	S01 07	E 36 52	5430	24.5	15.5
91.36/021	Limuru Togi Farm	S01 07	E 36 39	7400	21.1	9.8
91.36/025	Kabete National Laboratories	S01 15	E 36 46	5700	23.7	12.5
91.36/0567	Magadi Soda Works	S01 53	E 36 17	2040	34.8	23.[illegible]
91.36/178	Nairobi Medical Research Laboratories	S01 18	E 36 48	5655	25.9	1[illegible].[illegible]
91.37/041	Machakos School	S01 32	E 37 17	5500	25.0	1[illegible].6
91.38/000	Kitui, D.C.	S01 22	E 38 01	3860	27.2	15.[illegible]
91.38/014	Kitui Dam	S01 21	E 38 00	3860	26.5	14[illegible]
93.38/001	Voi Meteorological Station	S03 24	E 38 34	1837	30.5	19.[illegible]
93.39/009	Kilifi, Kibarani Experimental Station	S03 33	E 39 50	50	29.9	[illegible]2.[illegible]
93.40/000	Malindi D.C.	S03 13	E 40 07	10	30.2	22.[illegible]
94.39/019	Mombasa Meteorological Station	S04 03	E 39 39	54	30.1	22.[illegible]
89.34/028	Kakamega Forest Station	N00 14	E 34 25	5500	25.8	1[illegible].4
87.37/000	Marsabit	N02 19	E 37 59	4413	24.6	1[illegible].4

Source: E.A.M.D.

TABLE V-12 Highest Maximum Temperatures Recorded at Given Stations in Kenya

STATION NUMBER	STATION NAME	GEOGRAPHICAL COORDINATES		ALTITUDE		HIGHEST MAXIMUM TEMPERATURE
		Latitude	Longtitude	Feet	Metres	°F
89.35/026	Eldoret	N00 32	E 35 16	6863	2092	85.1
80.35/069	Equator Meteorological Station	000 01	E 35 33	9062	2762	75.1
90.39/000	Garissa Met. Station	S00 29	E 39 38	420	128	103.0
91.36/30	Kabete Observatory	S01 16	E 36 45	5971	1820	86.6
-	Kabondori (Embu)	S00 42	E 37 40	3750	1143	96.7
-	Kagumo (Nyeri)	S00 29	E 36 37	5900	1793	91.0
90.35/03	Kericho D.C.	S00 23	E 35 17	6500	1982	93.0
93.39/009	Kibarani (Kilifi)	S03 33	E 39 50	50	15	99.0
90.34/04	Kisumu Town	S00 06	E 34 45	3759	1146	98.4
91.36/37	Kiambu	S01 13	E 36 50	5700	1738	89.0
88.35/08	Kitale	N01 01	E 35 01	6200	1890	89.5
92.40/01	Lamu Meteorological Sta.	S02 16	E 40 54	30	9	95.0
92.37/00	Makindu Met. Station	S02 17	E 37 50	3280	1000	95.7
93.40/00	Malindi D.C.	S03 13	E 40 07	10	3	97.1
84.41/000	Mandera Met. Station	N03 57	E 41 52	758	231	104.0
-	Masara	S01 01	E 34 15	4000	1219	99.0
94.39/00	Mombasa Kilindini Port	S04 03	E 39 39	640	19	96.0
86.39/00	Moyale D.C.	N03 32	E 39 03	3650	1113	95.3
91.30/10	Nairobi Station	S01 17	E 36 50	5450	1661	89.9
90.36/02	Naivasha D.C.	S00 43	E 36 26	6234	1901	90.6
90.36/20	Nakuru Station	S00 17	E 36 04	6070	1851	92.9
-	Nanyuki	N00 01	E 37 04	6389	1948	83.6
91.35/01	Narok Met. Station	S01 08	E 35 50	6200	1890	89.8
91.37/18	Thika D.C.	S01 03	E 37 04	4900	1494	91.0
93.38/01	Voi	S03 24	E 38 34	1837	560	99.1

Source: E.A.M.D.

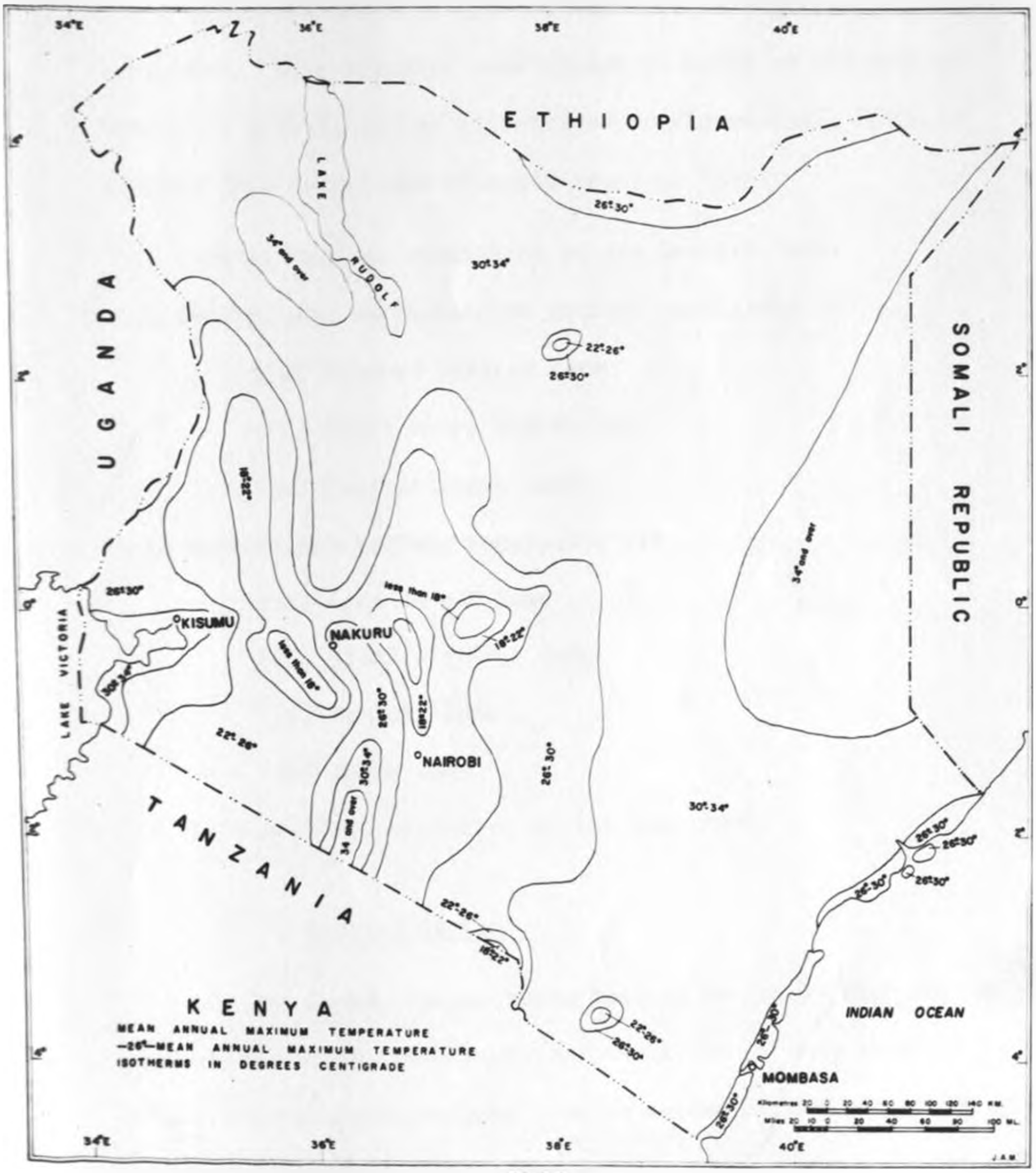

KENYA
MEAN ANNUAL MAXIMUM TEMPERATURE
—26°—MEAN ANNUAL MAXIMUM TEMPERATURE
ISOTHERMS IN DEGREES CENTIGRADE
ETHIOPIA
SOMALI REPUBLIC
UGANDA
TANZANIA
LAKE RUDOLF
LAKE VICTORIA
INDIAN OCEAN
KISUMU
NAKURU
NAIROBI
MOMBASA
34° and over
30°-34°
26°-30°
22°-26°
18°-22°
less than 18°
34 and over
30°-34°
Kilometres 20 0 20 40 60 80 100 120 140 KM.
Miles 20 10 0 20 40 60 80 100 ML.
34°E
36°E
38°E
40°E
4°
2°
0°
2°
4°
J.A.M.

FIG. 2.16

that the interpretation of the characteristic water components will very much reflect the spatial variation of climate. It is in this regard, that a systematized regional climatic description based mainly on the rainfall and temperature characteristics is essential. This climatic subdivision is based on the work of Griffiths (1958), and as illustrated on Figure 5-17, Kenya is divided into four broad climatic regions, namely :-

1. Coastal Region, consisting of the Coastal Zone.
2. Central and North-Eastern Region, consisting of:
    - (2a) Mandera Garissa Zone
    - (2b) Mount Kenya Slopes Zone
    - (2c) Central Kenya Zone
3. Rift Valley Region, consisting of:
    - (3a) Lake Rudolf Zone
    - (3b) Kitale-Kericho Zone
    - (3c) Nanyuki Zone
    - (3d) Narok Zone
4. Lake Region, consisting of the Lake Zone.

1. Coastal Region

On the Coast, temperatures tend to be fairly high during the day and night, with a diurnal variation of only about 7° to 9°C. Afternoon temperatures usually exceed 30°C during January to March, and night temperature at this time of the year may not fall much below 25°C. The coolest months are July and August, when the afternoon temperatures are about 28°C and the night temperatures may be as low as 20°C. The wettest months are April and May and the driest January and February. In the extreme

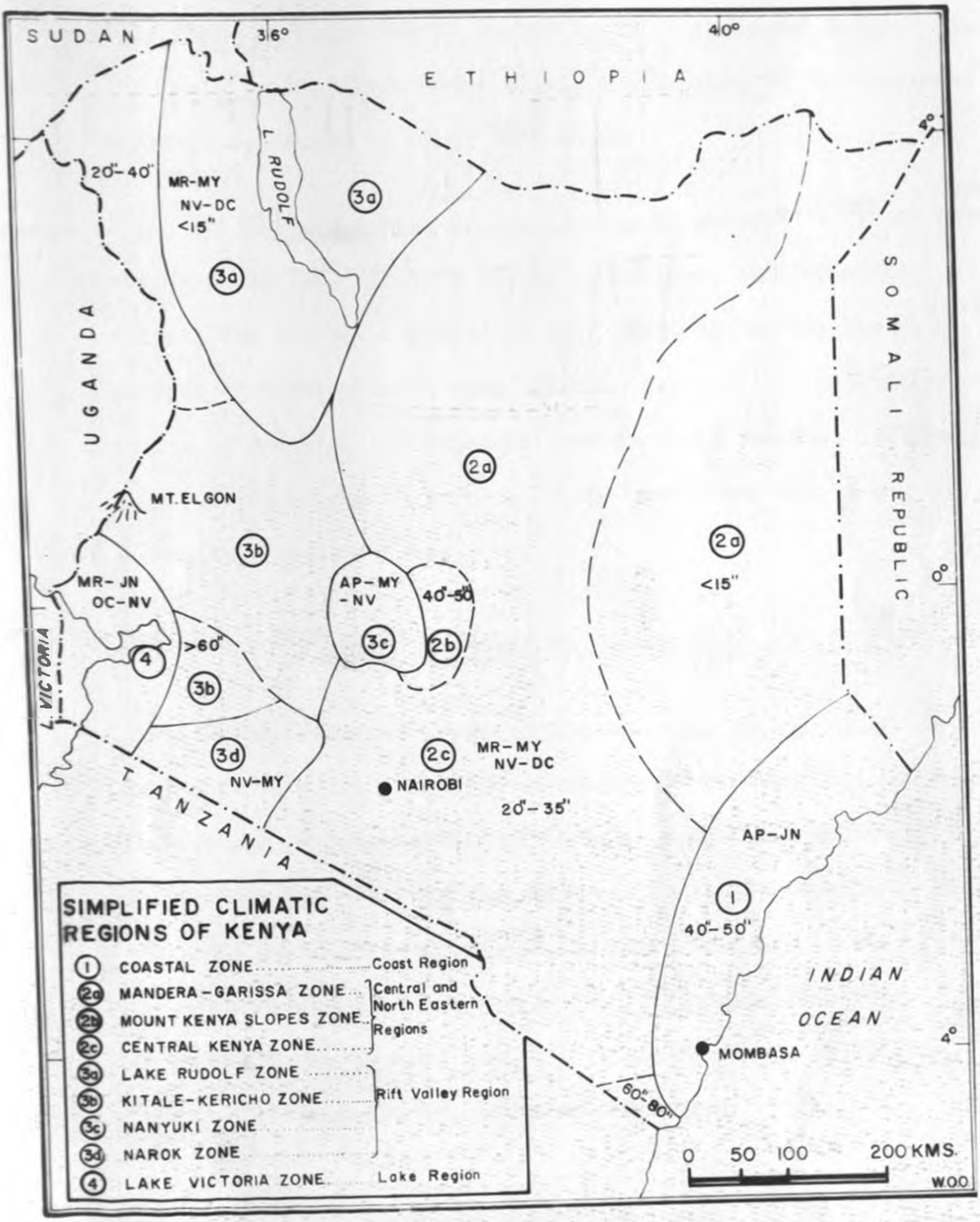

SUDAN
36°
40°
ETHIOPIA
3°
L. RUDOLF
20"-40"
MR-MY
NV-DC
<15"
3a
3a
UGANDA
SOMALI REPUBLIC
2a
2a
<15"
MT. ELGON
3b
MR-JN
OC-NV
AP-MY
-NV
40"-50"
3c
2b
0°
L. VICTORIA
4
>60"
3b
3d
NV-MY
2c
MR-MY
NV-DC
NAIROBI
20"-35"
TANZANIA
AP-JN
1
40"-50"
INDIAN OCEAN
4°
MOMBASA
60"-80"
0 50 100 200 KMS.
W.O.O.
SIMPLIFIED CLIMATIC REGIONS OF KENYA
① COASTAL ZONE .... Coast Region
2a MANDERA-GARISSA ZONE ...
2b MOUNT KENYA SLOPES ZONE ..
2c CENTRAL KENYA ZONE .... Central and North Eastern Regions
3a LAKE RUDOLF ZONE ....
3b KITALE-KERICHO ZONE ....
3c NANYUKI ZONE ....
3d NAROK ZONE .... Rift Valley Region
④ LAKE VICTORIA ZONE .... Lake Region

FIG. 5.17

north, Lamu, enjoys annual rainfall of about 35 inches a year. This rises to well over 50 inches in the area around Vanga. From the humid coast, where annual means are between 30 and 50 inches, rainfall decreases to about 50 inches.

The Taita District in the Coastal hinterland is rather hot and dry. At Voi, altitude nearly 2,000 feet, and 100 miles inland, the average rainfall is only about 500 mm per annum, whereas at Mombasa it is over 1000 mm. Considerably more rain occurs in November and December than in April and May. Afternoon temperatures may be as high as on the coast, but the nights are generally somewhat cooler.

2. Central and North-Eastern Region

The daily range of temperature of this area is about 15°C during the hot dry season (Mid-December to Mid-March). The main rain season is from Mid-March until the end of May and there is a secondary rainy season from Mid-October to Mid-December. In the parts of the Eastern Region, however, November is usually the wettest month~~s~~ of the year. Rainfall varies from over 40 inches in the Central Region to less than 15 inches in the Eastern and North-Eastern parts of the Region.

2a. Mandera - Garissa Zone

Although having rains in the period, March to May and at the end of the year is greatly influenced by the relatively dry, warm air sweeping down from Ogaden, amounts are correspondingly lower, being less than 15 inches in general and below 5 inches around Wajir. In the north, the months of June to August are almost completely dry but near Garissa some rain is recorded in all months.

The principal features of this region include high temperatures, low and extremely erratic rainfall. Most areas in this zone experience mean annual temperatures of 80°F or more except the higher spots such as Moyale and the area close to the highland fringe. The real problem of this zone is the unreliability of rainfall. Over the greater part of the area, rainfall is likely to fall below 30 inches in at least 30 of every 100 years.

On the whole temperatures are a little above those at sea levels and reach mean annual temperatures in the upper eighties. Diurnal variation is about 20°F. Relative humidity is low, at about 60 per cent and evaporation is high being nearly 100 inches per year at Mandera.

2b. Slopes of Mount Kenya Zone

Like Central Kenya, this zone, because of the proximity of the mountain and the corresponding ascending currents, rainfall is greater. The annual average is between 40 inches and 55 inches with the rainy season beginning in Mid-October. The mean annual maximum and minimum temperature for the area is about 18°C and 6°C respectively.

2c. Central Kenya Zone

The region experiences double maxima of rainfall with the average annual fall of about 20 to 35 inches, with July as the driest month with less than 1 inch. Rainy days number from 70 to 100 but in the Naivasha-Nakuru belt, this can increase to 130. The amount and frequency of rain is largely governed by altitude, rainfall generally increases up to about 8,000 feet and then gradually decreases. At Nairobi the average annual rainfall is about 875 mm.

Temperatures vary from 56° to 73°F but are nearly constant at 83°F when reduced to sea level. Diurnal variation is about 20°F. Except in the extreme north, mean monthly temperatures vary by about 8°F. Relative humidity is about 2.5 mm per day and 35 inches per year.

3. Rift Valley Region

Many of the healthiest areas are found in the Kenya Highlands which form the Central part of the Rift Valley Region. At altitudes above 6,000 feet, there is quite a large diurnal range of temperature, sometimes over 20°C during the hot, dry season.

The rainfall in the highlands is generally over 1,000 millimetres in the Kericho District but parts of the Rift Valley itself, for example, Naivasha, are rather dry. In the western districts, Trans-Nzoia and Uasin Gishu, the main rainy season is from April to September with August as the wettest month. Further east and south, April becomes the wettest month, with other slight maxima in August and November. In all cases, January is the driest month.

3a. Lake Rudolf Zone

Rainfall is less than 15 inches over the whole zone with a minimum of about 6 inches in the central lake area. The variation in the annual amounts is quite large and the time of the fall is quite unpredictable. March, April and May are normally the rainy months, but there is a secondary maxima in the November-December period. Heavy rains can occur in July and August and in all the rainfall picture is a very unsettled one. Falls of 1.5 inches to 2 inches per day can be recorded and there are about 20 rainy days per year.

March, with a mean monthly temperature of 87°F, is the hottest month, while the August mean of 82°F is the coolest. Although the mean annual range is small the diurnal range of 20°F is high. The relative humidity is low, generally averaging 45 per cent.

3b. Kitale - Kericho Zone

With exception of the northern part of the zone where the rainfall is less than 40 inches, this is a high rainfall zone, with a range of about 40 to 75 inches. Around Kericho, the rainfall is about 60 to 70 inches, with a range of 50 to 95 inches. Most of the months from March to October have over 5 inches of rain, but as in the main part of the zone, January is dry. Here, there are 200 rainy days in a year. To the west of the zone around the

Kisii Highlands a north to south-west air flow causes orographic precipitation, so that over 2 inches of rain falls in each month. In the rest of the area, the fall is somewhat less and is in the order of 40 to 50 inches with a range of 20 to 60 inches. January with less then 1 inch is a dry month. There are 100 to 150 rainy days per year and the rainy period usually has falls exceeding 5 inches per month.

The diurnal variation of temperature is of the order of 30°F and the relative humidity is of the order of 50 per cent, surprisingly low for such a moist zone.

3c. Nanyuki Zone

This small zone lies to the west of Mount Kenya and covers about 400 square miles. There are two periods of rain, April to May and August to November. Over one-sixth of the annual rainfall of 25 inches to 30 inches comes in April but amounts exceeding 5 inches are unusual. The range is about 20 to 40 inches and there are about 110 rainy days per year. This is in excess of the number that would normally be expected from such rainfall.

The diurnal range is about 25°F to 30°F and the relative humidity is about 60 per cent.

3d. Narok Zone

This is a zone of about 2,000 square miles around Narok, extending downwards towards Lake Eyasi in Tanzania. Rain falls mainly during November to May with an annual average of 25 to 30 inches. The variation is very large and annual amounts of 10 to 50 inches can occur. During June to October, falls mostly total about one inch. About 100 rainy days are recorded each year. The average relative humidity is 60 per cent. It can get very hot from October to April in the low lying areas and Magadi (2010 feet) frequently records temperatures of over 40°C with night temperatures not falling much below 25°C.

4. Lake Region

The region which covers parts of south-western and north-western areas of Kenya, has varying conditions from the hot and relatively low lying plains north and south of Kisumu, where the annual rainfall is only about 1000 millimetres to the hills of Kakamega and Kisii, where the nights are cool, with relatively moderate temperatures with annual rainfall of over 1750 mm.

The wet and dry seasons are not very much marked but rainfall occurs in two periods, March to June, and October to November and there is no really dry month.

Owing to the proximity of Lake Victoria, there is little variations in mean monthly temperature, only about 4°F but from October to March the maximum afternoon temperature at Kisumu often exceeds 30°C.

The relative humidity at Kisumu is about 62 per cent.

2. SURFACE WATER HYDROLOGY

"Strictly speaking, hydrology is the science of water, although by usage the word has come to mean the water as it occurs on, over and under the earth's surface as stream flow, water vapour, precipitation soil moisture, and groundwater." (Ward, 1967). An attempt is made in this section to describe and explain the hydrology of Kenya. This is necessary in order to provide information on the various hydrological components which may throw light onto the state of groundwater resources of the country and the factors governing its occurrence, distribution and quality.

"Often, there is too little water for man's needs. Sometimes there is too much; Some regions have abundant lakes and rivers and other areas are practically devoid of water. What causes floods and drought and why water is so unevenly distributed over the earth, may be attributed to the factors governing the hydrologic cycle. Geological factors, soils and vegetation influence the distribution of water, but it is mainly the weather and climate that form and sustain lakes and rivers, create deserts, produce floods and droughts". (U.N.D.P., 1968).

Kenya experiences a wide variation in climate due to great differences in altitude. Along the coastline lies a narrow tropical belt behind which stretch large areas of semi-arid and arid conditions. The land then rises steeply to the temperate highlands through which runs the Rift Valley with its many extinct volcanoes. In a country of such extremes, water is often in short supply and hence the importance of this study.

Kenya is fortunate in that it possesses extensive groundwater resources which, with the exception of the Nairobi area where conservation measures have been implemented as a result of preliminary work of Gevaerts (1957), are underdeveloped. The mean water table is about 78 m below the surface, which is considerably deeper than that generally obtained in other parts of Africa. The subject of underground water which is the main concern of this study is examined in detail in Chapter Six and Seven.

a. Surface Water Drainage Systems

The drainage system of Kenya to-day, is governed by the Rift Valley, running north to south from the Mediterranean Sea in the north to Lake Malawi in the south. Its average width is about 64 Km. From the flanks of the Rift Valley, water flows westwards to Lake Victoria and eastwards to the Indian Ocean. Within the Rift Valley are internal drainage networks.

Kenya is divided into five main drainage areas and these include:

I. Lake Victoria drainage area
II. Rift Valley drainage area
III. Athi River drainage area
IV. Tana River drainage area
V. Ewaso Nyiro drainage area

NB/ Ngiro & Nyiro → different!
No difference – they mean the same thing!!

Table V-13 gives the drainage basins and their approximate areas. The enumerated drainage areas are shown in Figure 5-18. Hydrometric stations in each of the drainage areas for measuring and recording of data to provide information on which the development of water resources can be planned are operated by the Hydrology Section of the Water Department and these are shown in Table V-14.

I. Lake Victoria Drainage Area

This drainage area comprises the whole areas west of the Rift Valley which drains into Lake Victoria and Lake Kioga. The lake basin receives a good rainfall which is well distributed over the area. It is in fact, the only area where rainfall is consistent from the watershed of the catchment to the outfall of the river system.

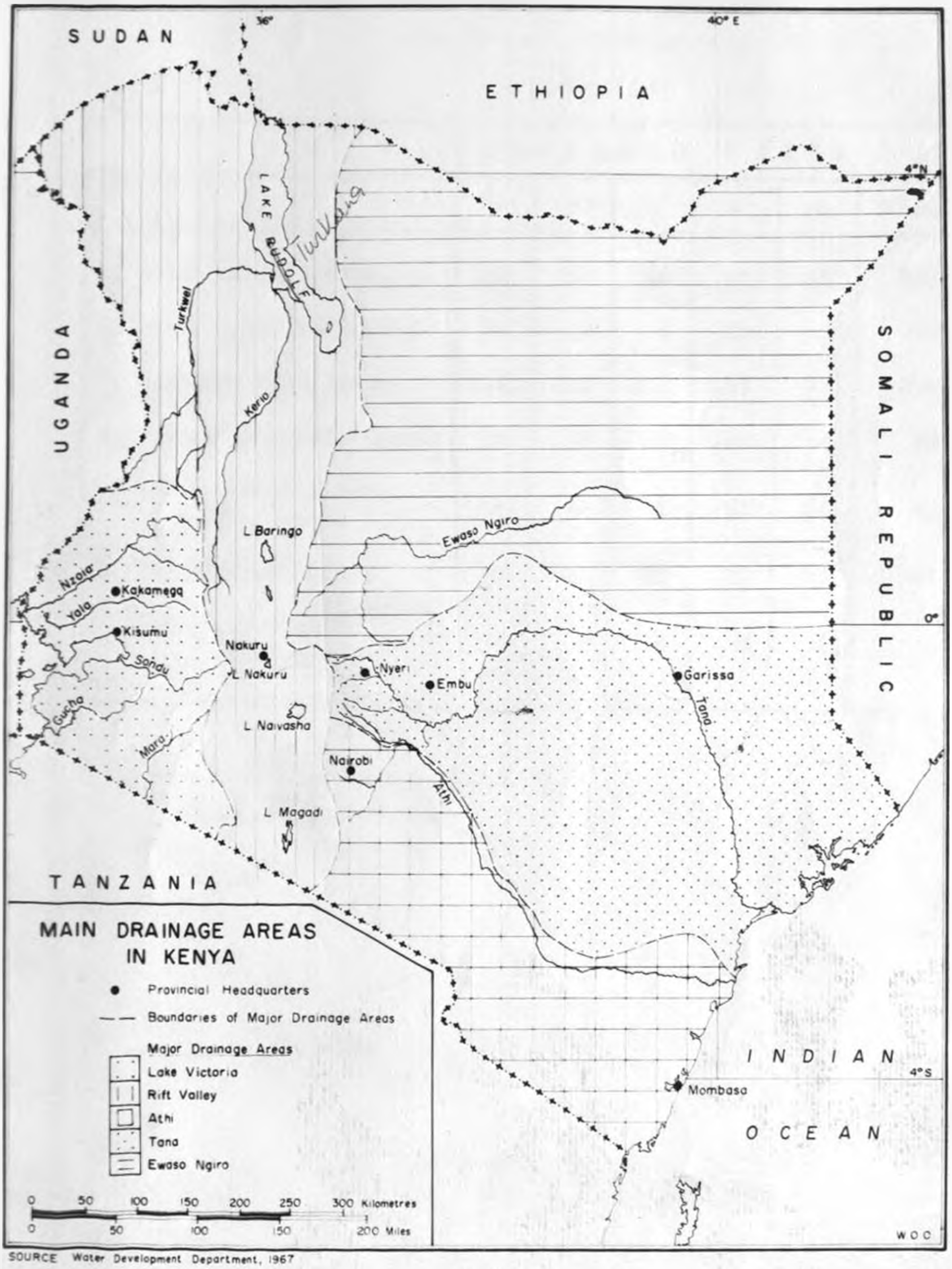
Kyoga

For efficient development of water resources it is useful to know the total amount of water available for various uses. The variability of this amount is almost as important as its average value. The water resources of this drainage area consist of many perennial rivers and the lake itself. Details of expected annual yields of rivers on Lake Victoria catchment area are given on Table V-15. The data in this table highlight the difference in runoff contributions per unit area of land between the different portions of the basin.

TABLE V-13 Drainage Basins and Approximate Area

Drainage Area	Approximate Area		Percentage of Total area of Kenya
	Sq.ml.	Sq.km.	
1. Lake Victoria	19,000	49,000	8.4
2. Rift Valley	49,000	127,000	21.8
3. Athi River	27,000	70,000	12.0
4. Tana River	51,000	132,000	22.7
5. Ewaso Ngiro	79,000	205,000	35.1

Source: CEGE (1968)



SOURCE Water Development Department, 1967

FIG. 5.18

TABLE V-14 *Hydrometric Stations in Kenya (1968)

	DRAINAGE AREA					
	1	2	3	4	5	TOTAL
1. River Gauging Stations	101	57	66	95	42	361
2. Water Level Recorders	11	2	6	15	8	42
3. Standard Rain Gauges	224	150	220	161	73	828
4. Autographic Rain Gauges	16	8	12	14	4	54
5. Storage Rain Gauges (Mt. Kenya)	-	-	1	21	20	42
6. Evaporation Pans	22	13	22	15	9	81
7. Full Hydro-Metric Stations	4	2	6	6	2	20

*Include those run by E.A.M.D.

Source: CEGE (1968)

TABLE V-15 DETAILS OF EXPECTED ANNUAL YIELDS OF RIVERS IN LAKE VICTORIA CATCHMENT AREA

RIVER	LOCATION	CATCHMENT AREA	MEAN ANNUAL FLOW (A)	LOW YEAR FLOW (B)	DERIVATIONS (A)	DERIVATIONS (B)
		sq.mls.	acre-feet	acre-feet		
(a) Nzoia Yala Area						
1. Nzoia	Broderick Falls	3,295	937,000	424,500	8 years of records	Record of low year*
2. Nzoia	Luambwa Fery	4,930	2,000,000	900,000	Comparison of 3½ years of records with 1(A)	By comparison with 1(B)
3. Yala	Abom Bridge	1,069	576,000	290,000	8½ years of record	Recorded low year*
(b) Central Nyanza Lake						
4. Nyatome	Asembo	12.5	6,250	2,700	500 acre feet/ sq.ml.	45% of A
5. Awach	Kombawa	32.0	16,000	7,200	- " -	45% of A
(c) Kano Plains						
6. Kibos	Kisumu Waterworks Intake	44	24,000	11,000	23 years of records	Probability
7. Nyando	Ahero	1,050	300,000	102,500	8 years of records	Recorded low year*
8. Cherongil	Near Rai	119	6,200	2,700	Partial records of 3 years	All low years*
9. Awach	Awach mkt Near Rae Girls'					
(d) South Nyanza						
9. Sondu	Sondu T.C.	1,006	810,000	203,000	8 years of records	Recorded low year*
10. Awach (N)	Kendu	199	100,000	45,000	500 acre feet/ sq.ml.	45% of (A)
11. Kuja	Mc Calder Mine	1,150	273,000	121,000	Existing records	Recorded low year*

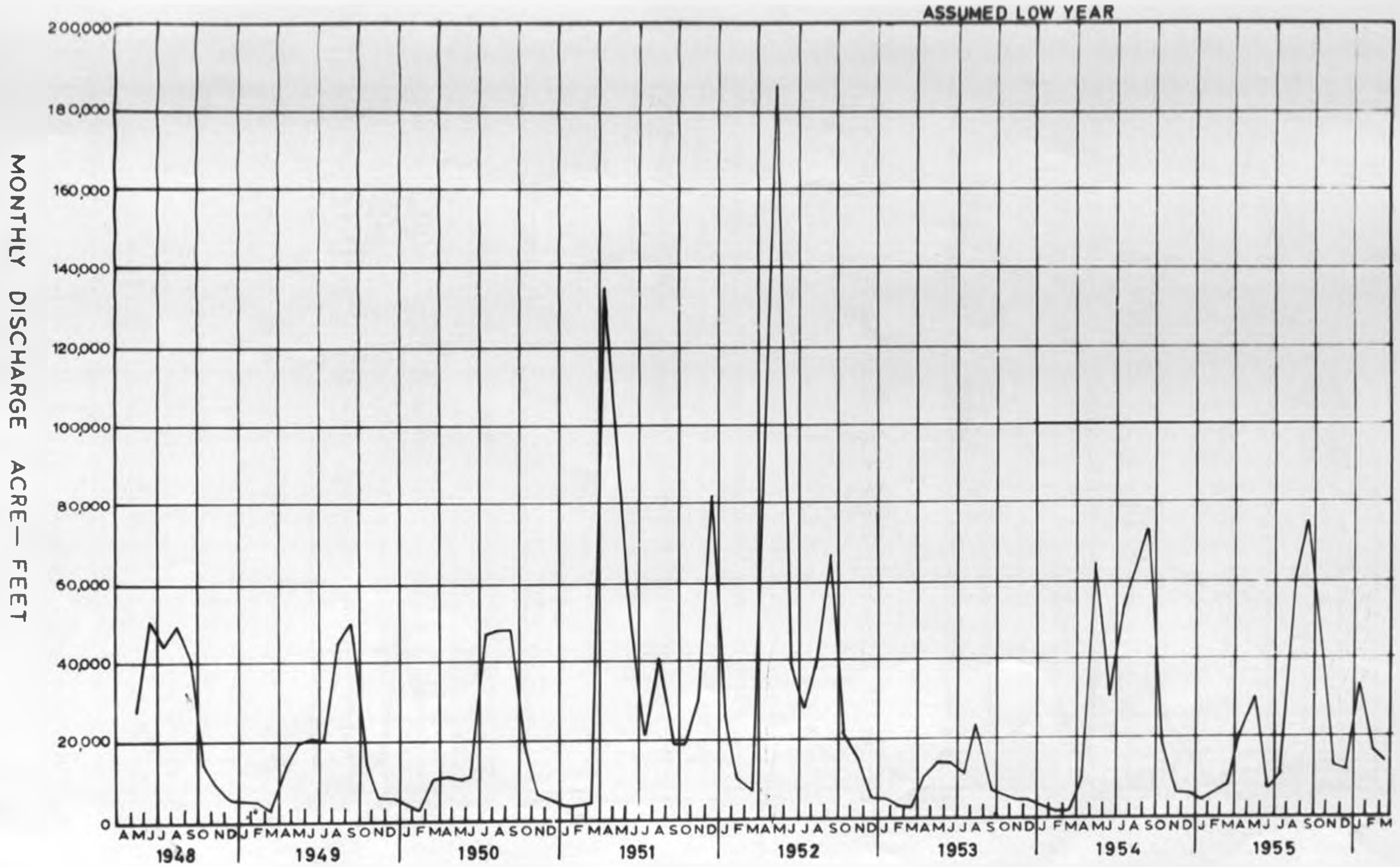
*All low year records taken during "water year" April 1953 to March 1954

Source: Sir Alexander Gibb and Partners (1956)

For efficient planning of river water the annual regime of the rivers is quite important for the discharge of the rivers (as indicated in Figures 5-19, 5-20, 5-21 as given by Sir Alexander Gibb and Partners (1956), for Nyando, Kibos and Sondu Rivers respectively, and Figures 5-22, 5-23, 5-24 for Nzoia River at Webuye Broderick Falls, Mumias and Ukwala respectively, as shown by UNESCO (1971)) varies from season to season, from year to year and finally from one river to the other. Such variability increases the difficulty of planning the most efficient use of river water. The variability is mainly due to rainfall. Any particular year may have one or two periods of high water at the time of long and short rains. Occasional years have no high water season, where both the long and short rains fail.

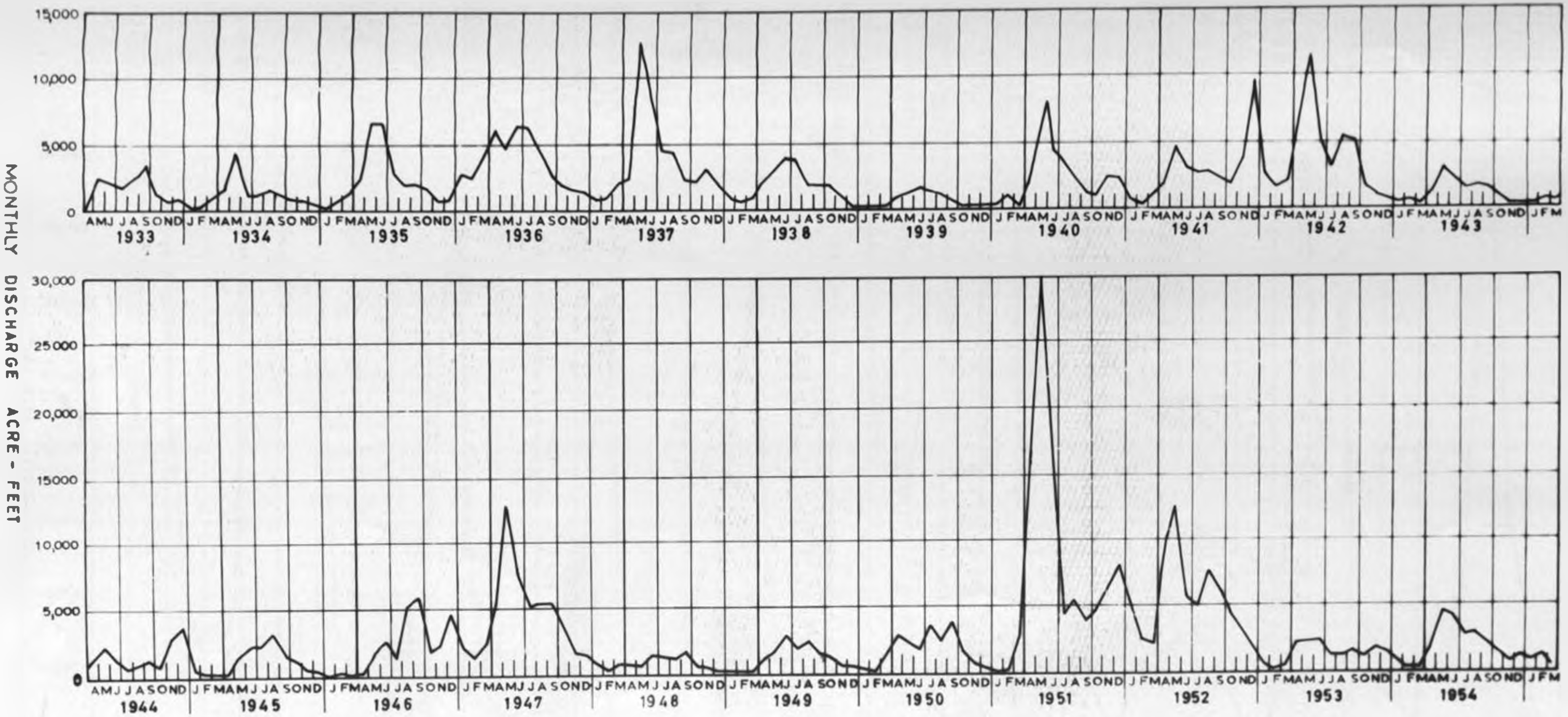
As may be noted from Figure 5-19, records of Nyando River flow at Ahero have been kept since May, 1948. The period is not long enough to permit a mathematical analysis of flow probabilities. In consequence, it has been assumed that a "low year" flow might approximate to the values of flow which were recorded in the year between April, 1953 and March, 1954. This period of twelve months contains the lowest flows recorded over the years of record for 8 of the 12 months, and for the other months the actual flows are still fairly close to the lowest recorded values.

Figure 5-20 gives the monthly discharge of the Kibos River at Kisumu Water Supply Intake Works since 1933. Figure 5-21 gives the characteristics of monthly flows of the Sondu River near



Hydrograph of Nyando River at Ahero

FIG. 5.19



Hydrograph of Kibos River Kisumu Water Supply Intake Works

FIG 5 20

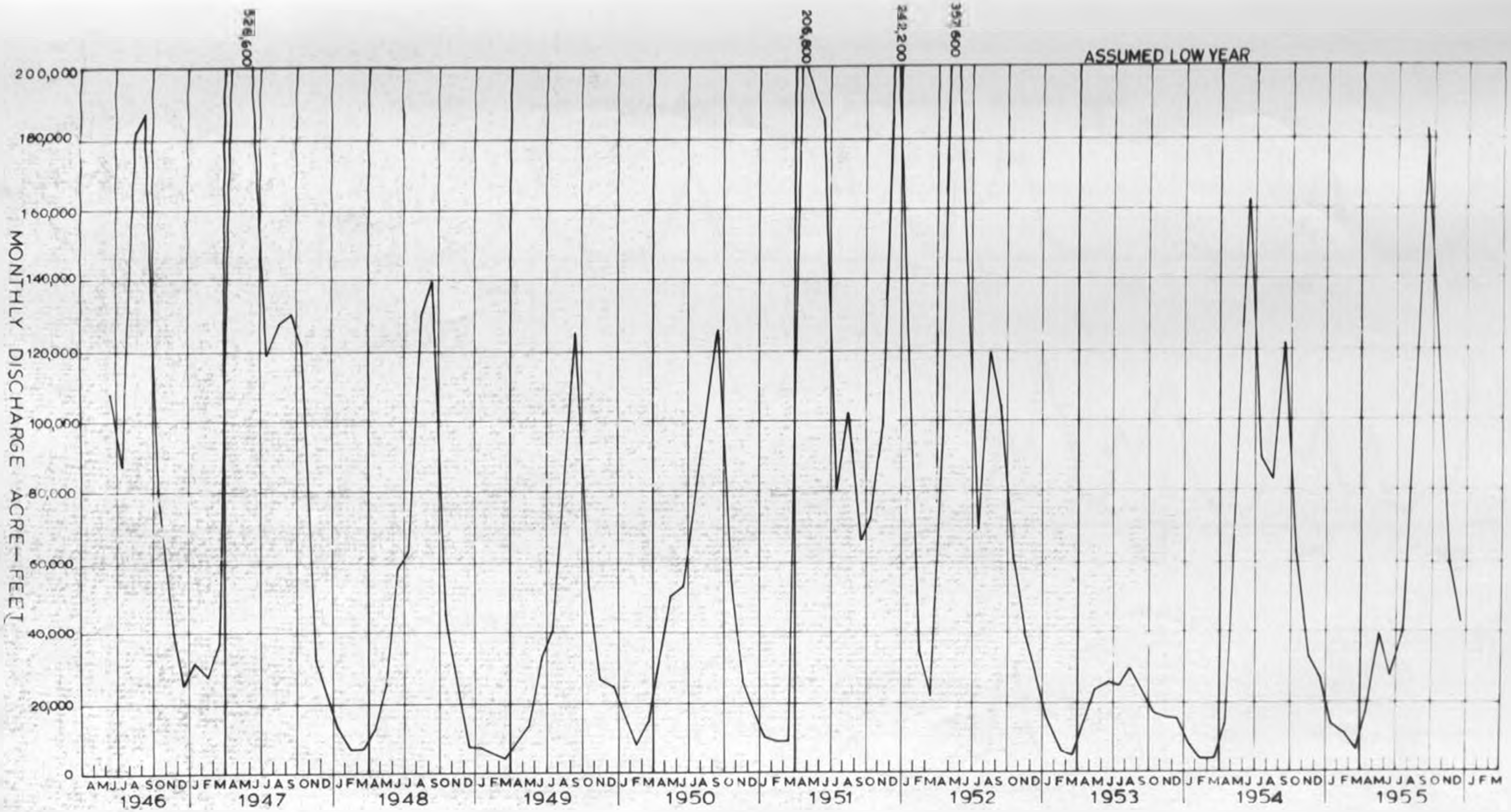


FIG 5 21 Hydrograph of Sondu River at Sondu Village

Variation of Average Monthly Discharge of the Nzoia River at Broderick Falls.

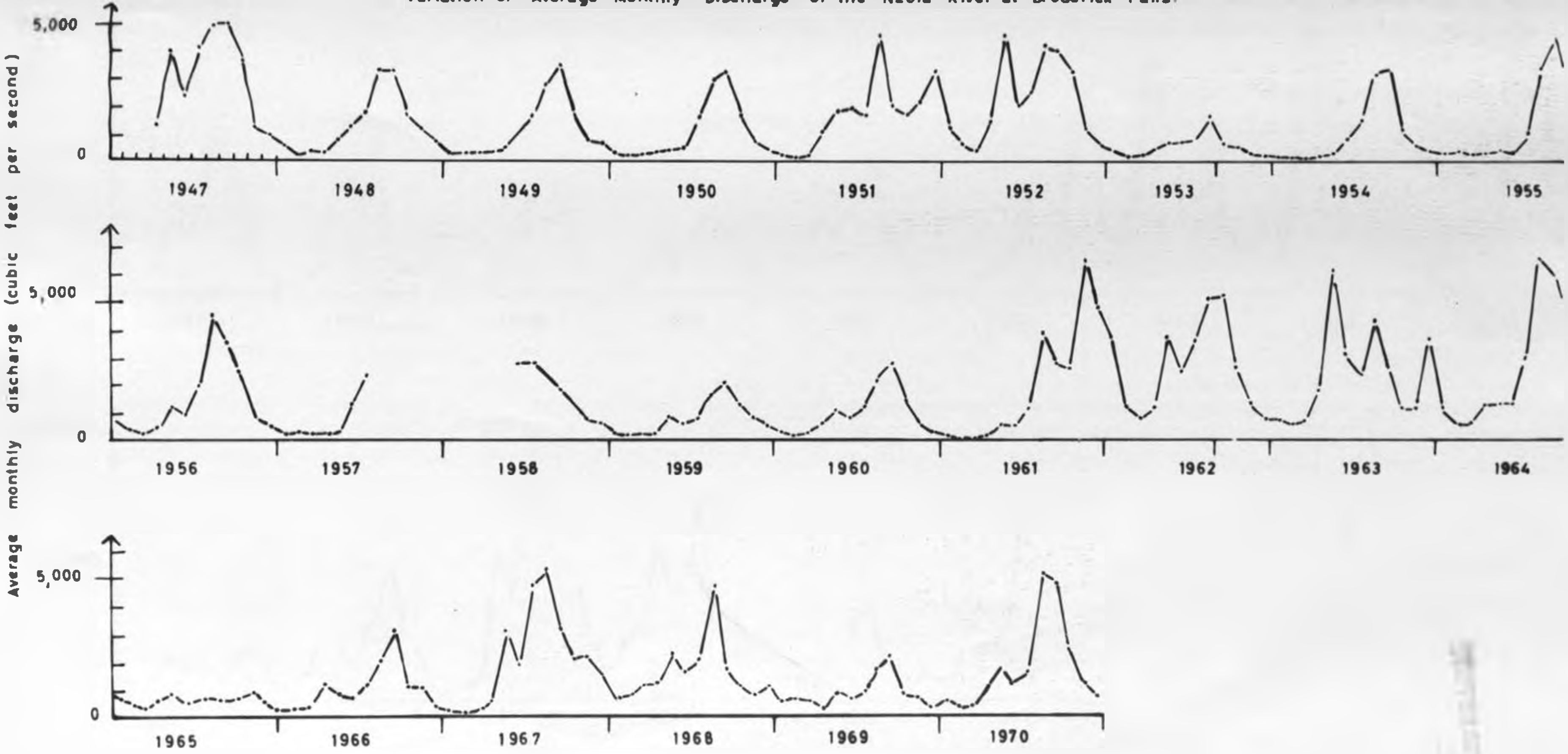
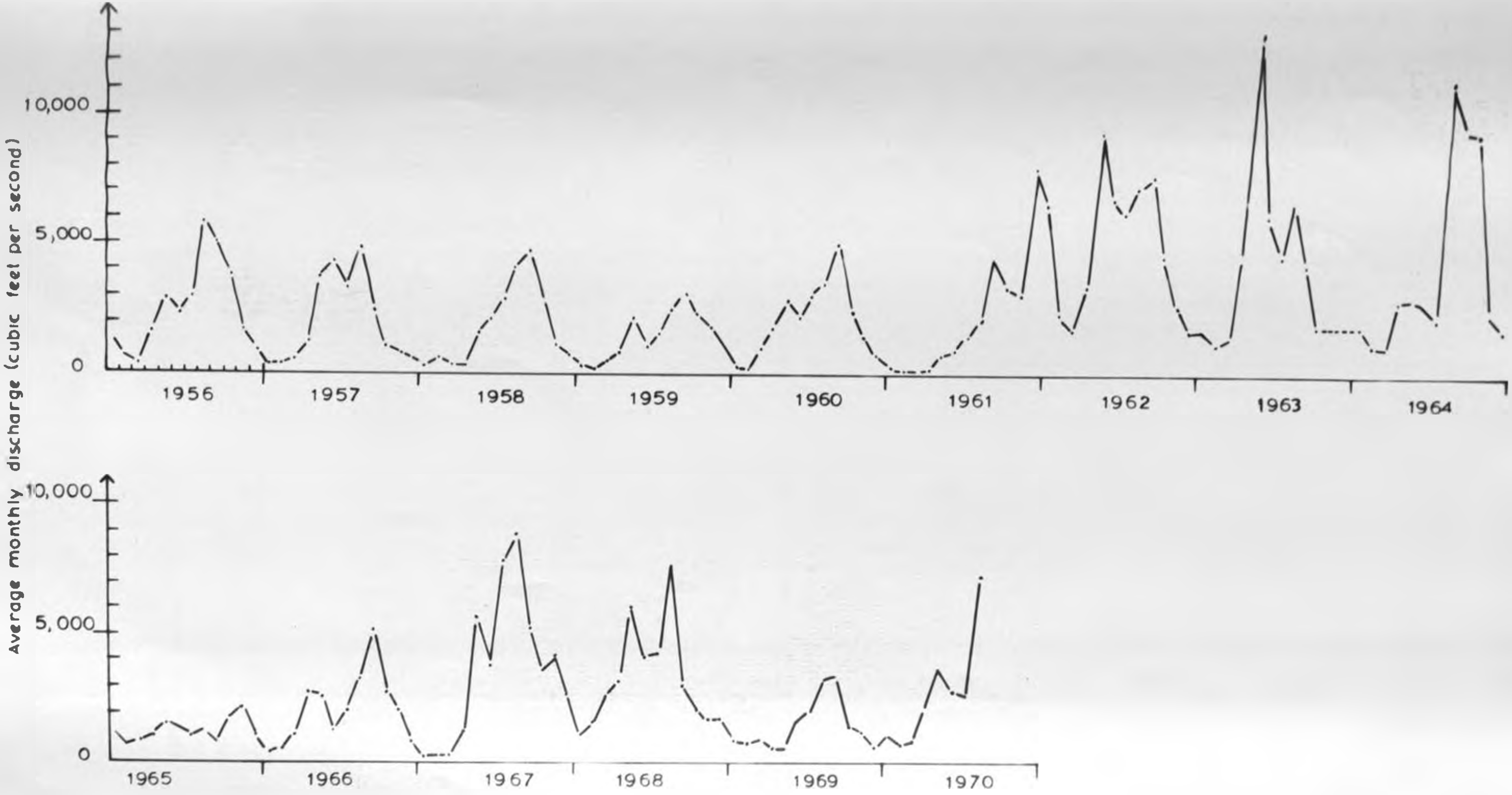


FIG 5.22



Variation of average Monthly Discharge of the Nzoia River at Mumias

FIG 5.23

Variation of Average Monthly Discharge of the Nzoia River at Nzoia Village (Ukwala)

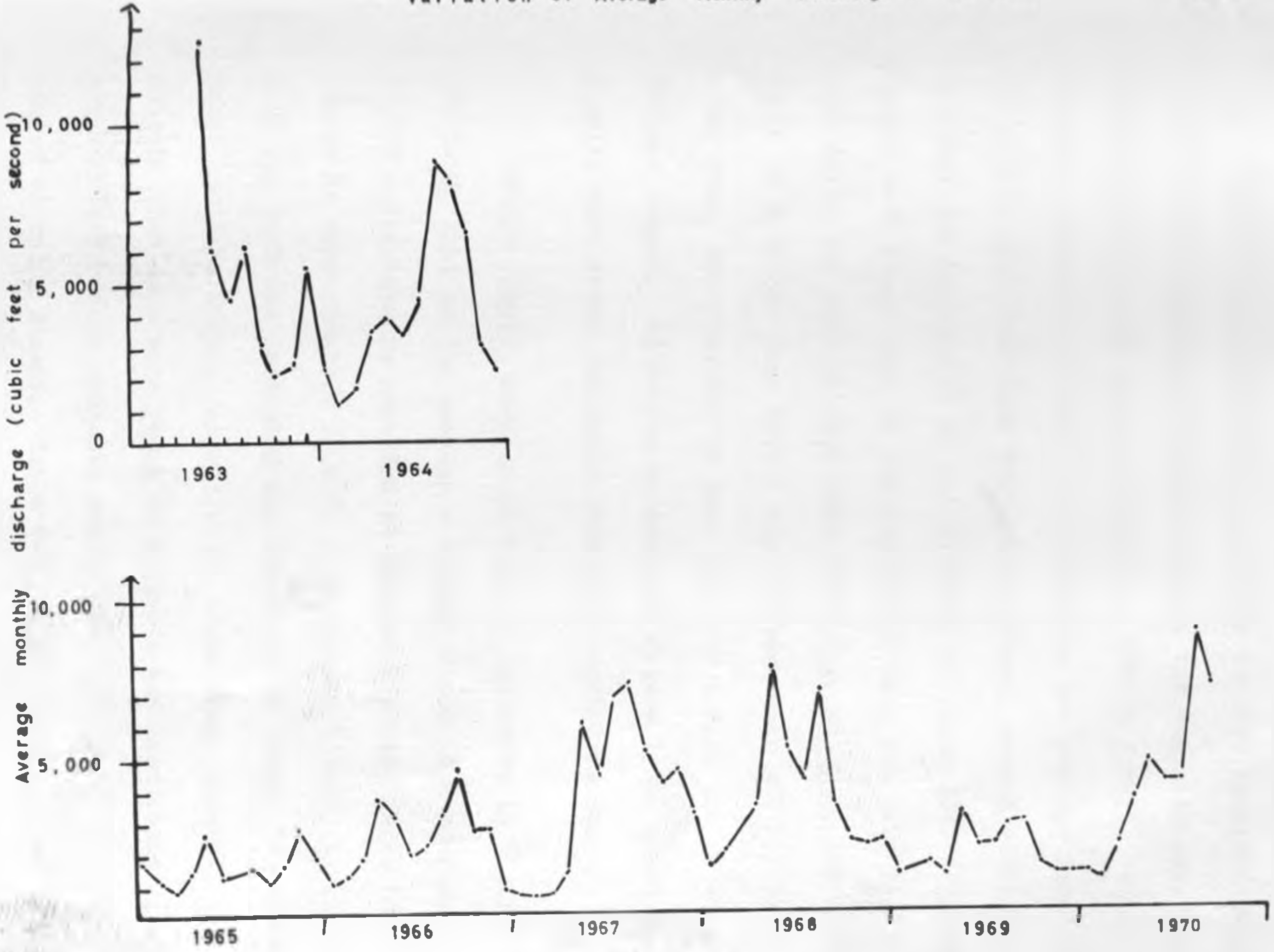


FIG. 5.24

Sondu Village while Figures 5-22, 5-23 and 5-24 represent the flow pattern of the Nzoia River at Broderick Falls Webuye, Mumias and Ukwala Village respectively.

Figures 5-25 and 5-26 present the average recorded extreme flow duration curves of the Nzoia River for two stations, i.e. Broderick Falls and Mumias as given by UNESCO (1971). Flow duration curves are useful for indicating the average length of any period with flow less than some critical amount which may be required for irrigation or for dilution of industrial effluents. Figure 5-25 shows that on the average 12 days per year have a mean daily low flow of less than 200 c.f.s. at Broderick Falls while 45 days per year have a flow of less than 400 c.f.s. In a dry year, the flow may be less than 200 c.f.s. for 82 days and perhaps longer. At Mumias as shown in Figure 5-26, there is usually more water available than at Broderick Falls.

UNESCO (1971), have shown that as indicated in Figures 5-27 and 5-28, that on the average a 10-year flood of approximately 13,000 c.f.s. can be expected at Broderick Falls, while that at Mumias is approximately 22,000 c.f.s. Grundy (1963), in Figures 5-29 and 5-30 has indicated the frequency of annual floods for the Nzoia and Yala Rivers respectively. From these figures, it is evident that many more years of accurate and continuous records, are required before reliable estimates can be made of the recurrence period of major floods. Table V-16, gives the computed values of expected flood flows on the Nyado, Kibos and Cherongil Rivers as given by Sir Alexander Gibb and Partners (1956). These values are based upon probable maximum 24-hour rainfall and the characteristics of

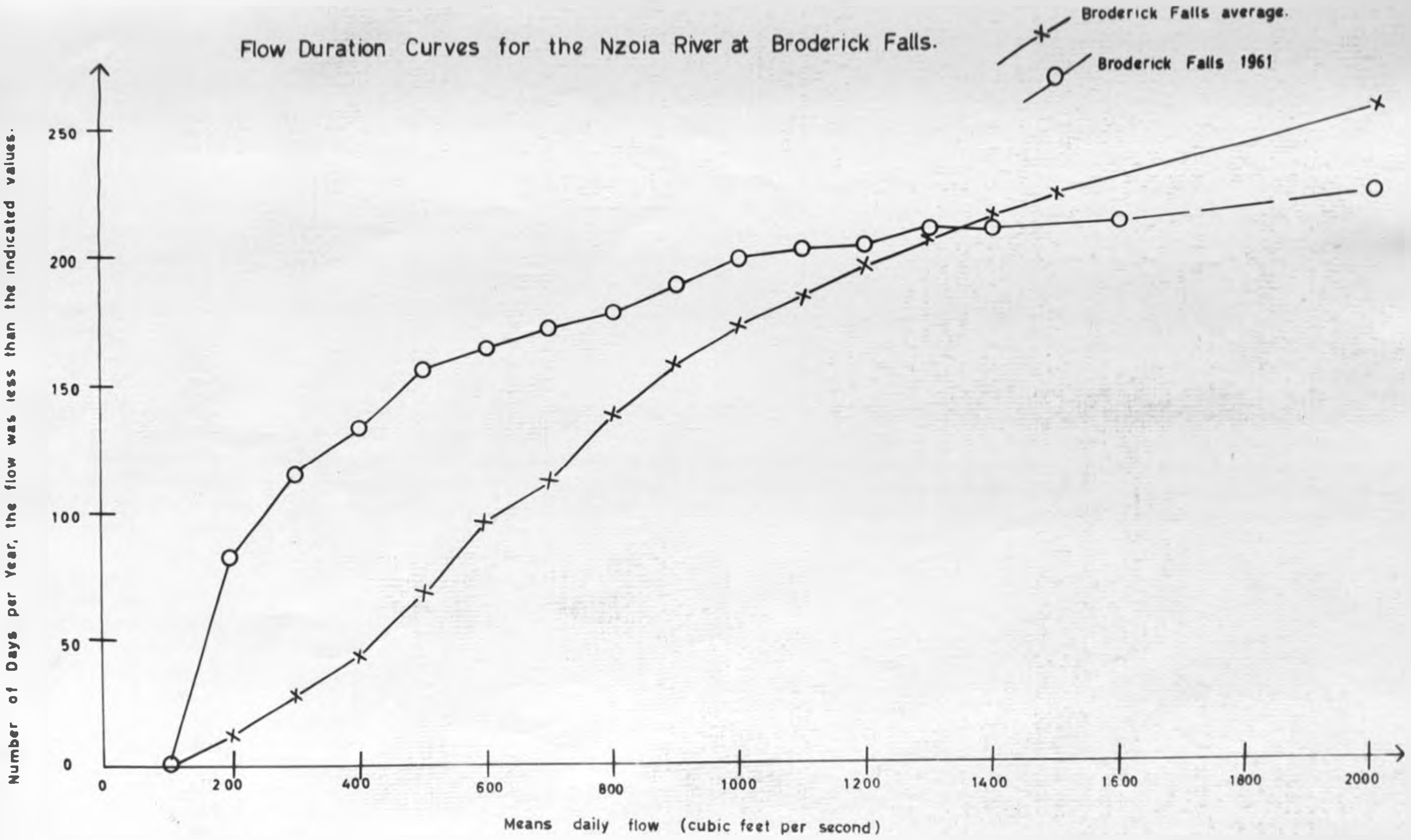

Flow Duration Curves for the Nzoia River at Broderick Falls.

FIG 5 25

Flow Duration curves for the Nzoia River at Mumias.

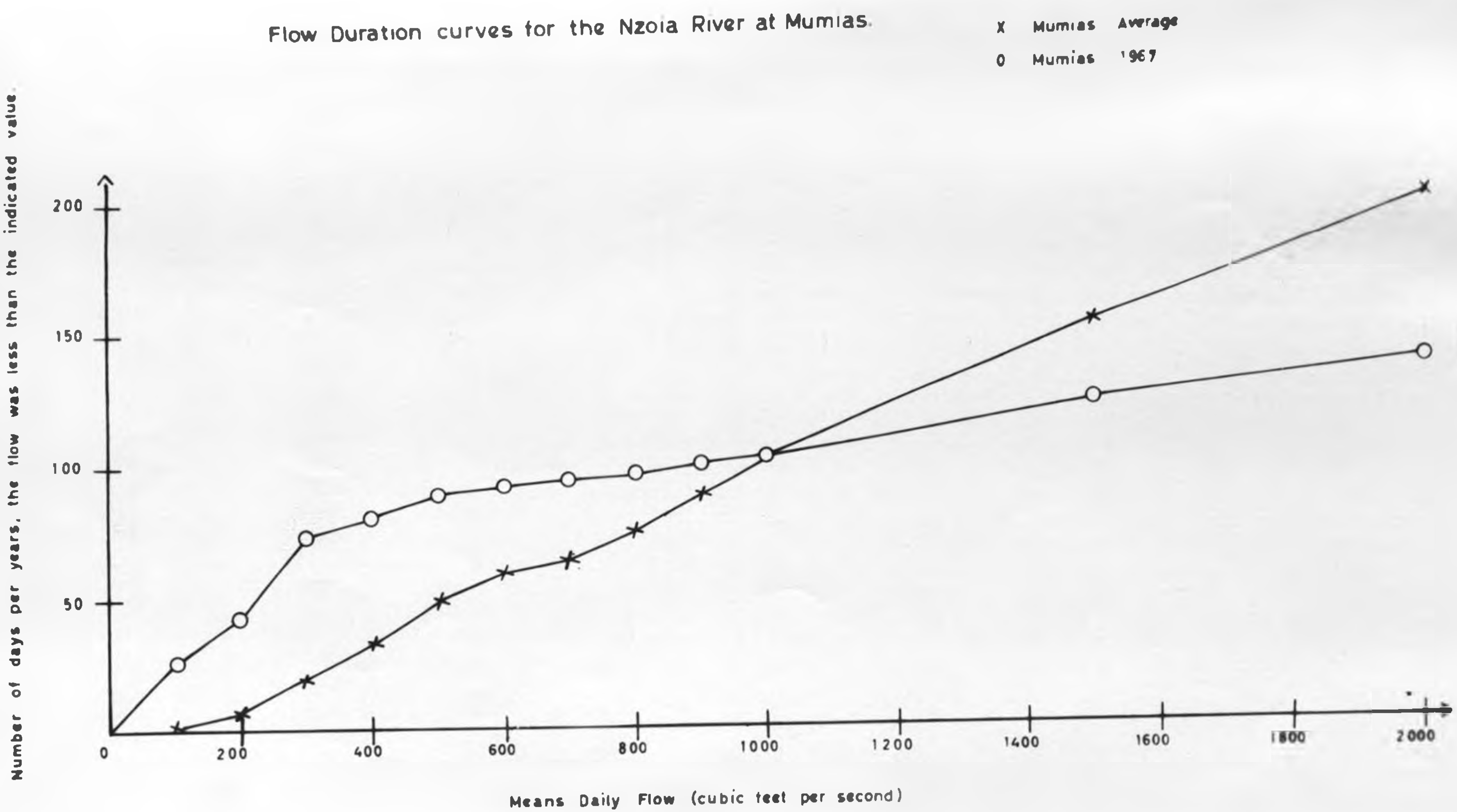
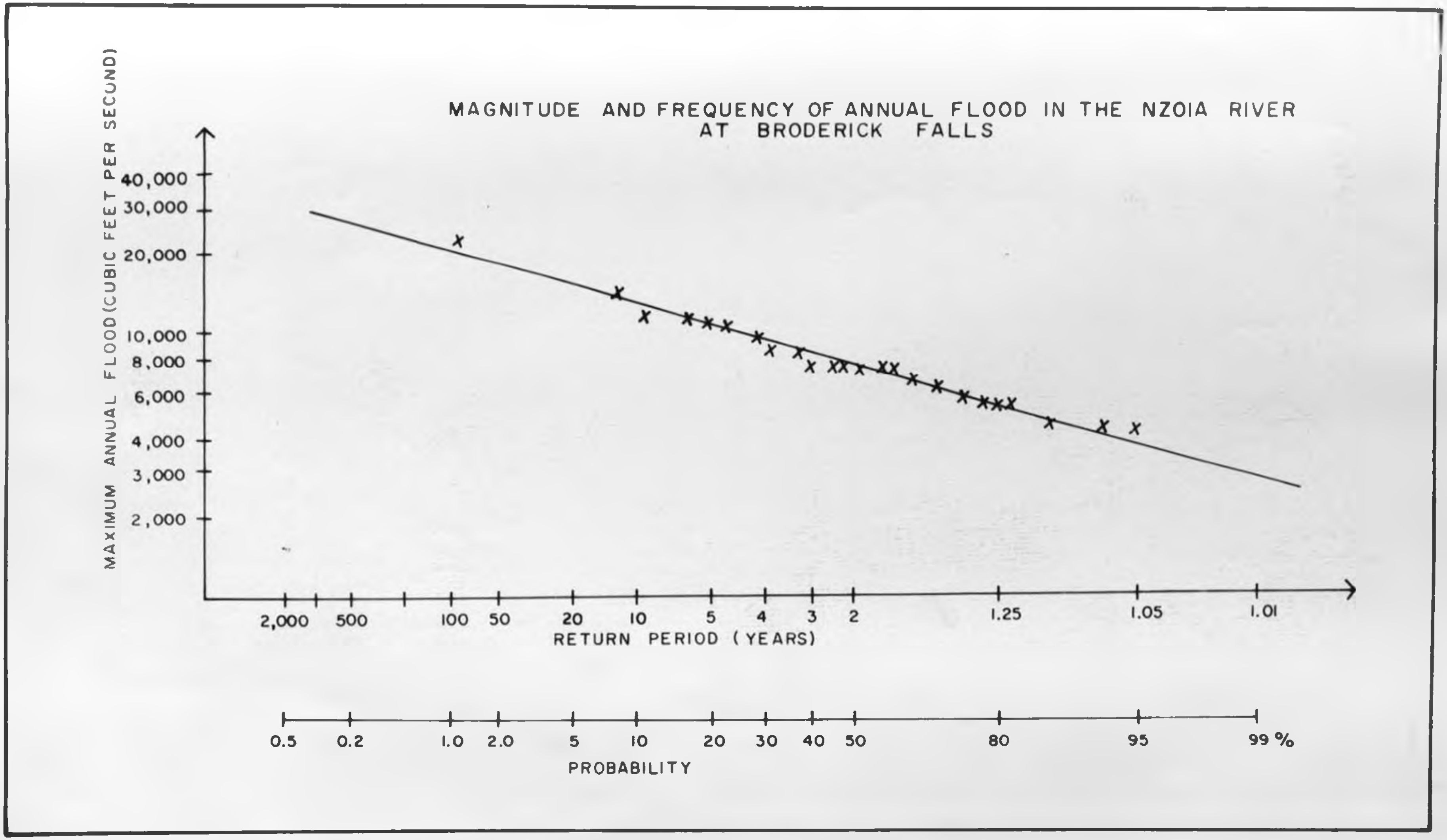


FIG. 5 26



MAGNITUDE AND FREQUENCY OF ANNUAL FLOOD IN THE NZOIA RIVER AT BRODERICK FALLS

FIG. 5.27

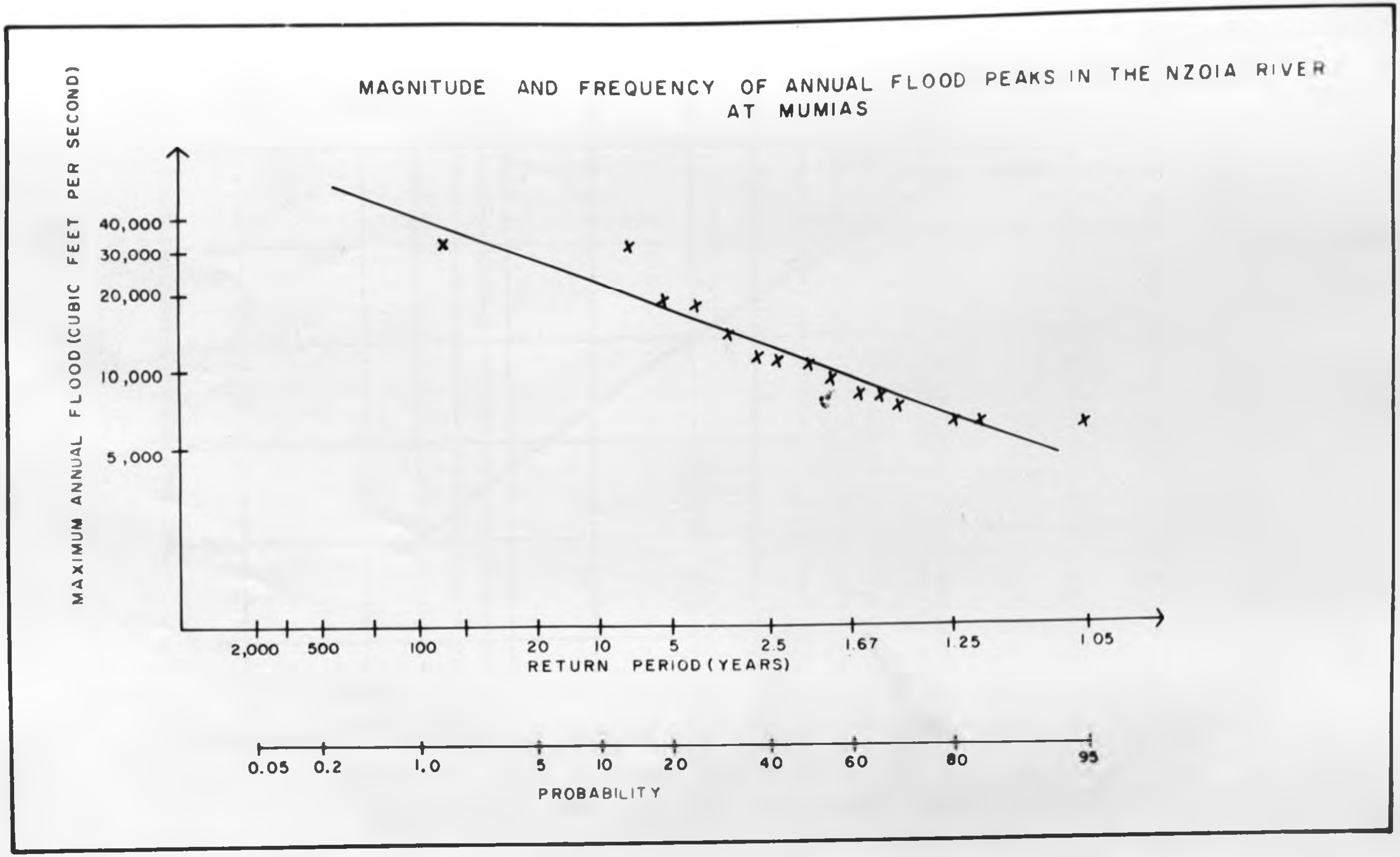
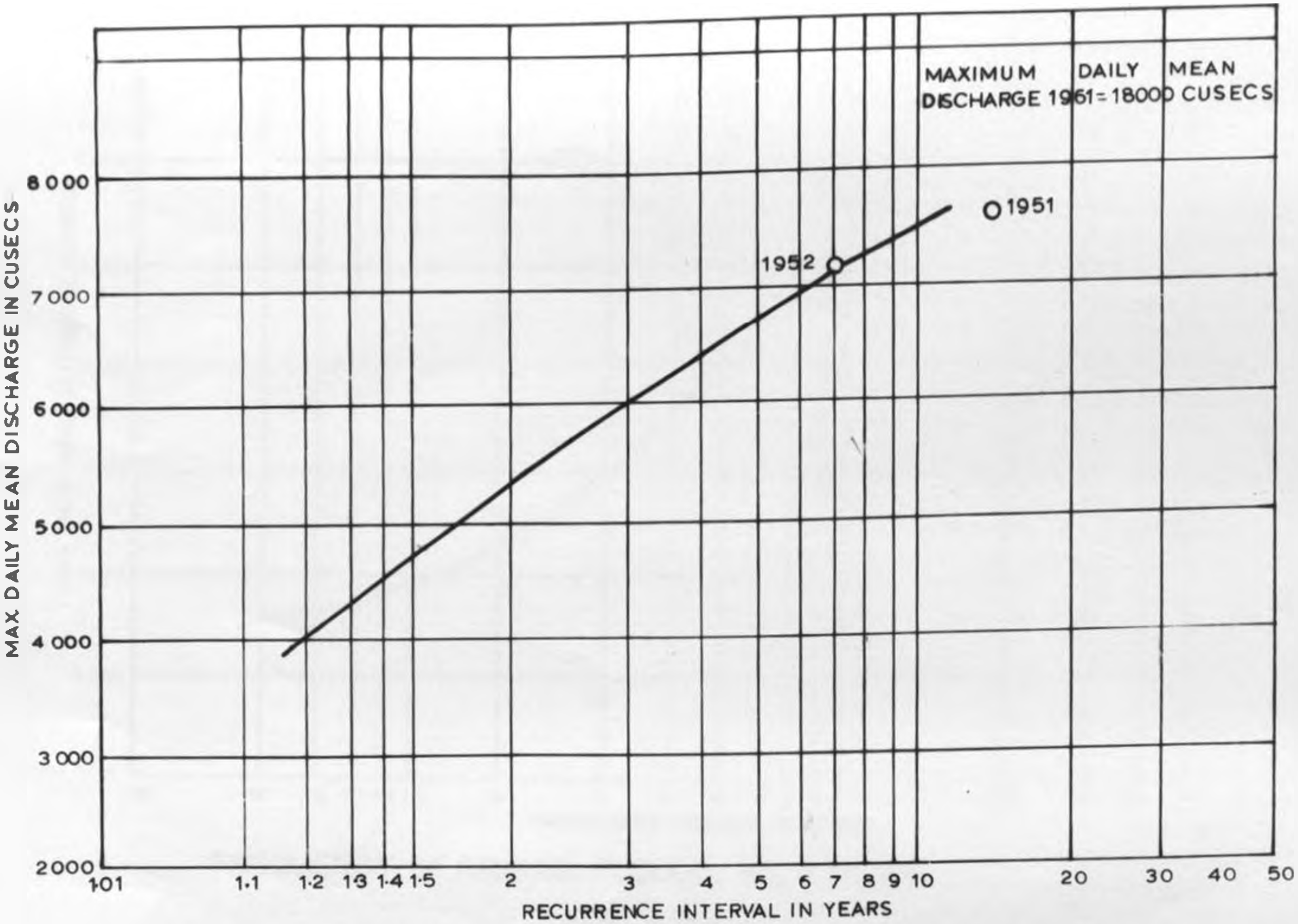
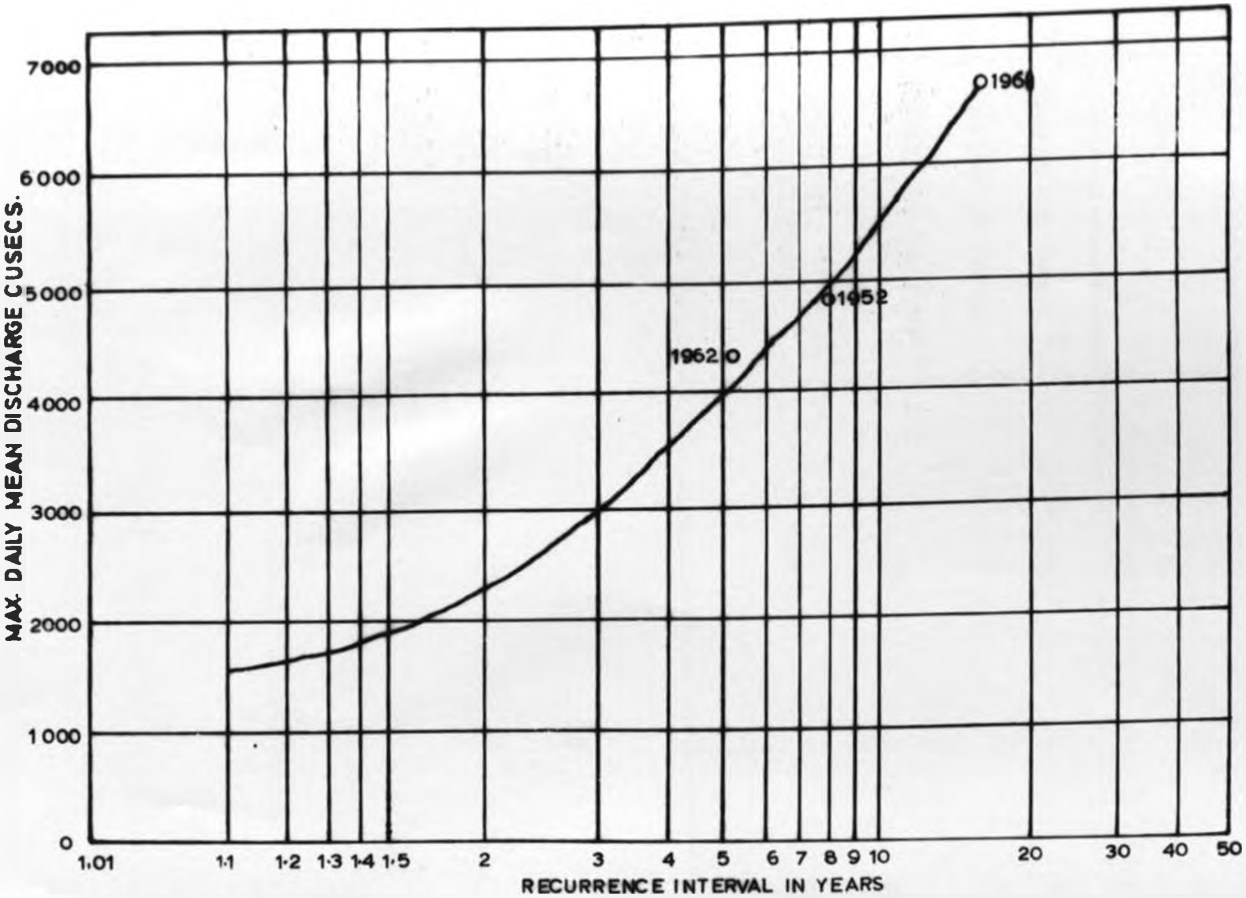

MAGNITUDE AND FREQUENCY OF ANNUAL FLOOD PEAKS IN THE NZOIA RIVER AT MUMIAS

FIG. 5.28



FREQUENCY OF ANNUAL FLOODS, NZOIA RIVER.

FIG. 5.29



FREQUENCY OF ANNUAL FLOODS, YALA RIVER

FIG. 5.30

TABLE V-16 EXPECTED FLOOD FLOWS ON THE KANO PLAIN

River	Expected High Flood (say once in ten years) Cusecs	Probable Maximum (Say once in 100 years) Cusecs
?? Nyando at Awasi ?	20,000	35,000
Nyando at Ahero	27,500	48,000
Kibos at Railway Bridge	7,500	13,000
Cherongil at Main Kisii Road	9,000	15,000

the catchment.

It is during the periods of low flow that volume of water in a river becomes critical for water supply in industry, irrigation, and domestic use. Figure 5-31 which is based on the data on Table V-17 given by UNESCO (1971), shows the return period of annual daily minimum flows for each of the last 23 years at Broderick Falls and each of the last years at Mumias.

The discharge of the Kibos River at Kisumu Water Supply Intake Works since 1933 (represented in Fig. 5-20) have been used by Sir Alexander Gibb and Partners (1956), to determine the reliability and percentage probabilities shown in Table V-18. Sir Alexander Gibb and Partners (1956) have also adopted the ten per cent "low year" discharge of the basin for estimating water availability. For the purposes of determining the monthly discharge that may occur to give the "ten per cent low year" discharge, the twenty per cent monthly figures have been given. It will be seen, however, that from Table V-16, the two totals, annual basis on "ten per cent low year" and twenty per cent monthly basis are approximately the same.

In the adopted "low year" the total discharge is 91,500 acre feet. The dry season flow of the basin is approximately 350 cusecs (10 cumecs).

II. Rift Valley Drainage Area

The Rift Valley, is an area of internal drainage discharging into Lake Rudolf in the north and Lake Natron in the South.

Within this main area are several sub-drainage systems discharging into a number of smaller lakes within the Rift Valley floor. Their waters are saline and the only lakes with relatively low salinity are Naivasha and Baringo. The dry season flow of the area is very small.

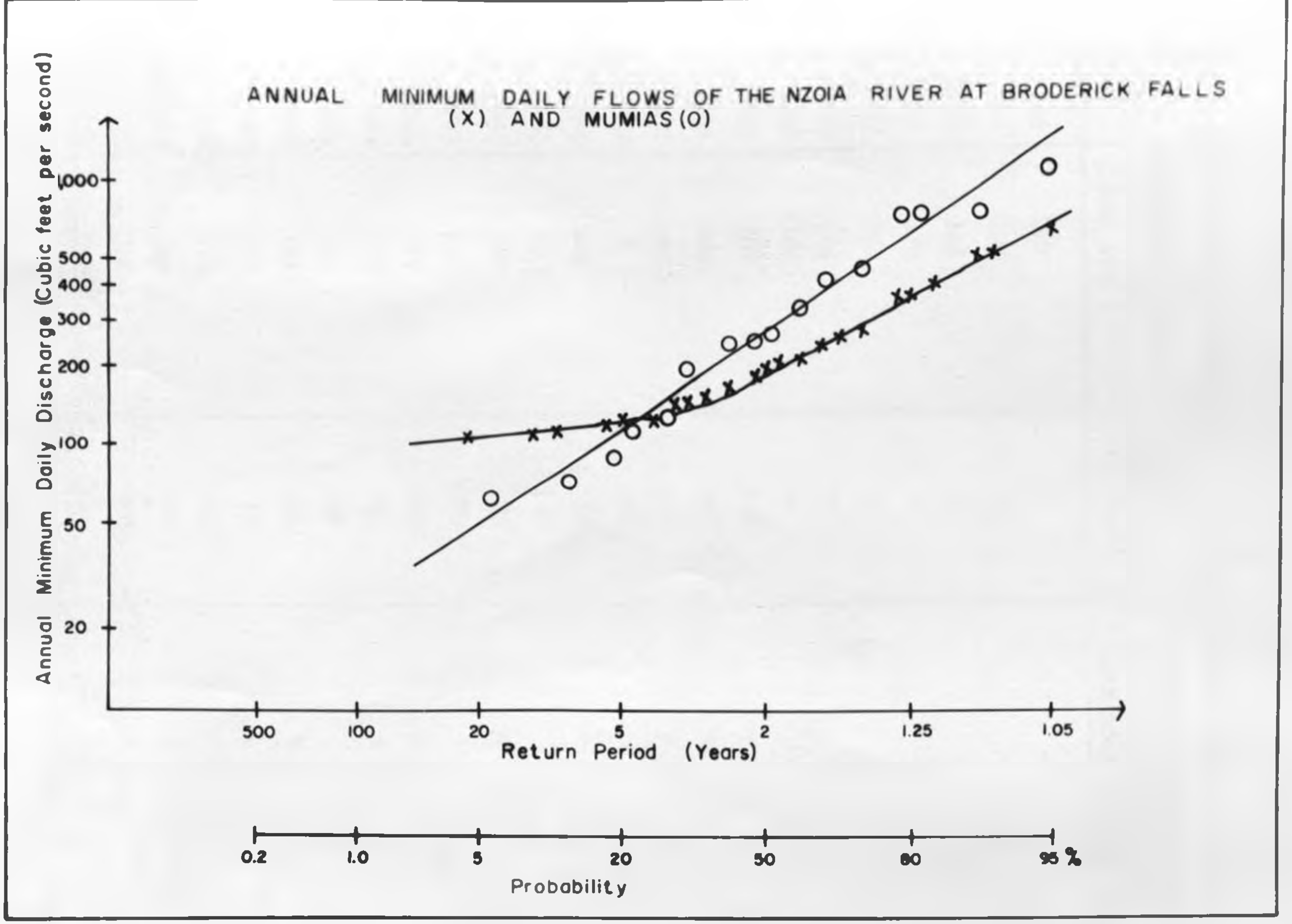

ANNUAL MINIMUM DAILY FLOWS OF THE NZOIA RIVER AT BRODERICK FALLS (X) AND MUMIAS (O)
Annual Minimum Daily Discharge (Cubic feet per second)
1000
500
400
300
200
100
50
20
Return Period (Years)
500
100
20
5
2
1.25
1.05
0.2
1.0
5
20
50
80
95 %
Probability

FIG. 5.31

TABLE V-17 ANNUAL DAILY MINIMUM FLOWS OF THE NZOIA RIVER AT BRODERICK FALLS AND MUMIAS

Year	Broderick Falls (cubic feet per sec.)	Mumias (cubic feet per sec.)	Downstream change as a percentage of the flow at Broderick Falls
1948	207	-	-
1949	110	-	-
1950	116	-	-
1951	126	-	-
1952	368	-	-
1953	141	-	-
1954	106	-	-
1955	166	129	- 22
1956	202	247	+ 22
1957	193	247	+ 28
1958	-	195	-
1959	145	76	- 53
1960	140	140	0
1961	104	93	- 11
1962	677	1071	*
1963	399	761	+ 91
1964	503	761	+ 51
1965	363	445	*
1966	196	275	+ 40
1967	170	62	- 64
1968	512	782	*
1969	284	335	+ 18
1970	276	405	+ 46
1971	250 (approx)	-	-

* Lowest flows not at the same time of year

TABLE V-18 PERCENTAGE PROBABILITY OF OBTAINING LESS THAN THE INDICATED DISCHARGE AT KIBOS GAUGING STATION
R.G.S. 1 HA 4*

Acre-feet per month

Month	10%	20%	30%	50%	95%
April	400	650	840	1,880	14,150
May	920	1,770	2,530	4,250	15,800
June	1,290	1,960	2,520	3,580	8,860
July	1,050	1,540	1,920	2,640	5.610
August	1,030	1,530	1,980	2,740	6,660
September	990	1,370	1,700	2,380	6,170
October	620	840	1,040	1,460	3,960
November	380	590	790	1,250	4,820
December	0	220	480	1,140	7,370
January	0	70	170	480	3,600
February	0	75	220	520	2,240
March	25	220	390	780	3,400
YEAR					
Monthly basis ..	6,705	10,835	14,580	23,100	82,640
Annual basis ..	11,400	14,400	17,300	24,100	76,000

*Kisumu Water Supply Intake Works

The relatively less importance of the streams in this area, in terms of water resource development warrant no further detail in this study. Suffice to say that the streams in this area are of restricted nature in terms of long distance flow.

III. Athi River Drainage Area

The Athi River drainage area comprises the southern part of the country east of the Rift Valley, draining the southern slopes of the Aberdares and the flanks of the Rift Valley. The Athi River, which in its lower reaches is known as the Sabaki, discharges into the Indian Ocean. An important contribution to the flow in the lower reaches is provided by the Tsavo River.

A list of small streams and springs which provide the recharge of the Athi River at its source as given by Whiston (-), is shown in Table V-19. Their discharges are also given in this table.

Due to extraction and evaporation losses, discharge of the streams further down-stream, as recorded in various gauging stations may be considerably less. At the end of a very dry season, river flow may be sustained only by the spring flows, but at other times the flow recovers increments for a certain distance along the river channel derived from groundwater bodies downstream of the main springs. When the channel passes out of such groundwater bodies, the flow begins to decrease. The point at which this discharge occurs is known as the point

TABLE V-19 SMALL STREAMS AND SPRINGS THAT PROVIDE THE RECHARGE OF ATHI RIVER AT ITS SOURCE

STREAM	APPROX. AVERAGE DISCHARGE (CUSECS)	MINIMUM RECORDED DISCHARGE CUS.)	DATE OF MINIMUM RECORDED DISCHARGE
KAMITI	3.5	0.15	Jan. 1951
RIARA	1.0	0.13	Jan. 1951
GETHARAINI & MISERARA	1.0	0.20 (estimated)	Feb. 1946
TIGONI	0.4	0.16	Dec. 1946
ITHANJI	0.1	0.004	Feb. 1946
TUSOGA	2.0	1.84	Dec. 1950
KARURA, MAIN SPRING	0.9	0.79	Feb. 1947
MWETETA	1.0	0.58	Sept. 1951
GETATHURU	0.6	0.19	(Jan. 1950 & Jan. 1951)
MATUNDU & THIGIRI	0.4	0.04	Feb. 1951
MATHARI & BAGICHI	0.6	0.03	Jan. 1934
NAIROBI (KIKUYU SPRINGS)	2.0	1.26	April 1950
NIANGARA (DISCHARGE FROM ONDIRI SWAMP)	0.3	Nil	(many times)
MBAGATHI (ALL SPRINGS)	2.8	1.20	Feb. 1951
TOTALS.	16.6	6.61	

of maximum flow, though this point may vary according to season. Losses of flow downstream of the point of maximum flow are greater in the lower reaches of the rivers. These losses, as given by Whiston, (-) are shown in Table V-20.

Floods in this areas as shown by the available data in this period, have not been excessive, except in the case of those resulting from the storms which occurred near Nairobi in 1957 and those of 1961. The high flows and resulting damage to property were outstanding. The highest floods as computed and given by the Hydraulic Branch (1958-1961) are given in Table V-21 and further details of the Summary of surface water statistics of this drainage area is given in Table V-22.

IV. Tana River Drainage Area

The Tana River drainage area, mainly comprises, the Tana River and its tributaries which drain the eastern slope of the Aberdare range, the Southern slopes of Mt. Kenya and the Nyambeni range and discharge into the Indian Ocean.

In Table V-23 the annual total flows which have been computed for each hydrological year, from the beginning of March to the end of February by Alexander Gibb and Partners (1959), at Kamburu and Garissa are given. The period was chosen because the river flow at the beginning of March is least affected by the rainfall of previous months. The very great variation in annual flow from 44% of the average to 173% the average of the 11-year period is a noteworthy feature of this table.

TABLE V-20 PRINCIPAL LOSSES OF RIVERS OF THE ATHI DRAINAGE AREA

RIVER	DATE	GAUGING POINT	DISCHARGE (CUSECS)	LOSS (CUS)	DISTANCE (MILES)
MBAGATHI	Feb.1947	RGS.3AA1	1.41	0.76	7
		Magadi road Bridge	0.65		
NAIROBI	20.2.45	Nairobi-Thika railway bridge	2.18	2.18	5
		Getharaini confluence	Nil		
MATHARI	10.9.52	Jeanes School-Kabete road Br.	2.82	0.90	¾
		Jeanes School	1.92		
GETATHURU	11.4.45	Jeanes School	0.32	0.294	12
		Above Nairobi confluence	0.026		
	8.2.50	Jeanes School	0.291	0.291	7½
		Nairobi-Kiambu road	Nil		
KARURA	18.1.50	Centre of Karura Forest	1.58	0.464	3
		Above Ruaraka confluence	1.116		
RUARAKA	1.2.50	RGS. 3BA.10	2.60	1.06	1½
		Nairobi-Kiambu Road	1.54		
RUARAKA	8.1.51	RGS. 3AB.10	1.48	1.18	3½
		½ mile u/s from Karura confluence	0.30		
KAMITI	24.2.51	Due N.of Kiambu	1.67	1.484	6½
		¾ mile u/s from Nairobi-Thika Road. (No diversions)	0.186		

RIVER	POSITION	DATE	PEAK FLOOD (CUSECS.)	CATCHMENT AREA (SQ. MILES)	CUSECS PER SQ. MILES	NATURE OF CATCHMENT
KIRICHWA DOGO	RING ROAD NAIROBI	25.4.51	2300	2.1	1095	Half residential, rest coarse grass and some native gardens; fairly steep slopes.
KIRICHWA KUBWA	BELOW KIRICHWA DOGO CONFLUENCE	25.4.51	7200	8.2	880	Mainly residential. Large gardens, bush on valley slopes. Steep slopes.
NAIROBI	PUMWANI	25.4.51	19,500	32	609	Kikuyu Native Reserve in upper course. Residential in lower course. Steep slopes.
NAIROBI	AINSWORTH BRIDGE	25.4.51	17,300	29	596	As for Pumwani but slightly less residential area.
NAIROBI	3BA2	25.4.51	6,800	13.2	515	Kikuyu Native Reserve. Steep slopes.
NIANGARA	RGS.3BA4	25.4.51	1,600	8	200	As for RGS.3BA2.
VETATHI		1940	350	1.6	220	0.4 sq.mls.rock. Remainder red soil & a little black cotton. Moderate slopes.
MBAGATHI	RGS. 3AA4	28.5.51	13,200	105	126	Upper catchment steep slopes with grass and bush, partly residential. Lower catchment coarse grass on black cotton. Gorges with moderate slopes above.

TABLE V-21 Computed Floods for the Athi River Drainage Area

RIVER ATHI DRAINAGE AREA

TABLE V-22 SURFACE WATER STATISTICS

RIVER	R.G.S.	CATCHMENT AREA SQ.MILES	MEAN FLOW		MINIMUM FLOW		LOWEST ANNUAL MEAN FLOW			No. OF YEARS' RECORDS
			CUSECS.	CUSECS PER SQ.MILE	CUSECS	DATE	CUSECS	CUSECS PER SQ.MILE	DATE	
MBAGATHI	3AA1	19.9	2.61	0.131	0.81	1950	1.86	0.0935	1946	6
MBAGATHI	3AA4	10.5	34.58	0.329	NIL	1951	19.05	0.1915	1950	2
MATHARI & BAGICHI	FT. OF MAX.FLOW.	7.2	2.0	0.278	0.033	1934	0.65	0.09	-	-
NAIROBI	3BA2	15.0	3.37 (5.37)	0.224 (0.358)	0.04 (2.04)	1946	0.84 (2.84)	0.056 (0.189)	1949	19
GETATHURU	3BA7	27	3.18	0.117	NIL	7 DIFFERENT YEARS	0.57	0.021	1949	19
KARURA	3BA9	16	5.0	0.312	0.07	1946	1.49	0.093	1945	30
RUARAKA	3BA10	33.7	11.3	0.305	0.12	1946	2.89	0.086	1945	21
GETHARAINI	3BA15	10	4.18	0.418	0.08	1945 1946	0.91	0.091	1945	20
RIARA	3BB1	9.6	2.35	0.244	0.01	1935 1946 1947	0.65	0.068	1935	26
RIARA	3BB10	15.3	4.34	0.284	NIL	1951	2.16	0.141	1950	2
KAMITI	3BB6	22.5	10.25	0.455	0.34	1946	3.06	0.136	1944	20
KAMITI	3BB9	11.7	7.36	0.63	0.07	1951	3.54	0.303	1950	4
KIU	3BB11	15.6	6.24	0.400	NIL	1951	1.56	0.10	ESTIMATED	2
TOTALS			98.76		1.87		41.23			

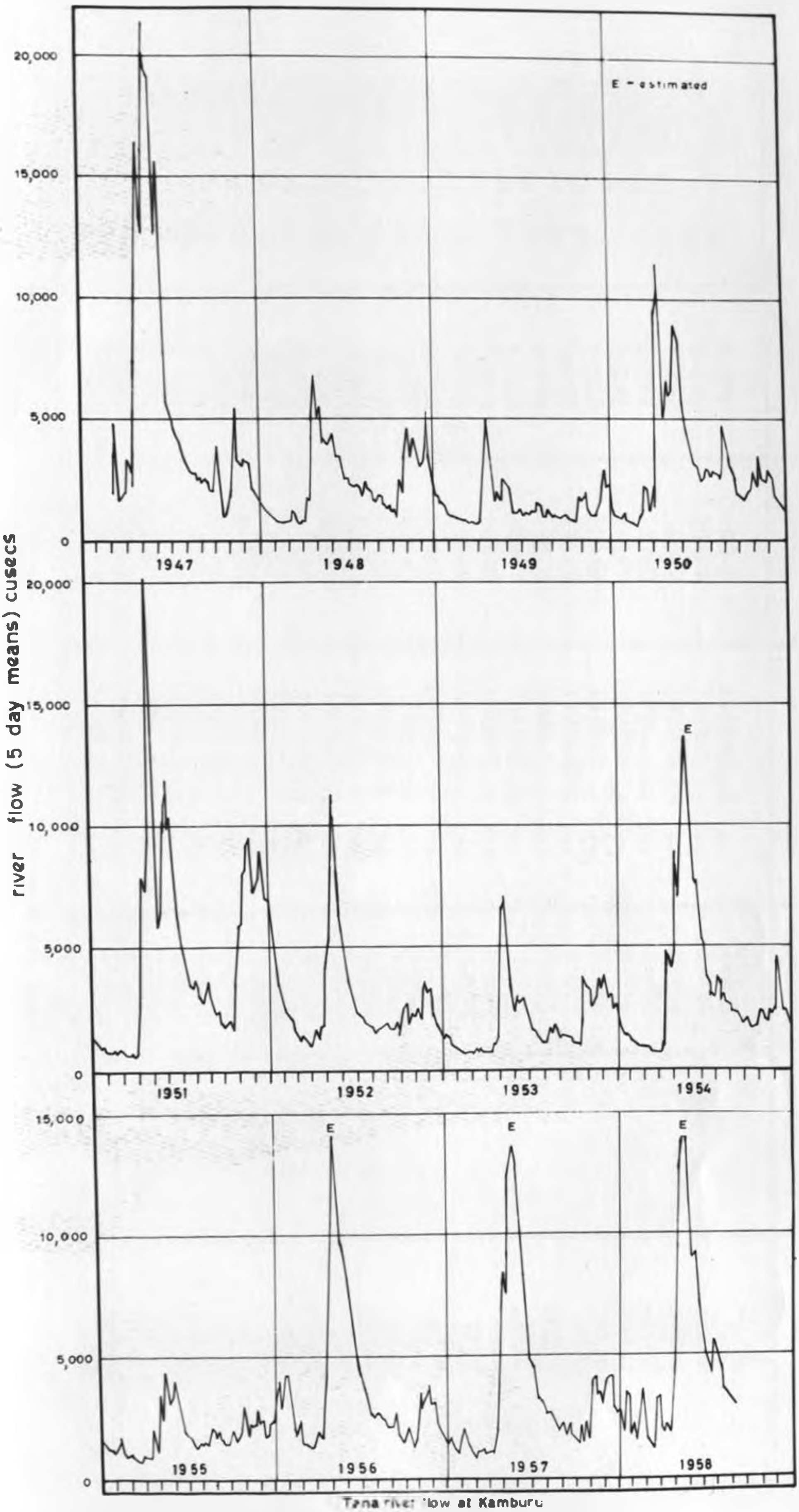
TABLE V-23 Annual Flows (1st March to 28th February) at Kamburu and Garissa

YEAR	KAMBURU		GARISSA	
	Flow mill.acre-ft.	Percentage of average	Flow mill.acre-ft.	Percentage of average
1934-5 ..			2·348	71·7
1935-6 ..			2·402	73·4
1936-7 ..			4·195	128·2
1937-8 ..			5·139	157·0
1938-9 ..			3·086	94·3
1939-40 ..			1·892	57·8
1940-1 ..			3·964	121·1
1941-2 ..			4·819	147.2
1942-3 ..			3·837	117·3
1943-4 ..			2·547	77·8
1944-5 ..			1·946	59·5
1945-6 ..			1.853	56·6
1946-7 ..			2·784	85·1
1947-8 ..	3·271	147.7	5·529	168·9
1948-9 ..	1·735	78·4	2·800	85·6
1949-50 ..	0·969	43·7	1·180	36·0
1950-1 ..	2·168	97·9	3·004	91·8
1951-2 ..	3·837	173·2	7·519	229·7
1952-3 ..	1·729	78·1	2·098	64·1
1953-4 ..	1·448	65·4	2·061	63·0
1954-5 ..	2·435	110·0	3·263	99·7
1955-6 ..	1·624	73·3	2·062	63·0
1956-7 ..	2·401	108·4	4·004	122·4
1957-8 ..	2·748	124·1	4·214	128·8
Average ..	2·215		3·273	

Figure 5-32 reflects the considerable seasonal and annual variations in river flow, which also indicate the corresponding variations in rainfall as given by Sir Alexander Gibb and Partners (1959). They have used the relationship between rainfall on the catchment and annual flow to estimate discharge between the years 1908-1957. These estimations are given in Table V-24. These flows are given in order of magnitude in Table V-25 and are plotted as a histogram in Figure 5-33. This table suggests that 1949 to 1951 are exceptionally low and high years respectively. The probability of occurrence of any discharge can be estimated from this table or by statistical analysis.

The long-term average annual flow at Kamburu has now been estimated at 2,230 acre-feet and its variations have been assessed. The long term flow of the tributaries can best be deduced indirectly because most of them have been measured for short periods. The yearly total measured flow of the tributaries suggest that they contribute a fairly constant percentage of the flow at Kamburu as shown on the data from the Water Department given in Table V-26.

A large number of tests to determine the amounts of suspended sediment have been made within the Tana Catchment and a list of samples given by Sir Alexander Gibb and Partners (1959) is shown in Table V-27. At ten stations sufficient results are available to correlate discharge and suspended sediment. The yearly load at Kamburu has been plotted against the yearly discharge and this is shown in Figure 5-34 as given by Sir



Tana river flow at Kamburu

FIG. 5.32

TABLE V-24 Estimated and Measured Annual Flows at Kamburu

Year: 1st March to 28th February	Flow: mill. acre-ft.	Percentage of average	Year: 1st March to 28th February	Flow: mill. acre-ft.	*Measured Flow: mill. acre-ft.	Percentage of average
1908-9	1.802	80·8	1933-4	1·622		72·7
1909-10 . ..	2·335	104·7	1934-5	1·493		66·9
1910-1	1·493	66·9	1935-6	2·416		108·3
1911-2	2·297	103·0	1936-7	2·458		110.2
1912-3	3·165	141·9	1937-8	3·216		144·2
1913-4	2·355	105·6	1938-9	2.030		91.0
1914-5	2·496	111·9	1939-40 . ..	1·097		49·2
1915-6	2·197	98·5	1940-1	2·271		101.8
1916-7	2·580	115·7	1941-2	2·615		117·3
1917-8	3·203	143·6	1942-3	2·200		98·7
1918-9	1·557	69·8	1943-4	1·599		71·7
1919-20 . ..	2·560	114·8	1944-5	1·605		72·0
1920-1	2·747	123·2	1945-6	1·831		82·1
1921-2	1·255	56·3	1946-7	2·094		93·9
1922-23 . ..	2·583	115·8	1947-8	3·071	3.270	146·6
1923-4	3·621	162·4	1948-9	1·995	1·735	77·8
1924-5	1·673	75·0	1949-50 . ..	0·969	0·969	43·4
1925-6	1·618	72·6	1950-1	1·953	2·168	97·2
1926-7	2·605	116·8	1951-2	3·837	3·837	172·0
1927-8	1·789	80·2	1952-3	1·541	1·729	77·5
1928-9	1·795	80·5	1953-4	1·808	1·448	64·9
1929-30 . ..	2·486	111·5	1954-5	2·400	2·435	109·2
1930-1	3.573	160·2	1955-6	1·972	1·624	72·8
1931-2	2·480	111·2	1956-7	2·297	2·401	107·6
1932-3	2·335	104·7	1957-8	3·014	2·748	123·2

Average .. .. 2,230 million acre-feet.
Standard deviation 0.659 million acre-feet.

*By recording gauge

TABLE V-25 Estimated and Measured Annual Flows at Kamburu in Order of Magnitude

Year: 1st March to 28th February	Flow: mill. acre-ft.	Percentage of average
1951	3.837	172.0
1923	3·621	162·4
1930	3·573	160·2
1947	3·270	146·6
1937	3·216	144·2
1917	3·203	143·6
1912	3·165	141·9
1957	2·748	123·2
1920	2·747	123·2
1941	2·615	117·3
1926	2·605	116·8
1922	2·583	115·8
1916	2·580	115·7
1919	2·560	114·8
1914	2·496	111·9
1929	2·486	111·5
1931	2·480	111·2
1936	2·458	110·2
1954	2·435	109·2
1935	2·416	108·3
1956	2·401	107·6
1913	2·355	105·6
1909	2·335	104·7
1932	2·335	104·7
1911	2·297	103·0
1940	2·271	101·8
1942	2·200	98.7
1915	2·197	98·5
1950	2·168	97·2
1946	2·094	93·9
1938	2.030	91·0
1945	1·831	82·1
1908	1·802	80·8
1928	1·795	80·5
1927	1·789	80·2
1948	1.735	77·8
1952	1·729	77·5
1924	1·673	75·0
1955	1·624	72·8
1933	1·622	72·7
1925	1·618	72.6
1944	1·605	72·0
1943	1·599	71·7
1918	1·557	69·8
1910	1·493	66·9
1934	1·493	66·9
1953	1·448	64·9
1921	1·255	56·3
1939	1·097	49·2
1949	0·969	43·4

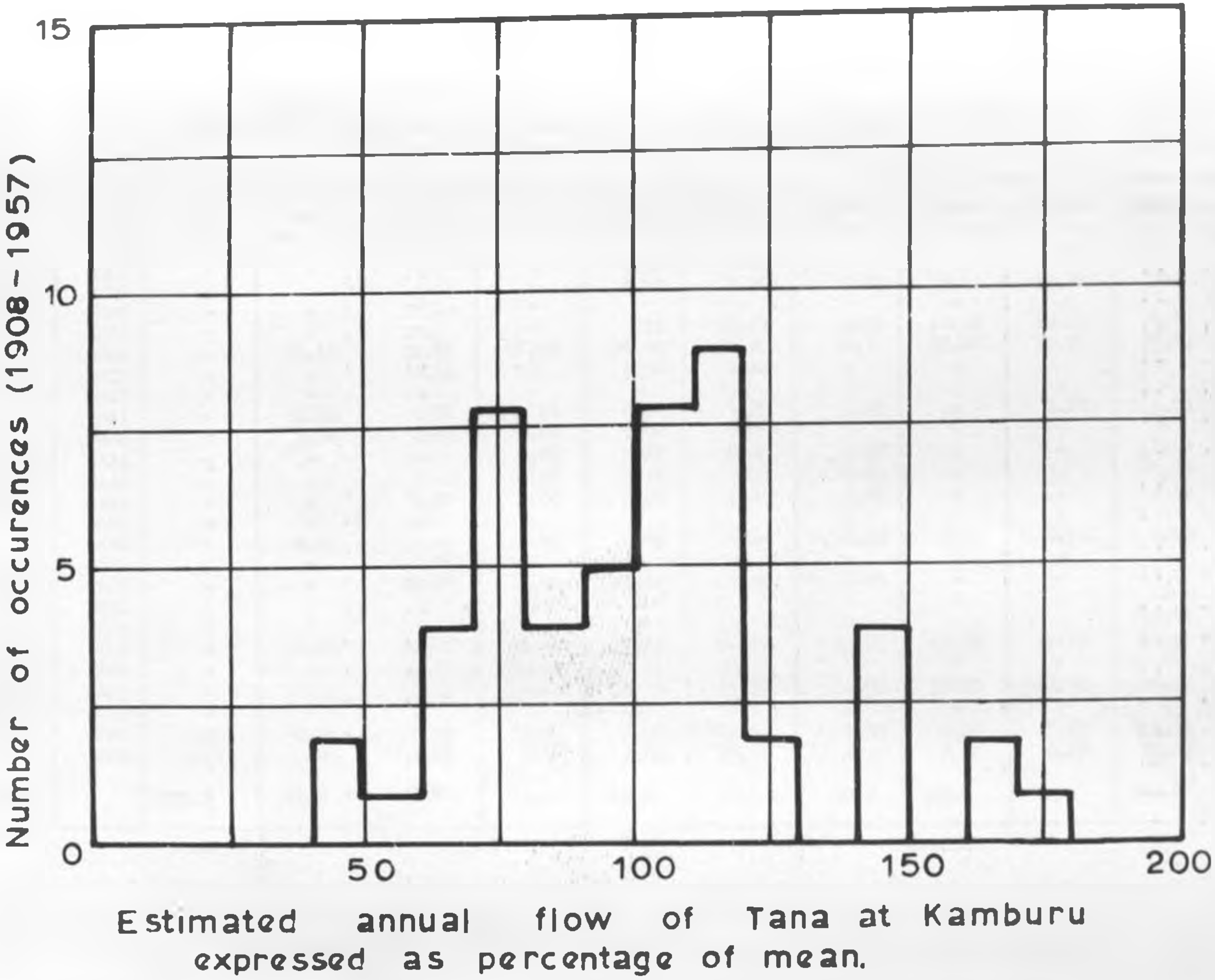


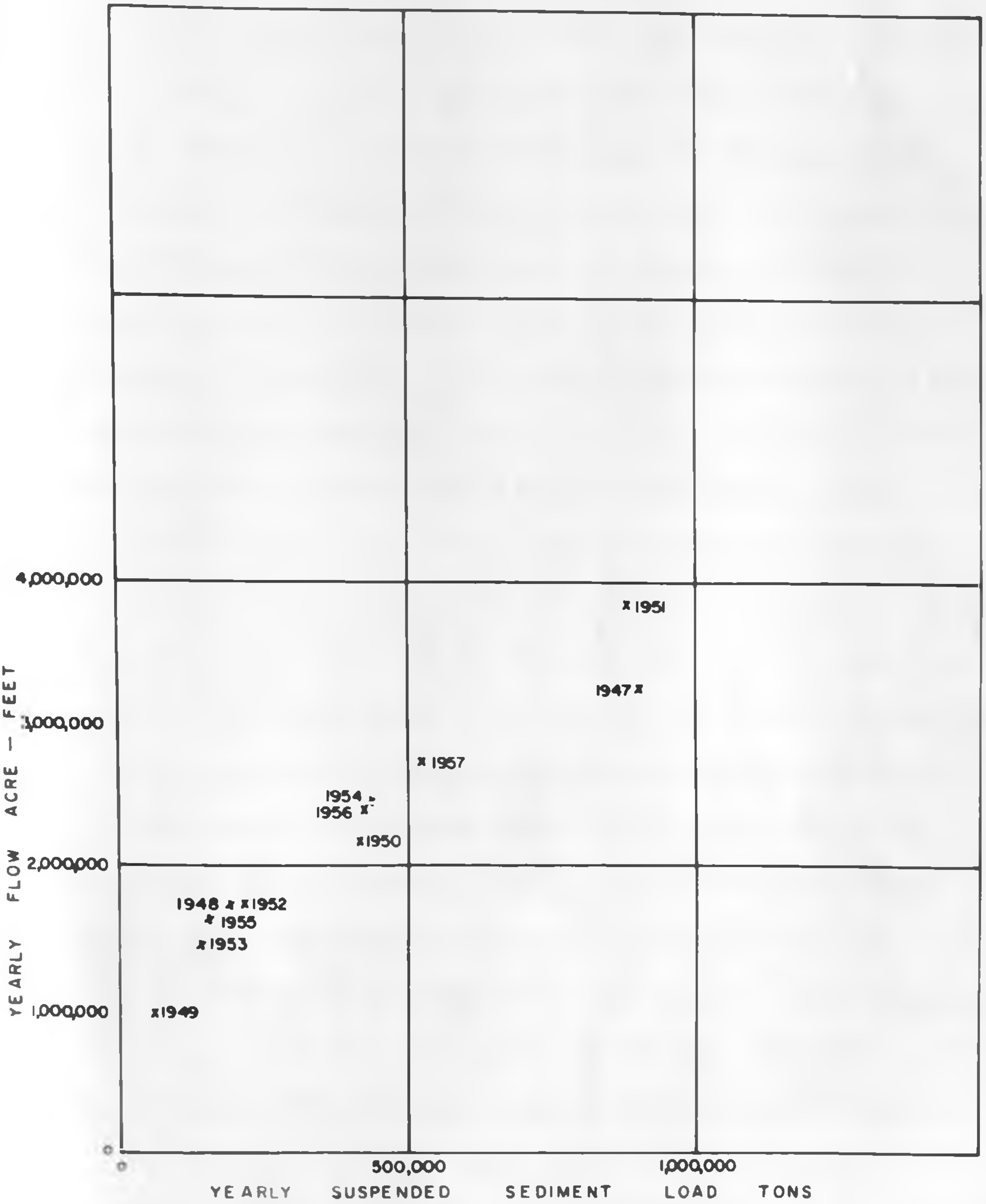
FIG. 5.33 FLOW HISTOGRAM FOR TANA RIVER.

TABLE V-26 Annual Flows of Various Gauges Expressed as a Percentage of Annual Flow at Kamburu (1st March to 28th February)

RIVER		Gauge	1947-8	1948-9	1949-50	1950-1	1951-2	1952-3	1953-4	1954-5	1955-6	1956-7	1957-8	Average
Rupingazi	..	4DC1	-	-	-	-	3.47	5.16	-	-	-	-	-	4.32
Nyamindi	..	4DB1	-	-	-	-	6.62	9.45	11.83	9.11	10.49	-	-	9.50
Muburara	..	4DA5	-	-	-	-	-	-	-	-	-	-	-	-
Thiba	..	4DA1	-	-	-	-	7.16	10.71	13.96	10.89	14.34	9.83	8.74	10.80
Thiba	..	4DD1	-	26.65	22.94	27.24	30.25	20.45	29.12	30.67	32.06	28.98	-	28.48
Ruamuthambi	..	4BC3	-	-	1.36	-	1.56	1.83	-	-	-	-	-	1.58
Ragati	..	4BB1	-	-	-	-	-	-	-	-	-	-	-	-
Sagana	..	4AA1	-	1.22	1.98	1.19	0.87	1.20	1.82	-	1.68	1.01	0.88	1.32
Thego	..	4AA2	-	1.04	1.51	1.09	1.08	0.96	-	-	-	-	-	1.14
Nairobi	..	4AA4	-	-	-	0.72	0.87	0.60	1.00	-	-	0.69	0.80	0.78
Sagana	..	4AA5	-	-	-	3.22	3.12	3.35	5.64	-	-	4.34	-	3.93
Amboni	..	4AB5	-	-	2.67	1.40	1.69	1.41	1.91	-	-	2.10	2.04	1.89
Muigu	..	4AB2	-	-	-	-	-	-	-	-	-	-	-	-
Muringato	..	4AB1	-	0.42	0.49	0.36	0.59	0.54	0.42	0.52	0.62	0.65	0.70	0.53
Chania	..	4AC1	-	-	4.36	-	-	-	-	-	-	-	-	4.36
Sagana	..	4AC3	-	-	13.07	8.45	8.47	8.28	10.05	-	-	10.67	10.08	9.87
Gura	..	4AD1	-	-	-	-	-	-	-	-	-	-	-	-
Sagana	..	4BA1	-	-	-	-	-	-	-	-	-	26.78	-	26.78
Sagana	..	4BC2	-	26.66	31.52	29.24	25.65	26.79	31.82	29.90	33.70	31.97	-	29.69
Mathioya	..	4BD1	-	-	21.27	15.48	12.91	15.75	-	-	-	-	-	16.35
Maragua	..	4BE1	-	-	14.49	13.62	10.79	11.68	10.98	10.80	10.54	12.30	-	11.90
Thaba Thaba	..	4BF1	-	-	-	-	-	-	-	-	-	-	-	-
Thika	..	4CB4	6.58	6.86	5.08	5.99	6.32	6.22	5.57	6.00	5.82	6.34	6.46	6.11
Chania	..	4CA2	9.73	8.86	9.05	7.19	7.44	10.39	8.19	8.83	8.09	8.67	8.57	8.64
Rainfall Index			127.1	93.6	61.7	92.3	150.9	79.5	87.8	106.2	92.9	103.0	125.3	

TABLE V-27 Upper Tana Catchment - Sediment Samples

Gauge	River	No of Samples
4AA1	Sagana	63
4AA2	Thego	45
4AA4	Nairobi	6
4AA5	Sagana	77
4AA7	Sagana	1
4AB1	Muringato	37
4AB5	Amboni	24
4AC3	Sagana	122
4BB1	Ragati	2
4BC2	Tana	100
4BC3	Ruamuthambi	3
4BD1	Mathioya	97
4BE1	Maragua	97
4CA2	Chania	86
4AC3	Chania	5
4CA4	Kimakia	3
4CA5	Sasumua	19
4CA6	Chania	22
4CA7	Kiburu	22
4CA8	Chania	3
4CB4	Thika	98
4CB5	Ndarugu	1
4CC1	Thika	2
4DA1	Thiba	1
4DA7	Thiba	3
4DB2	Nyamindi	2
4DC2	Rupingazi	2
4DD1	Thiba	113
4ED3	Tana	22



YEARLY SEDIMENT LOAD OF TANA AT KAMBURU
RELATED TO YEARLY FLOW

FIG. 5.34

Alexander Gibb and Partners (1959). This shows that a great proportion of the load is brought down in years of high flow. The normal sediment load in Table V-28, show seasonal variation. These results, according to Sir Alexander Gibb and Partners (1959), show that the rivers flowing from Mt. Kenya are less laden than those from the Aberdare range, while the Maragua and the Thika, carry more sediment than the Sagana. A summary of suspended load in thousands of tons in the Upper Catchment area are given in Table V-29. The results have been expressed as parts per 100,000 tons per day. There is a linear correlation between discharge and sediment load at each of the stations. This correlation appears as a linear band on logarithmic graph paper as shown in figures 5-35, 5-36, 5-37, 5-38, 5-39 and 5-40. It is necessary to choose a line to represent this relationships. Two parallel lines were drawn to envelope all but a few outlying points, a third line was then drawn to give the arithmetic mean of the sediment loads given by each line. This line as shown by Sir Alexander Gibb and Partners (1959), does not pass through the centre of points and may tend to give an over estimate of the load. However, because of the logarithmic scale, a line drawn through the centre of the points would under estimate the load. But as there is a simple arithmetic relationship between the results given by two parallel lines, it is simple to adjust the estimate to fit another line. There are fewer points for the Tana at Kamburu and they lie more closely on a straight line and a single line has been drawn through them.

TABLE V-28 Estimated Normal Suspended Sediment Loads in Tons per Day for Streams in Tana Drainage Area

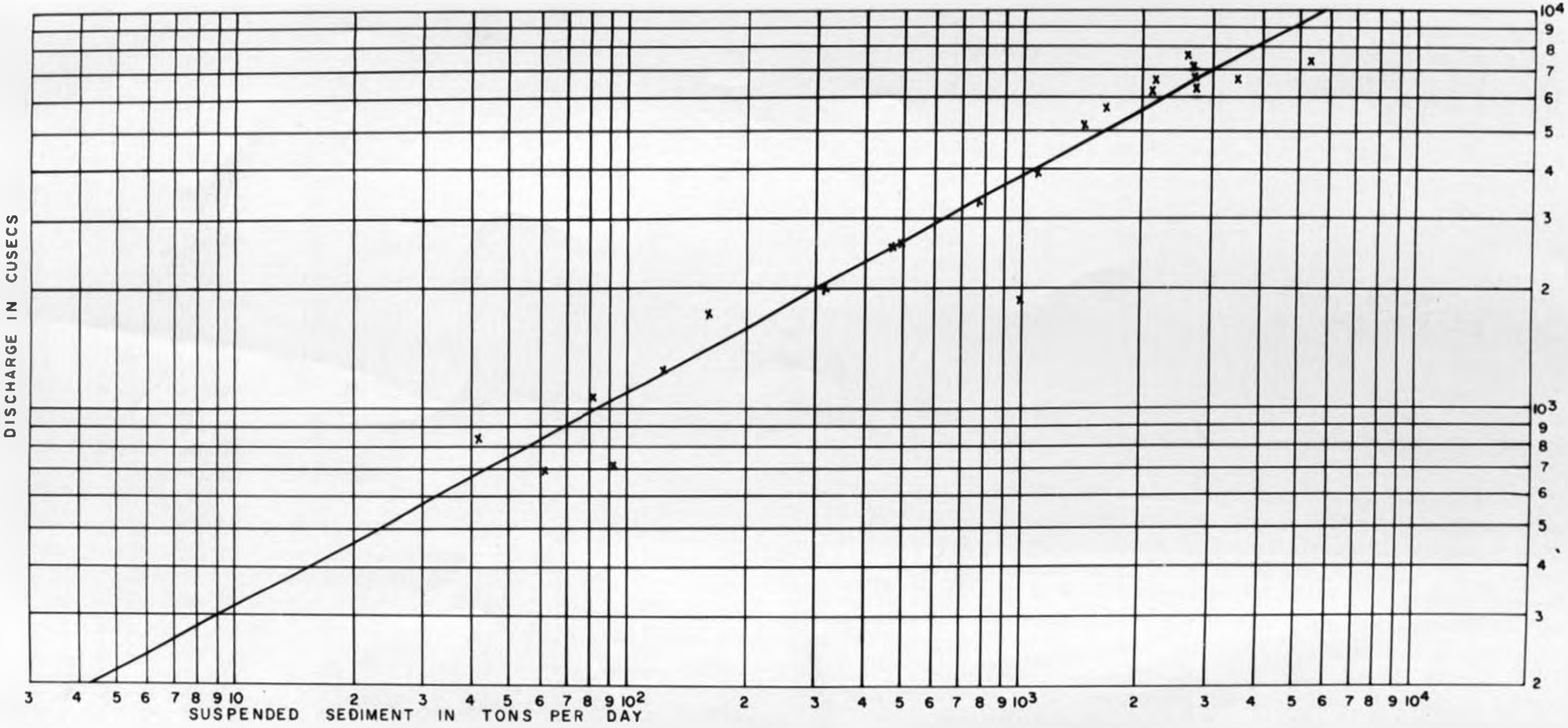
	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
4ED3 — Tana at Kamburu — 5 day means												
1 ..	513	201	110	426	4,272	3,674	801	492	402	320	738	965
2 ..	390	165	210	564	4,964	2,850	652	472	357	257	887	853
3 ..	335	150	127	1,058	6,046	2,185	554	425	315	195	954	914
4 ..	318	190	145	1,887	5,784	1,537	599	417	282	361	1,101	833
5 ..	269	144	165	3,951	5,439	1,160	577	402	211	442	1,085	621
6 ..	278	98	163	4,330	4,113	982	544	391	239	598	849	575
4 DD1 — Thiba — 10 day means												
1 ..	87	48	22	116	1,338	695	256	221	176	133	237	202
2 ..	54	34	24	526	2,224	434	208	192	131	166	247	159
3 ..	58	27	21	2,234	1,407	314	199	168	113	270	160	97
4AC3 — Sagana — 10 day means												
1 ..	72	31	22	139	1,003	378	65	78	100	85	338	366
2 ..	32	88	44	543	973	190	87	91	61	94	328	256
3 ..	42	20	39	1,096	673	117	132	114	35	214	230	149
4BE1 — Maragua — 10 day means												
1 ..	457	128	82	259	4,524	3,582	476	118	124	70	400	541
2 ..	218	138	227	2,299	3,713	1,606	512	134	80	84	1,228	508
3 ..	258	108	257	3,537	3,878	748	483	121	63	163	1,008	774
4CB4 — Thika — 10 day means												
1 ..	125	36	8	33	2,382	959	119	40	319	17	65	97
2 ..	72	23	13	332	3,839	460	94	33	256	448	238	87
3 ..	59	12	58	929	1,928	229	96	38	19	38	88	277
4CA2 — Chania — 10 day means												
1 ..	47	19	11	21	594	351	57	29	27	19	40	71
2 ..	32	16	11	96	890	200	37	24	23	21	56	75
3 ..	29	16	11	292	553	100	34	28	19	30	74	70

TABLE V-29 Summary of Suspended Sediment Loads in Thousand Tons for Streams in Tana Drainage Area.

(1st MARCH TO 28th FEBRUARY)

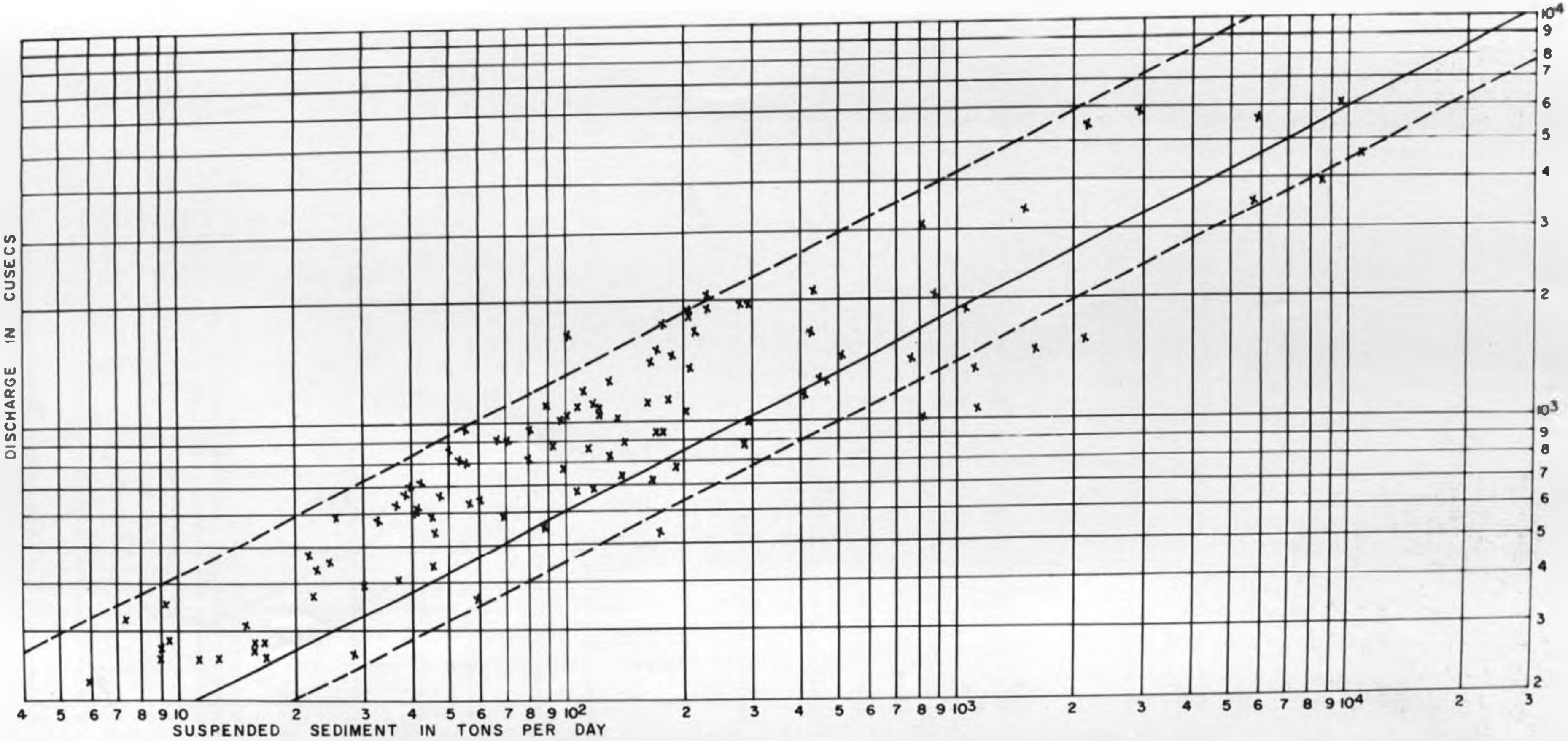
GAUGE RIVER	4ED3 Tana	4DD1 Thiba	4AC3 Sagana	4BEI Maragua	4CB4 Thika	4CA2 Chania
1947-8	906	-	-	-	-	-
1948-9	190	53	-	-	105	18
1949-50	67	11	25	44	5	5
1950-1	415	101	64	385	134	20
1951-2	885	492	164	820	191	82
1952-3	216	60	39	155	65	47
1953-4	142	-	43	75	16	11
1954-5	433	187	-	374	126	61
1955-6	153	66	-	65	24	12
1956-7	426	156	140	434	192	70
1957-8	523	-	141	-	229	88
Average (from normals) ..	411	131	85	335	141	41
Yearly average in acre-feet*	384	123	79	313	132	38
Yearly average x 50 (acre-feet)	19,200	6,150	3,950	15,650	6,600	1,900

*Converted at 55 lb./cubic foot.



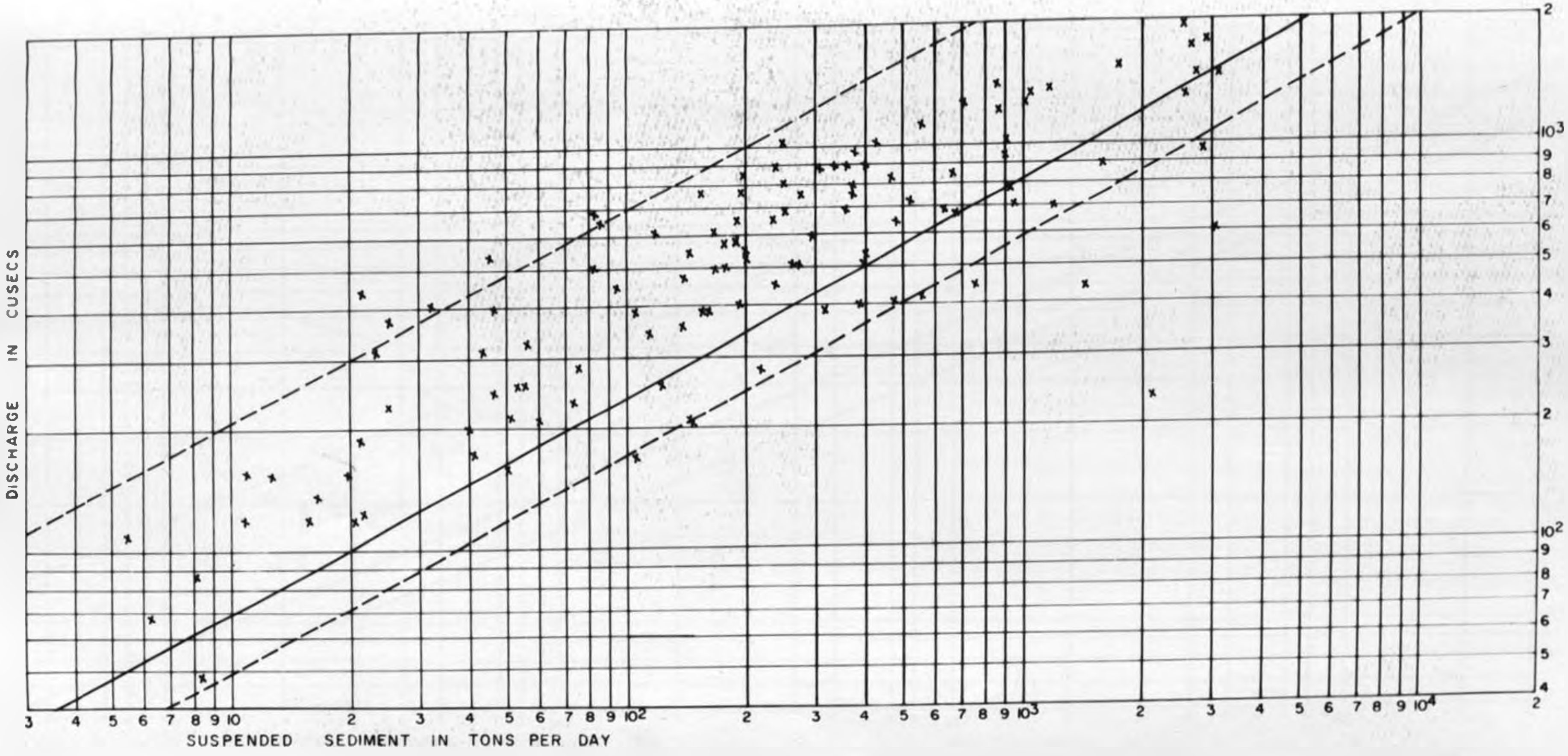
RELATIONSHIP BETWEEN DISCHARGE AND SUSPENDED SEDIMENT FOR TANA RIVER AT KAMBURU

FIG. 5 35



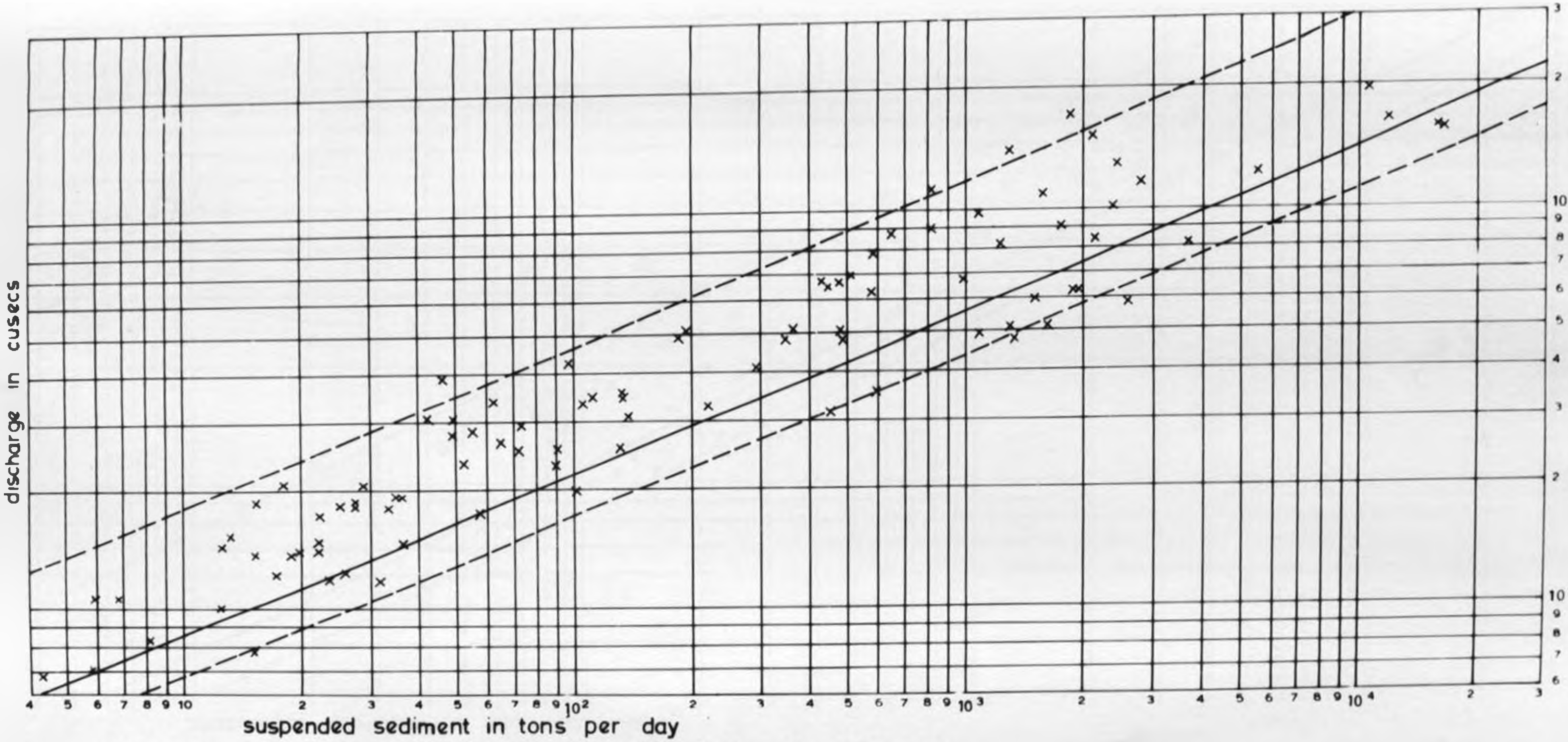
RELATIONSHIP BETWEEN DISCHARGE AND SUSPENDED SEDIMENT FOR THIBA RIVER

FIG. 5 36



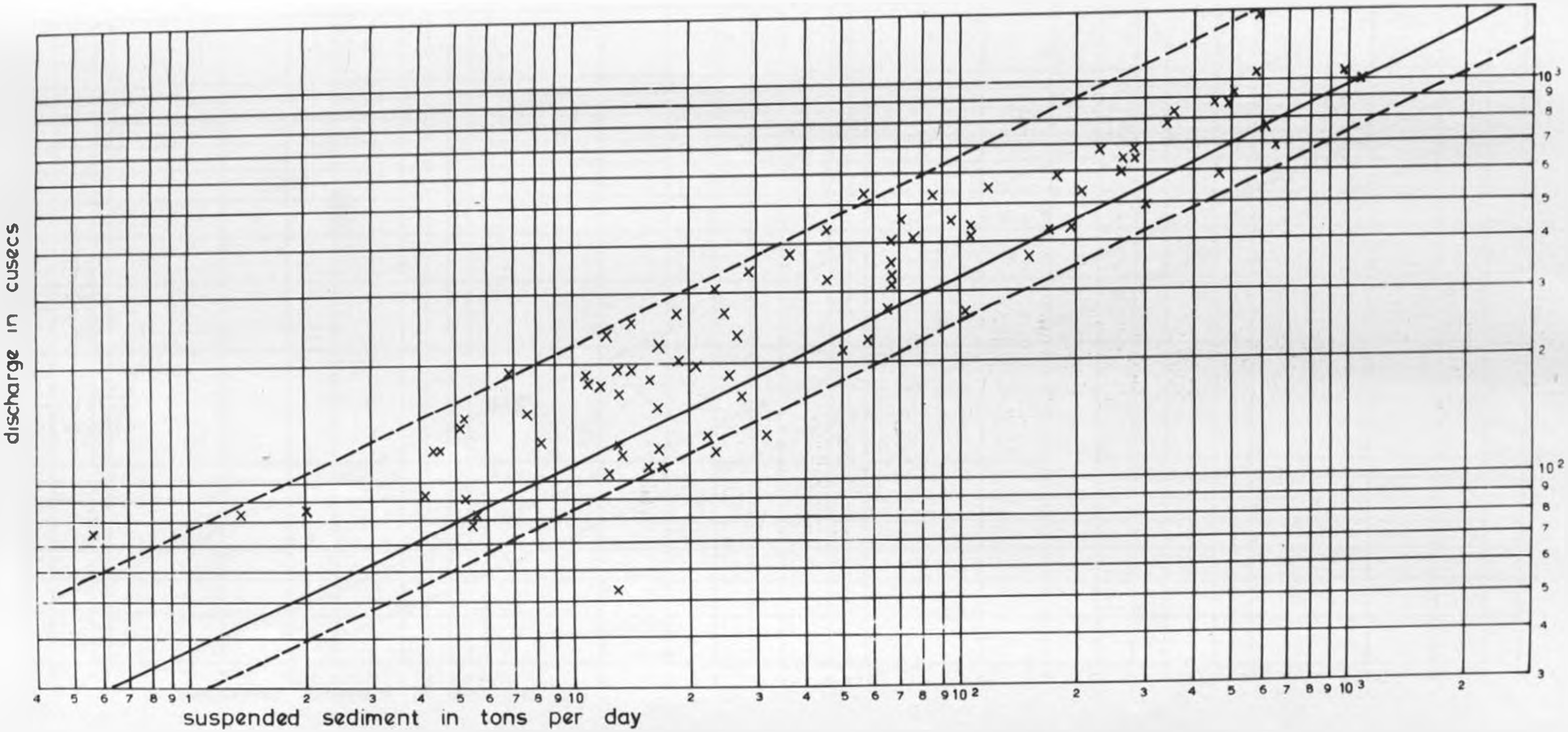
RELATIONSHIP BETWEEN DISCHARGE AND SUSPENDED SEDIMENT FOR SAGANA RIVER

FIG 5 37



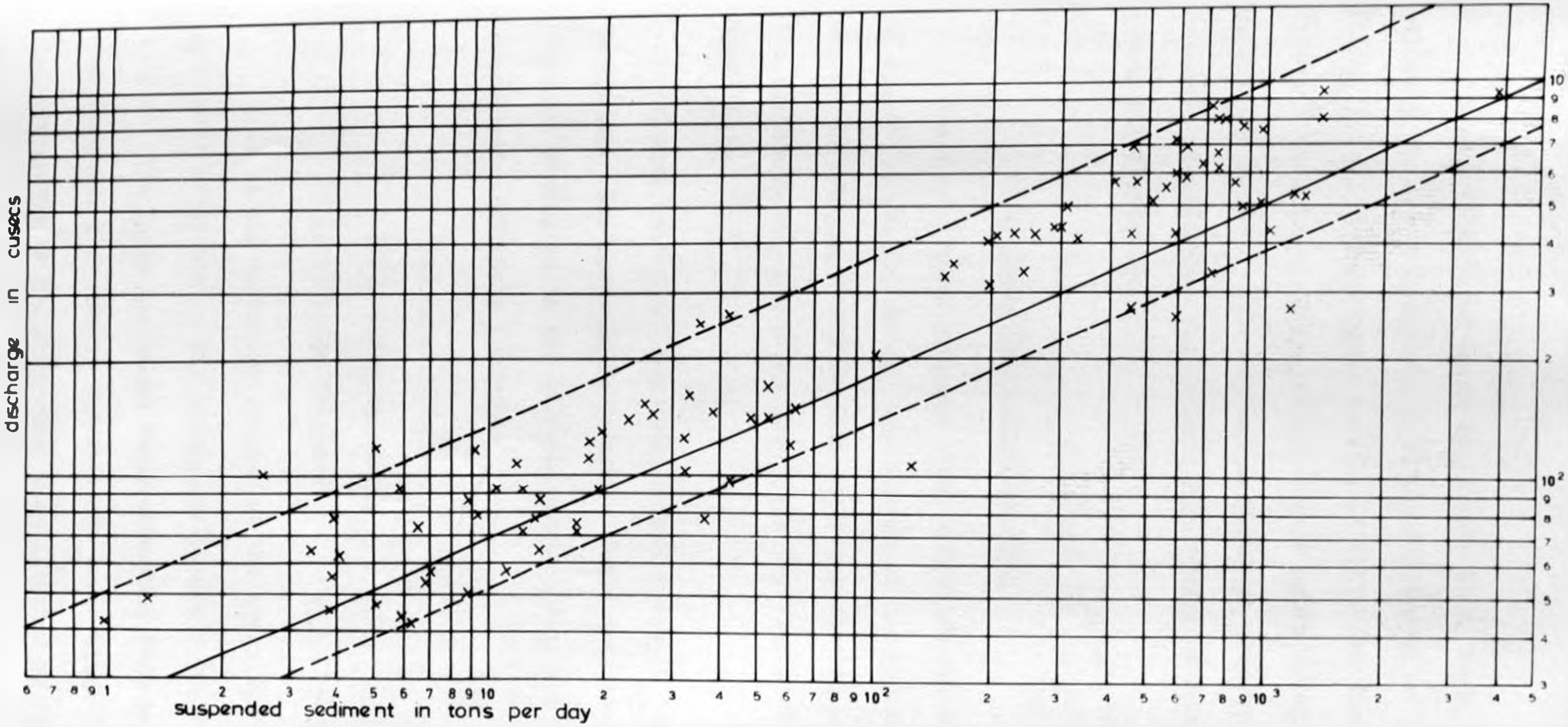
Relationship between discharge and suspended load for Maragua

FIG. 5.38



Relationship between Discharge and Suspended Sediment for Thika.

FIG. 5.39



Relationship beetwen Discharge and Suspended Sediment for Chania River

FIG. 5.40

Grundy (1963), as shown in Figures 5-41, 5-42, 5-43, 5-44 and 5-45, has calculated the recurrence interval of floods for Thika, Thiba, Tana-Kamburu, Tana-Grand Falls and Tana-Garissa Rivers respectively on logarithmic graph paper using the theory of extreme values. This particular drainage area is of great economic significance for Kenya's development of hydro-electric power and irrigation.

Never, expected this from you, definitely that must be a stranger.

Nyiro's ~~S~~ Western Kenya. Stupid you don't know what your reading avoid ~~bogus~~ imbecile comment of an undergraduate on his Thesis!!.

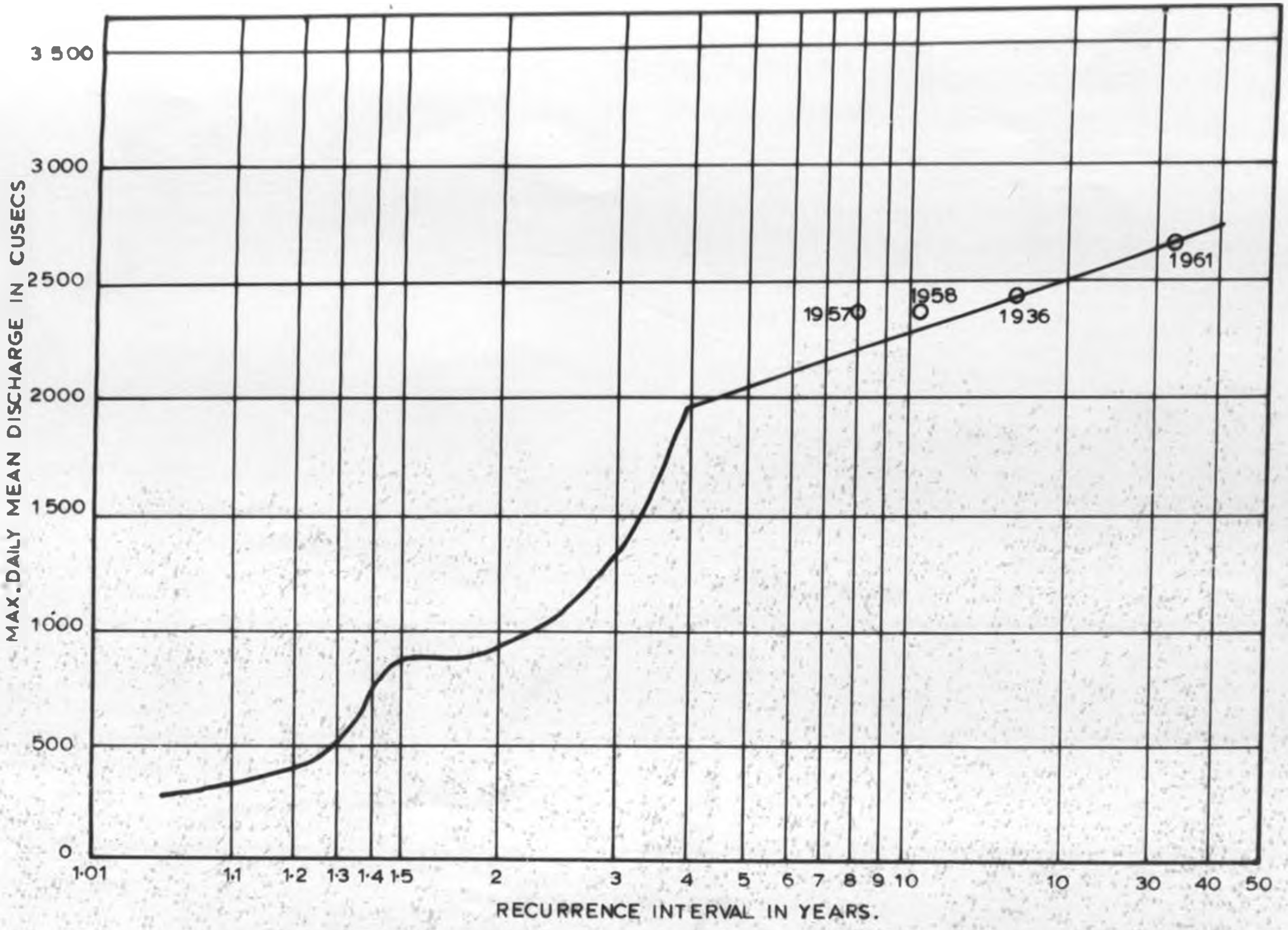
V. Ewaso Ngiro Drainage Area

The Ewaso Ngiro drainage area, comprises the northern part of Kenya and drains the northern slopes of the Aberdare Range and Mt. Kenya. During flood? seasons the river flow is absorbed in the Lorian Swamp, though in some years the flow continues into Somaliland.

Figure 5-46 shows the hydrological cycle in the Ewaso Ngiro Catchment. The Ewaso Ngiro Catchment falls into three fairly distinct divisions on the basis of hydrological set up, ecology, and climate and these include:-

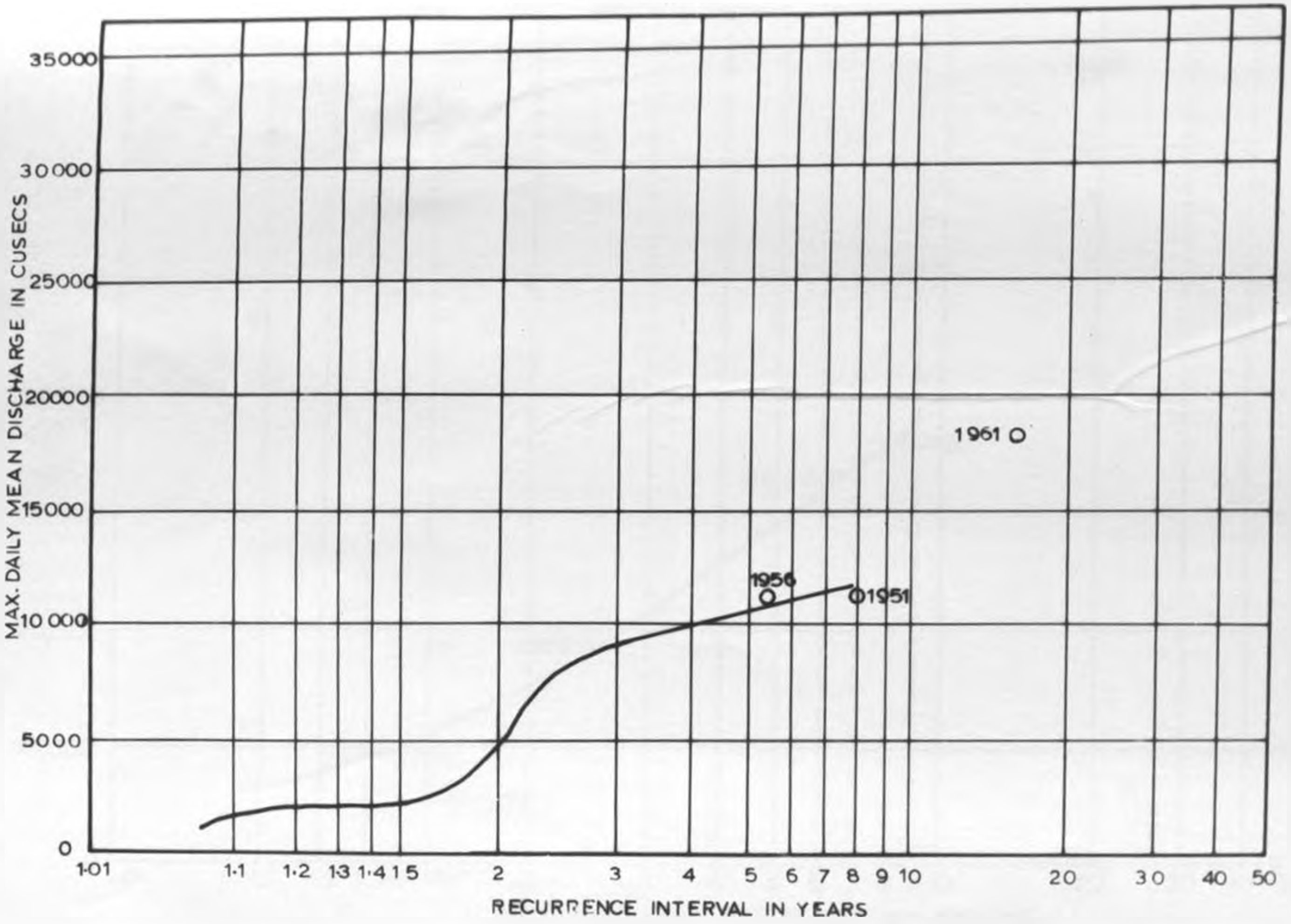
(i) Upper Catchment
(ii) Middle Catchment
(iii) Lower Catchment

Many of the tributary streams of the Ewaso Ngiro Upper Catchment originate on Mt. Kenya, particularly on the forested slopes. The Upper Catchment falls naturally into two divisions, the Ewaso Narok system in the west and Ewaso Ngiro in the East. The proportion of the main river flow provided by each of the two major tributaries varies from year to year as indicated in



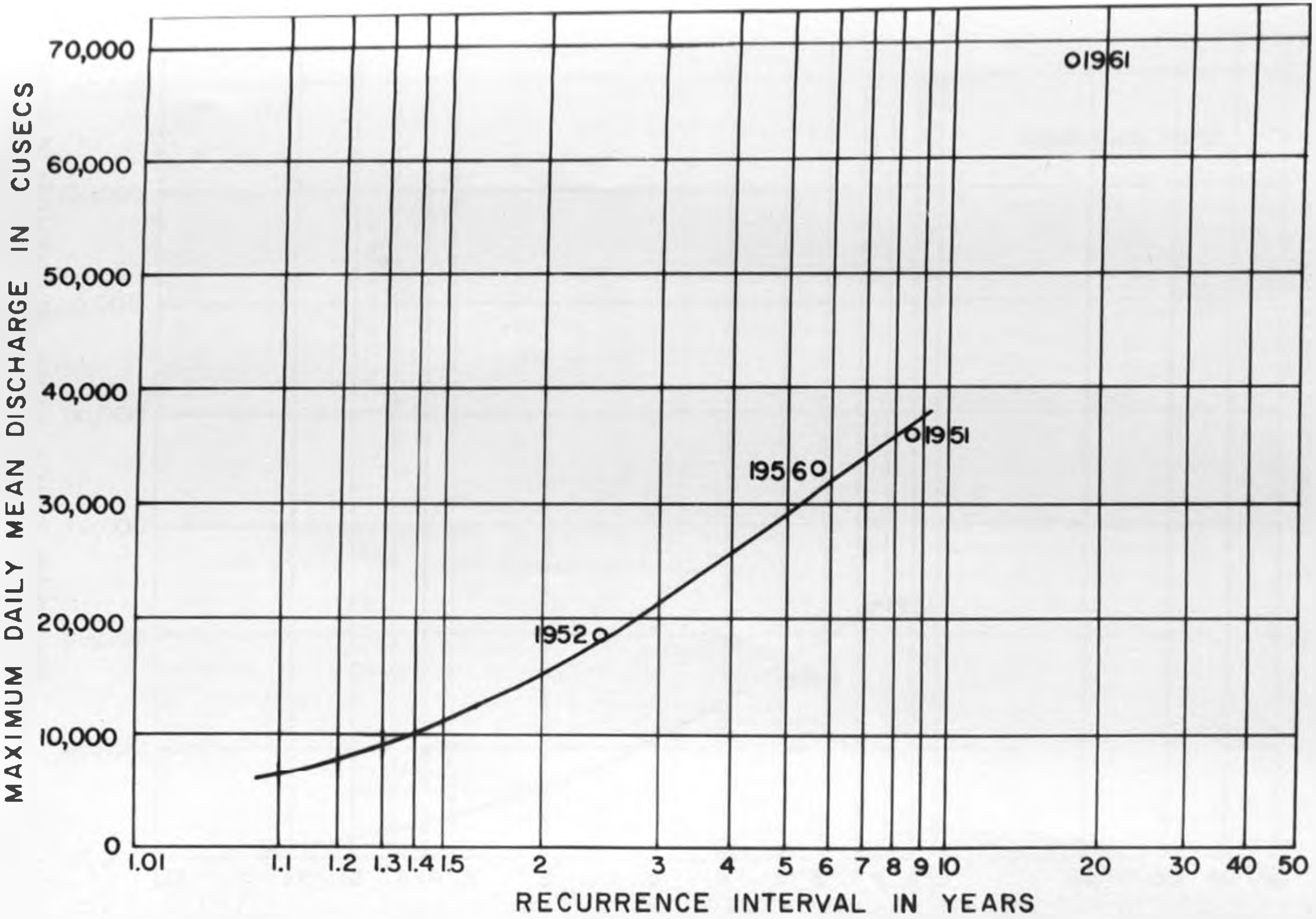
FREQUENCY OF ANNUAL FLOODS, THIKA RIVER

FIG. 5.41



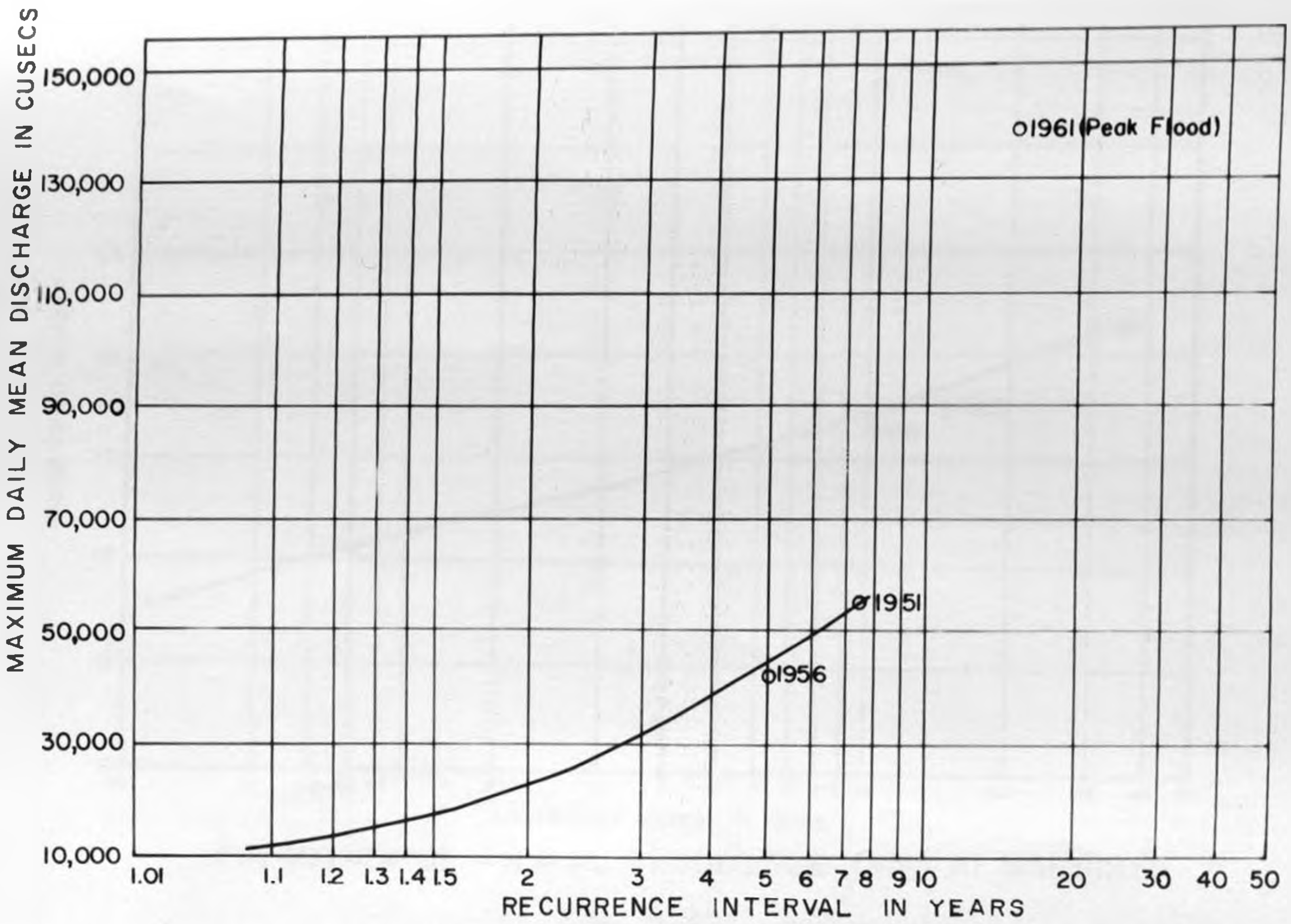
FREQUENCY OF ANNUAL FLOODS, Thiba River.

FIG. 5.42



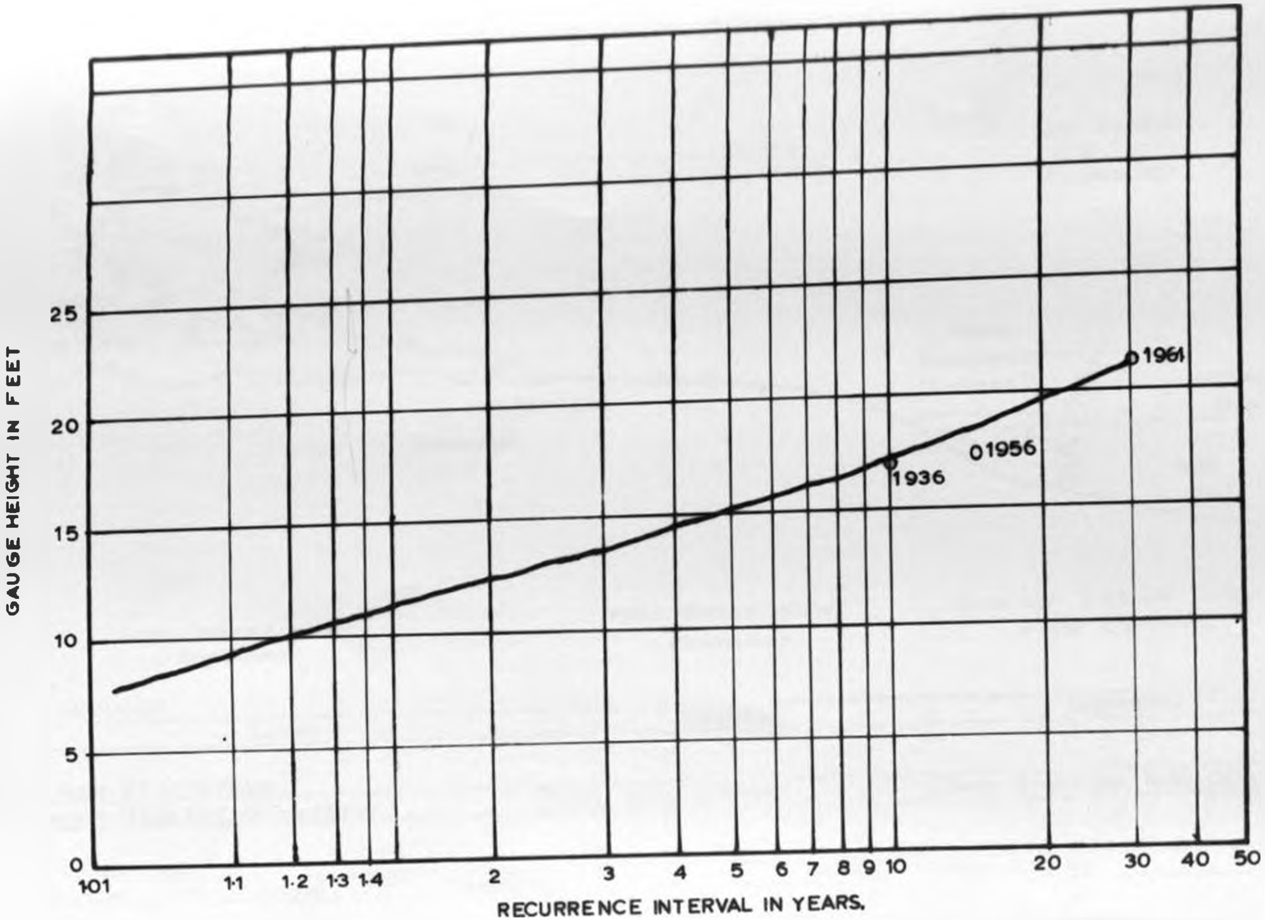
FREQUENCY OF ANNUAL FLOODS, TANA–KAMBURU RIVER

FIG. 5.43



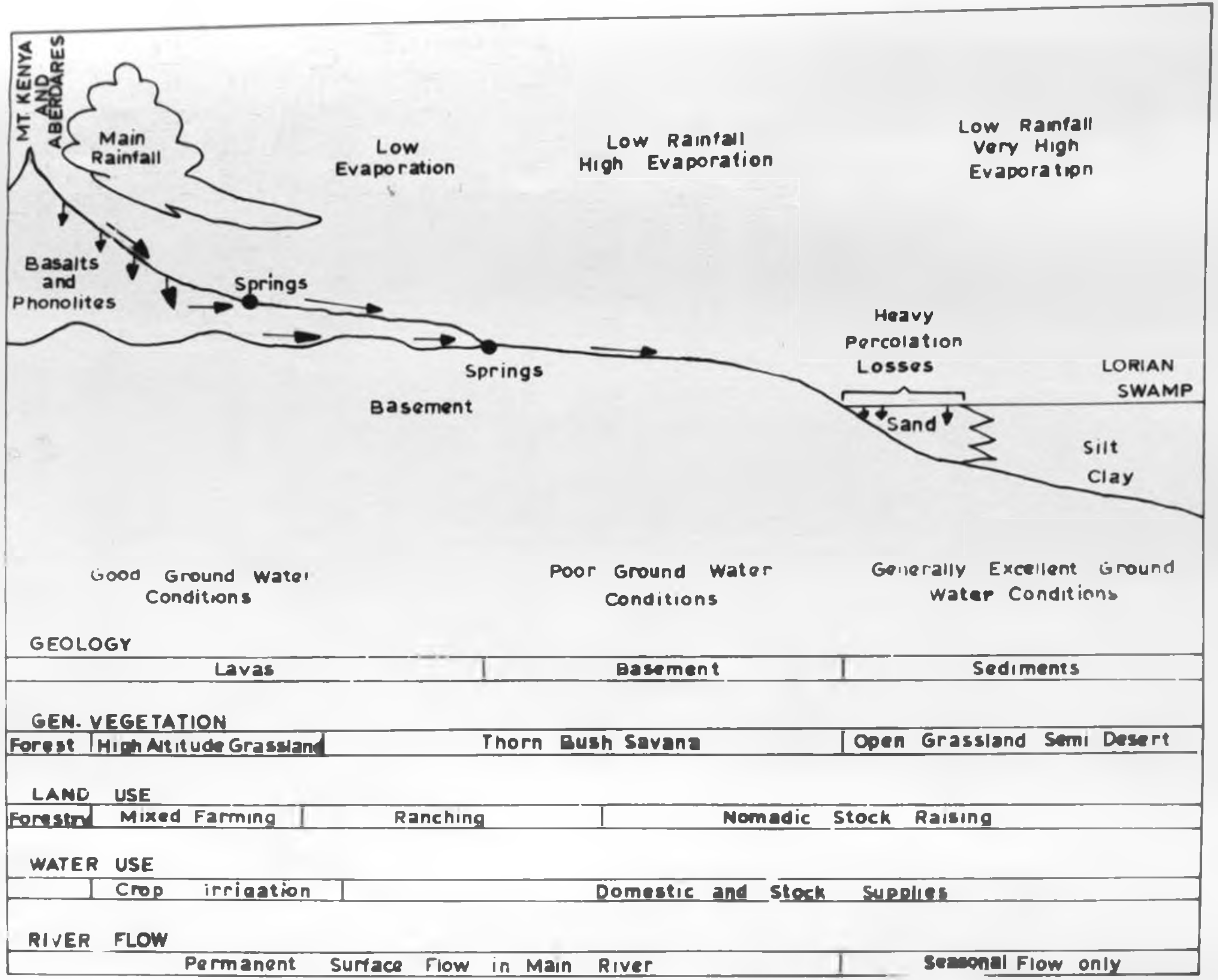
FREQUENCY OF ANNUAL FLOODS, TANA GRAND FALLS

FIG. 5.44



FREQUENCY OF ANNUAL FLOODS FOR TANA AT GARRISSA.

FIG. 5.45



The Hydrological cycle in schematic form.
FIG 5.46

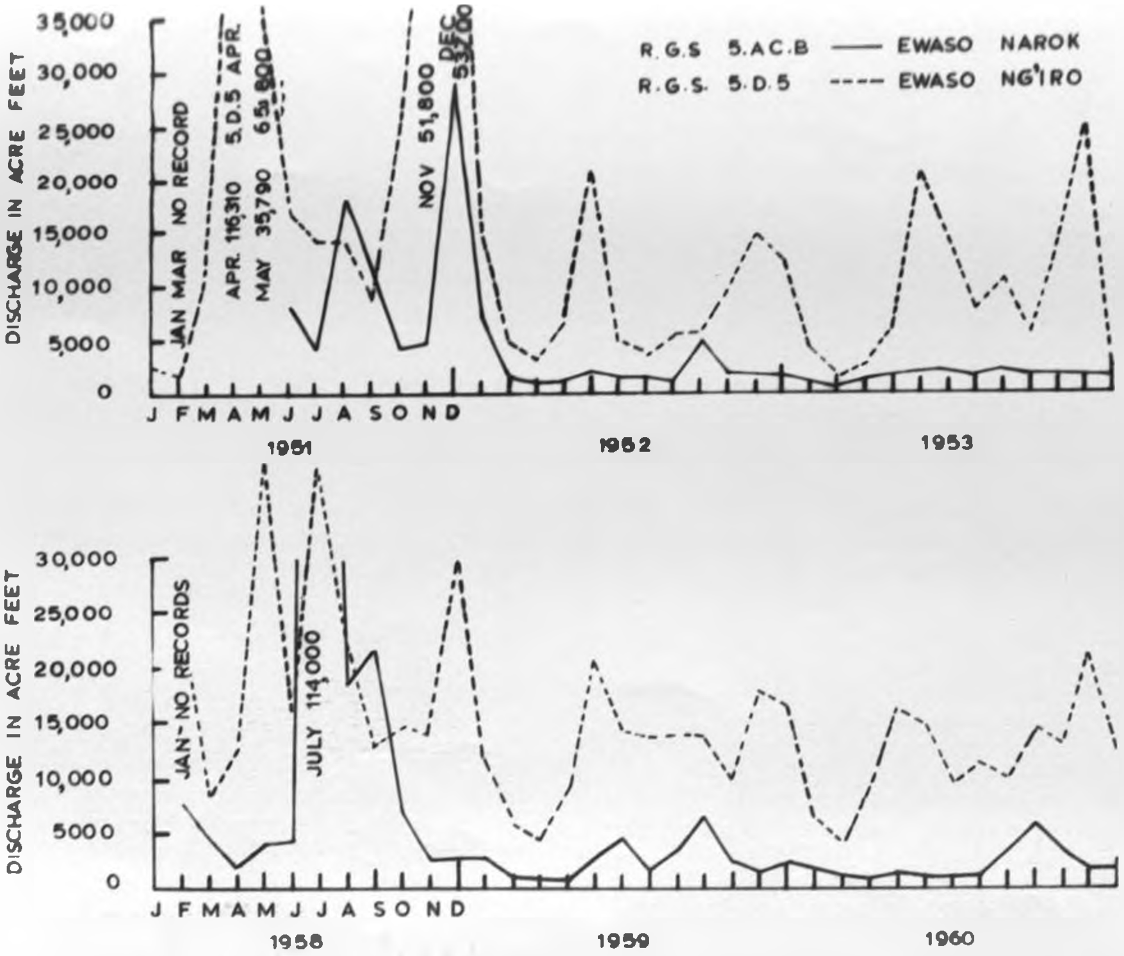
Table V-30. This table also demonstrates the extreme variability of the proportion of the total flow which is provided by the middle catchment. The variability of the flow of the two main streams is shown in Figure 5-47, from which the contrast between dry season flow and flood flow will be apparent as will the variability of flow during corresponding seasons of successive years. The patterns of flow of two tributaries are fundamentally different as a result of the different seasons of rainfall.

A statistical analysis of the river flow over a long period provides estimates of the quantities of water available for certain percentages of time. Table V-31, presents results of the discharge frequency analysis for two river gauging stations as given by the Water Department. A compromise must be adopted between the two extremes when estimating water availability on all - the year - round basis. A figure of 10 per cent probability implies that only during one day in ten (long-term average) will flow fail to exceed the calculated value. This is to be regarded as giving a reasonable basis for estimating the "minimum" quantity of water likely to be available and is a suitable one for agricultural purposes. Table V-32 summarizes the mean annual flow of all the main streams of the Upper Catchment from which the annual dry weather flow as based on the 10 per cent probability figures has been deducted to give the total available flood flow. The figures of total mean annual flow are based solely on actual gauging records and are thus not adjusted for abstractions.

The flood flow contributed by the Middle Catchment, varies widely from year to year and an examination of the gauging records shows that between 1950 and 1960, with exception of 1954-1959, for which no records are available, flood flows in excess of 200 cusecs

TABLE V-30 Breakdown of River Flow at Archer's Post

NAME	1951 (wet year)	1952 (dry year)	1960 (average year)
	%	%	%
Ewaso Narok	22	18	11
Northern Aberdares	7	15	11
West Slopes of Mt. Kenya .	6	23	16
Nanyuki Timau	9	37	40
Below Junction	56	7	22
TOTAL AT ARCHER'S POST ..	100	100	100



Hydrographs of monthly flows at the junction
(Period 1954-1957 omitted to lack of record)

FIG. 5.47

TABLE V-31   DISCHARGE FREQUENCY ANALYSIS OF TWO MAIN STREAMS

Probability of Daily Discharge not exceeding vales shown.

Acre-Feet

RIVER	10%	20%	25%	50%	75%	90%
Ewaso Ngiro ..	101	150	174	313	530	972
Ewaso Narok ..	22	27	32	65	133	252

TABLE V-32 Flood Flow Availability

Acre-Feet/Year

Regular Gauging Station		Name of Streams	Mean Annual Flow	Assumed Total "Low Flow"	Total Annual Flood Flow	Regular Gauging Station	Mean Annual Flow	Assumed Total "Low Flow"	Total Annual Flood Flow	Losses & Abstractions or Gains from Ungauged Streams, etc.	Regular Gauging Station	Mean Annual Flow	Assumed Total "Low Flow"	Total Mean Annual Flood Flow	Losses, Abstractions or Gains from Ungauged Streams, etc.
EWASO NAROK	5AA1	Equator and Springs	42,000 (15)	11,000	31,000	5AC11	12,000 (2)	4,000	3,000	-23,000	5AC8	41,000(4)	[illegible],000	32,000	+20,000
	5AB3	Pesi	12,000 (1½)	6,000	6,000	5AB2	8,000 (2)	4,400	3,600	-2,600					
	5AD1	Mutara	3,000	2,900	100	5AD3	600 (1½)	Nil	600	+ 500					
NORTHERN ABERDARES AND WESTERN MT. KENYA	5BA1	Moyo	2,600 (9)	1,100	1,500										
	5BB2	Ewaso Ng'iro ..	19,000 (8)	6,000	13,000										
	5BC2	Naro Moru ..	23,000 (14)	5,000	18,000										
	5BC5	Rongai	2,200 (10)	500	1,700	5BC4	48,000 (1½)	22,000	26,000	-29,000					
	5BC6	Burguret	16,000 (10)	4,000	12,000										
	5BC8	Ngobit	15,000 (2)	5,000	10,000										
	5BD2	Suguroi	2,400	600	1,800						5D6	168,000(6)	46,000	122,000	+50,000
NANYUKI-TIMAU SYSTEM	5BE1	Nanyuki	19,000 (15)	3,000	16,000										
	5BE2	Ontulili	11,000 (11)	2,000	9,000										
	5BE3	Kongoni	800 (10)	200	600										
	5BE4	Sirimon	10,000 (9)	2,000	8,000										
	5BE5	Teleswani ..	5,900 (13)	4,200	1,700	5BE20	80,000 (7)	34,000	46,000	-16,000					
	5BE6	Timau	4,700 (13)	3,000	1,700										
	5BE7	Liki	34,000 (16)	9,000	25,000										
	5BE19	Ngusishi	600 (2)	100	500							TOTALS:	55,000	154,000	
UPPER CATCHMENT TOTALS ..				65,600	157,600										
	5D2	Ngare Nything ..	1,800	1,300	500										
	5D4	Ngare Ndare ..	3,700 (3)	2,200	1,500										
	5D7	Isiolo ..	5,800 (1)	2,500	2,300										
				71,600	161,900										

(15) Number of years records to obtain mean.

TABLE V-33 Flood Flow Originating from the Middle Catchment and Reaching the Lorain Swamp (Expressed as the Number of Days in which the Flow Exceeded 200 CUSECS)

YEAR	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	TOTAL
1950				12	5	5	5						27
1951													
1952					Floods occurred in the middle and upper catchment but did not reach the Lorian Swamp due to a change of course below Melka Bulfayo								
1953													
1958	15			25								10	50
1959	3				15						25		43
1960				40						2		2	44

originated in this area and lasted for a minimum of 27 days (see Table V-33). These flows are important in that the flooding of the Lorian Swamp which provides essential grazing, can take place independently of floods originating from the Upper Catchment. These can be expected to reduce in frequency with the development of storage in that area. The highest known floods at Archer's Post occurred in 1951, when the maximum was reported to have been about 63,000 cusecs. The mean flow at Archer's Post is calculated to be 1062 acre feet per day. The minimum flow at Archer's Post which is required to carry the flow of the river to the Lorian Swamp is between 180 and 200 cusecs.

The three main river systems east of the Rift Valley namely Athi, Tana and Ewaso Ngiro have some similar characteristics. The headwaters occur in the high rainfall areas of volcanic rocks in which are the groundwater reservoirs which provide their water flows.

On leaving the volcanic rocks all the three rivers flow through a country of Basement complex rocks of areas which are semi-arid and subject to long periods of drought. In some years these dry periods are characterized by occasional rainstorms resulting in rapid runoff with heavy loads of silt. When this happens the intermittent tributary streams thus contribute significantly to flood and silt conditions downstream.

Further downstream the rivers traverse sedimentary formations in which they meander, overflow their banks and occasionally change their course. These sedimentary formations are generally permeable and the rivers lose water rapidly by percolation from their beds as well as by evaporation.

Comparison of minimum flow from headwaters of each of the three major rivers east of the Rift Valley is given in Table V-34. Table V-35 gives a summary of total surface water resources of Kenya as given by Water Department. This at once gives a picture of the great imbalance of surface water resources of Kenya and poses the question of where to obtain sufficient water for the well-being of the rapidly growing population.

CONCLUSION

In the first section of this chapter, quantitative analysis of the varying climatic conditions of the country has been carried out. The two important factors (i.e. rainfall and temperature) governing hydrogeochemical processes have been discussed though by no means exhaustively.

A regional treatment of the climatic set-up has been given, and although it does not, however, claim to be exhaustive, certain fundamental factors have been outlined.

It is necessary to appreciate the fact that from the characteristics of the two parameters of climate (i.e. rainfall and temperature) one can attempt to predict the nature of weathering that is likely to prevail in a given part of the country. One must, of course, work into the influence of other environmental factors as well before making firm conclusions on the resulting water quality. It is also worth noting that it is necessary to have a treatment not only of climatic factors

TABLE V-34 Comparison of Minimum Flows from the Headwaters of Each of the Three Major Rivers East of the Rift Valley

RIVER	CATCHMENT AREA		MINIMUM FLOW		CUSECS/ Sq.Ml.	LITRES/ Sq.Km.
	Sq.Mls.	Sq.Km.	CUSECS	CUMECS		
Athi	2210	5720	35	0.00	0.016	0.17
Tana	3500	9060	531	15.04	0.15	1.66
Ewaso Ngiro	1761	4560	24	0.68	0.014	0.15

TABLE V-35 Total Surface Water Resources of Kenya

Drainage Area	River	M.A.Runoff 1,000,000 cu.m.	Length Km.	Basin Area sq.Km.
1	Nzoia	1,920	258	12,960
	Yala	965	177	2,600
	Nyando	500		
	Sondu	1,235	110	5,200
	Guche-Migori	870	89	5,200
	Others	1,800*		
		7,290		
2	Melawa	184	108	780
	Gilgil	28		
	Molo	39		
	Perkerra	125		
	Others	430*		
		806		
3	Athi	750	547	44,000
	Tsavo	138		
	Njoro-Lumi	293		
	Others	113		
		1,294		
4	Tana (Garissa)	4,700	708	62,210
5	Ewaso Ngiro (Archer's Post)	740	531	57,000
	Total:	14,830		

but also other human and environmental factors that determine the water quality. This is necessary because water quality is a product of the closely related and jointly acting processes of the entire environment.

The second section of this chapter has given quantitative statements regarding surface water resources of Kenya. Where enough data exist problems of total water availability, the annual regime of the river, the frequency of low flows, floods and transport of sediments have been examined.

The relevance of subsurface water statistics given in this chapter to groundwater chemistry lies in the fact that the water chemistry is governed by the entire hydrogeochemical budget of any given area or country. For example, Hendrickson and Krieger (1960) have pointed out that the relationship of the chemical quality of water to stream discharge provides the key to the understanding of the hydrology and geochemistry of a drainage basin. They have continued to show that, there is a general inverse relationship which is not simple between the concentration of dissolved solids and the quantity of water being discharged by the streams. In considering such a relationship such factors as geology of the basin, rate of discharge rate and direction of change in discharge, duration of low flow before increase in discharge, season of the year and certain man-made factors, for example, the extraction of water through such activities as irrigation are taken into account. In discussing the occurrences of dissolved solids in surface waters, Langbein and Dawdy (1964), have indicated how the weathering rates are affected by rainfall and, consequently, how runoff affects the dissolved solids in surface waters. That surface water has great influence on the nature and rates of weathering which in turn determine the nature of the groundwater chemistry will be clearly shown in the next chapter.

SECTION III

6. GEOGRAPHIC AND GEOLOGIC BACKGROUND OF THE VARIATION OF GROUNDWATER CHEMISTRY IN KENYA.

7. WATER RESOURCE PLANNING AND DEVELOPMENT.

CHAPTER VI

THE GEOGRAPHIC AND GEOLOGIC BACKGROUND OF THE VARIATION OF GROUNDWATER CHEMISTRY IN KENYA

This chapter constitutes part of the main subject of this study and is to examine:-

(a) The statistical distribution of given ions in groundwater.

(b) The main geographic factors that underlie the variation of groundwater chemistry.

(c) The main geologic and geomorphological factors that control the groundwater chemistry.

The chemical composition of groundwater, as illustrated schematically in Figure 6-1, is a result of climatic, biologic, hydrologic, geologic and chemical processes that are active in any given environment. As already indicated above, this chapter is only concerned with the main geographic and geologic factors that control the groundwater chemistry. But by including the geographic factors, the important biological and hydrologic processes are also incorporated. This is largely because these are controlled by climate. For example, runoff is correlated with rainfall and temperature, so is vegetation density (and therefore the production of CO_2 when the vegetation decays). This should not, however, imply that these are the only factors that influence the composition of groundwaters.

Precipitation and air temperatures are controls of evapotranspiration, infil~~l~~tration, and therefore of the

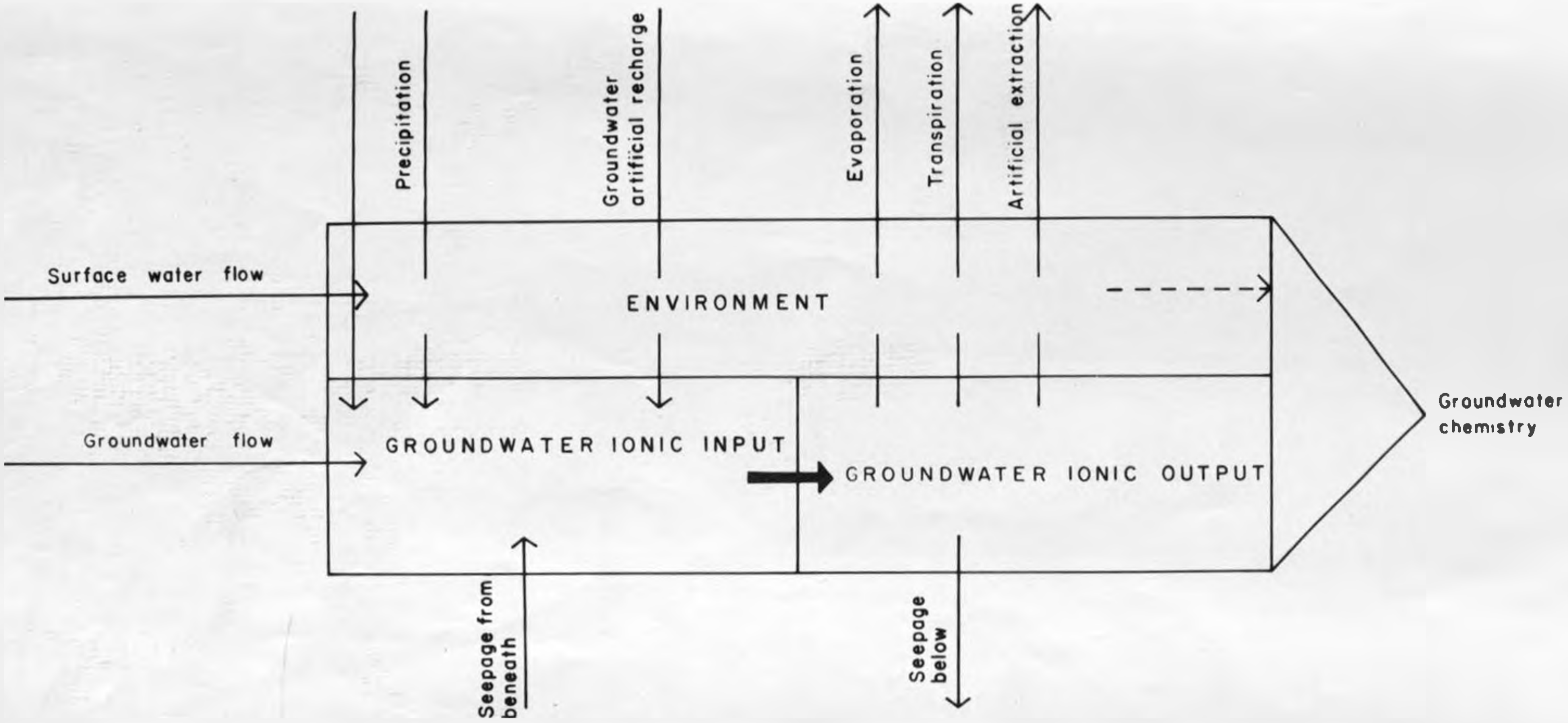


FIG 6.1 THE CONTRIBUTION AND EXTRACTION OF CHEMICAL CONSTITUENTS OF GROUNDWATER

recharge to the soil-water and groundwater systems. They therefore control the amount of water that is available for the chemical weathering which mobilizes ions from the rock minerals. This recharge and percolation through the groundwater aquifer to streams determines the intensity with which ions are leached out of rocks into streams. If groundwater recharge and leaching rates are high, for example in a cool, rainy climate, then chemical weathering (as measured by the transport of dissolved solids in streams) will be intense, but the concentration of ions in groundwater and streams will be relatively low, because the water is leached rapidly through the aquifer and does not have sufficient time to come into equilibrium with the rock minerals of the surroundings. In an area of low precipitation and high temperatures, on the other hand, groundwater recharge is low and the water may remain in contact with rock minerals for very long periods of time. Thus, groundwater in an arid region may be expected to have a greater concentration of dissolved solids than groundwater in the same rock type in a humid region. Precipitation is also of importance for other reasons but as it may be seen later, the major source of CO_2 for rock weathering is that produced by the microbiological breakdown of plant material in the soil. It is therefore roughly correlated with the amount of plant material and thus the precipitation and temperature.

The main components of groundwater recharge as shown in Figure 6-1, which is essentially the ionic budget of aquifers, include:-

(a) The infiltration and percolation of part of the total precipitation at the surface. Here the relationship between rainfall intensity and infiltration capacity is crucial.

(b) Seepage from surface water bodies such as streams, lakes, oceans and reservoirs.

(c) Intrusion of waters from other underground water bodies. (Juvenile water from the Crust)

(d) Artificial recharge through such processes as irrigation.

The climatic and surface water statistics, which are important in relation to the provision of groundwater recharge, and consequently groundwater chemistry in Kenya, have been outlined in chapter V. It must be appreciated that the amount of total dissolved solids in streams is related to the discharge. It has also been shown earlier in this chapter that there is a correlation between runoff and rainfall and consequently groundwater chemistry. In conclusion it may be appreciated that water availability will greatly determine the nature of groundwater chemistry in any one given environment.

As shown in Figure 6-1, the main groundwater discharge variables which provide for the escape of ions from the groundwater include:-

(a) Evaporation which leads to the extraction of water from groundwater as well as surface water, leaves water highly concentrated in soluble salts.

(b) Seepage from groundwater into surface water bodies. Here the geological and geographical setting and location of given groundwater body is important in providing a medium for the escape of ions from groundwater through seepage of this kind.

(c) Seepage of water from one aquifer into the other. Here the geologic and geomorphological factors which will be discussed below become important. It should, however, be noted that the slope of the aquifer is important because it determines the geographical gradient of the flowing groundwater body.

In examining the geologic factors influencing the groundwater chemistry, the following geologic and geomorphological components need special mention:-

i The chemical composition of the various rock units. This is particularly important because the supply of chemical ions to groundwater is obtained from the given rock or soil through the hydrologic and weathering processes.

ii Rock and soil mineralogy. As shown in the next chapter, different minerals respond differently to weathering processes. For example, it is known that neither the solubility of minerals nor their hardness is the same. This then means that solutions from these minerals to groundwater will be equally different.

iii The structural framework of the given soil or rock material determines the rate at which the water moves through the soil or rock. It also determines the direction of movement of water and therefore the mixing up of waters from different aquifers. As shown in the earlier paragraphs of this chapter, the rate of movement of water through a given aquifer, will determine the time that the water has to come into equilibrium with its surrounding rock or soil minerals and consequently the amount of the concentrated salts in the groundwater.

iv Geomorphological factors such as the nature of landforms, their location, aspect and location. The environmental factors examined, climatic and hydrologic parameters taken into account, are distributed over space and these are referred to as geographic factors in this study. Geographic and geologic factors are important controls of ions in groundwater. Other factors which may be important locally include dry fallout of dust, gaseous forms from the sea, land surfaces, volcanic eruptions and products of air pollution.

A Statistical Distribution of Chemical Ions in the Groundwaters of Kenya

For reliable statistical interpretation of a vast quantity of data, they should be homogenous. The problem of heterogeneity in this particular investigation has been effected by the classification of groundwater chemistry on [illegible] more than

where?

the basis of rock units shown in Figure 6-2. This is a simplified geological map of Kenya on the scale of 1:1 million. This map has been compiled specifically for this purpose. Where possible and especially when a sufficient number of samples exist, statistical treatment has been based on each one rock unit shown in the map. However, where there has been no sufficient number of samples in a given rock unit, various rock units have been combined on the bases of the similarity in the mineralogical-chemical composition and age for statistical interpretation. For example, Tertiary and Quaternary phonolites have been grouped into a single unit. Even if this has been done, the variability in the number of water samples acquired from each geologic unit is considerable.

This investigation is based on over 7,000 groundwater chemistry analyses taken from more than 500 boreholes and wells in the country. The depth from which the water for chemical analysis is taken is variable, ranging from a few feet in some boreholes and wells to well over several hundred feet below the surface in others. This raises the problem of water quality classification and since this has been discussed in Chapter II as a limitation, no further examination is presented here.

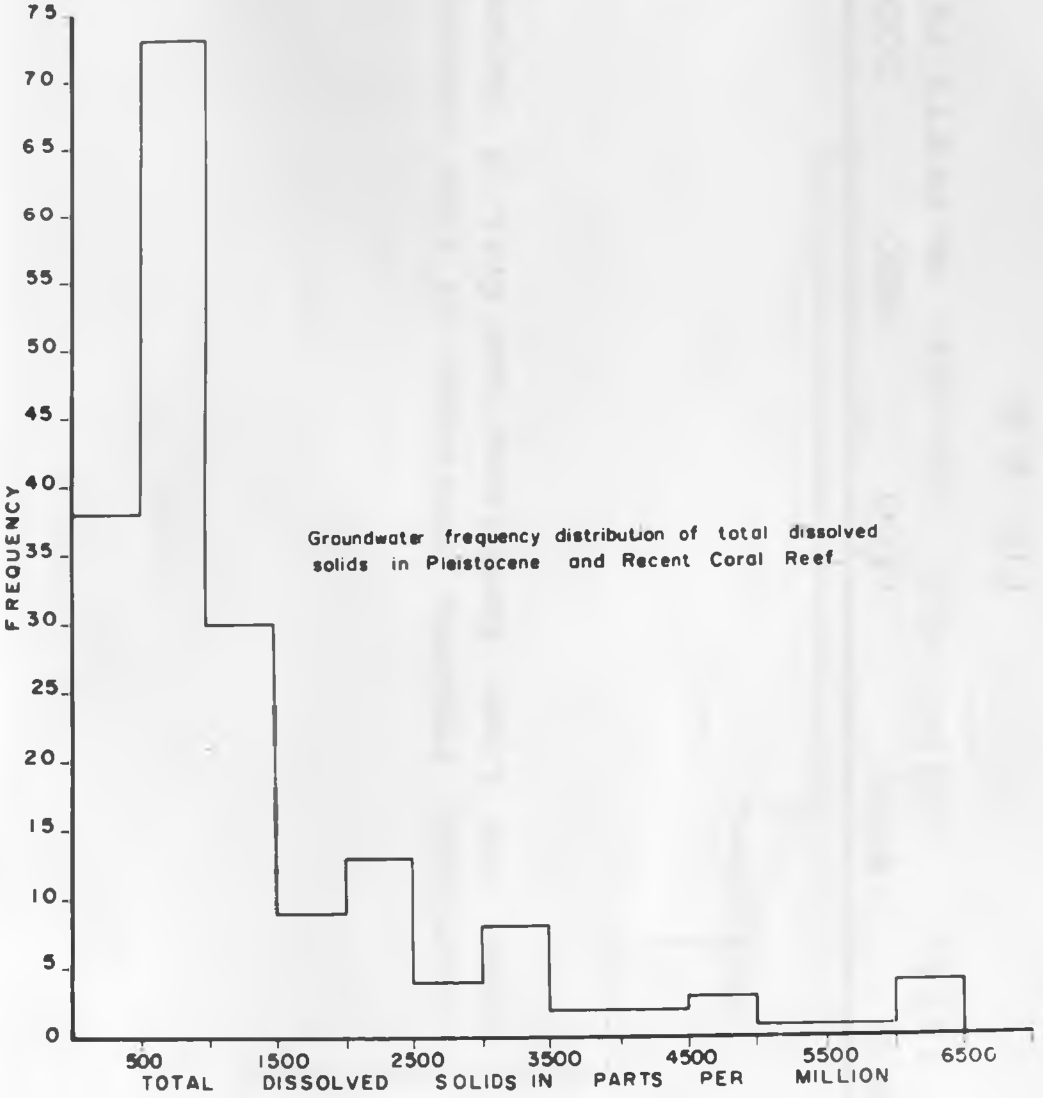
The first question to be answered is what sort of statistical distribution pattern best fits the various chemical ions in groundwater for the given geological units. From the frequency curves that were plotted for total dissolved solids, calcium and magnesium ions in groundwater for various rock units, as illustrated in Figures 6-3 to 6-29, it is clear that the concentrations of these ions, and indeed most of the other ions, in groundwater show large skewness.

Vistelius (1960), formulated a fundamental law of the geochemical processes according to which "The joint probability distribution function of the minor chemical elements deposited by natural chemical reactions has a large positive skewness." He goes on to state that the positive skewness indicates that the deposition of small concentrations of the minor elements by geochemical processes is, as a rule, more stable than the deposition of large concentrations of the same elements by the same geochemical processes. The quantity of the deposited elements in the form of small concentrations being not less than that in the form of large concentrations.

For groundwater samples for each rock unit, cumulative frequencies of total dissolved solids, calcium and magnesium plotted on logarithmic probability paper as shown in Figures 6-30 to 6-38, result in straight lines. This is an indication of log-normally distributed data (Tenant and White, 1959). This is in conformity with the lognormal laws of geochemistry advanced by Ahrens (1954, 1957, 1963, 1965) according to which "The concentration of an element is lognormally distributed in a specific igneous rock" and a subsidiary law, namely, "The abundance of an element in any igneous rock is always greater than its most prevalent concentration." The difference may be immeasurably small or very large as is determined solely by the magnitude of the

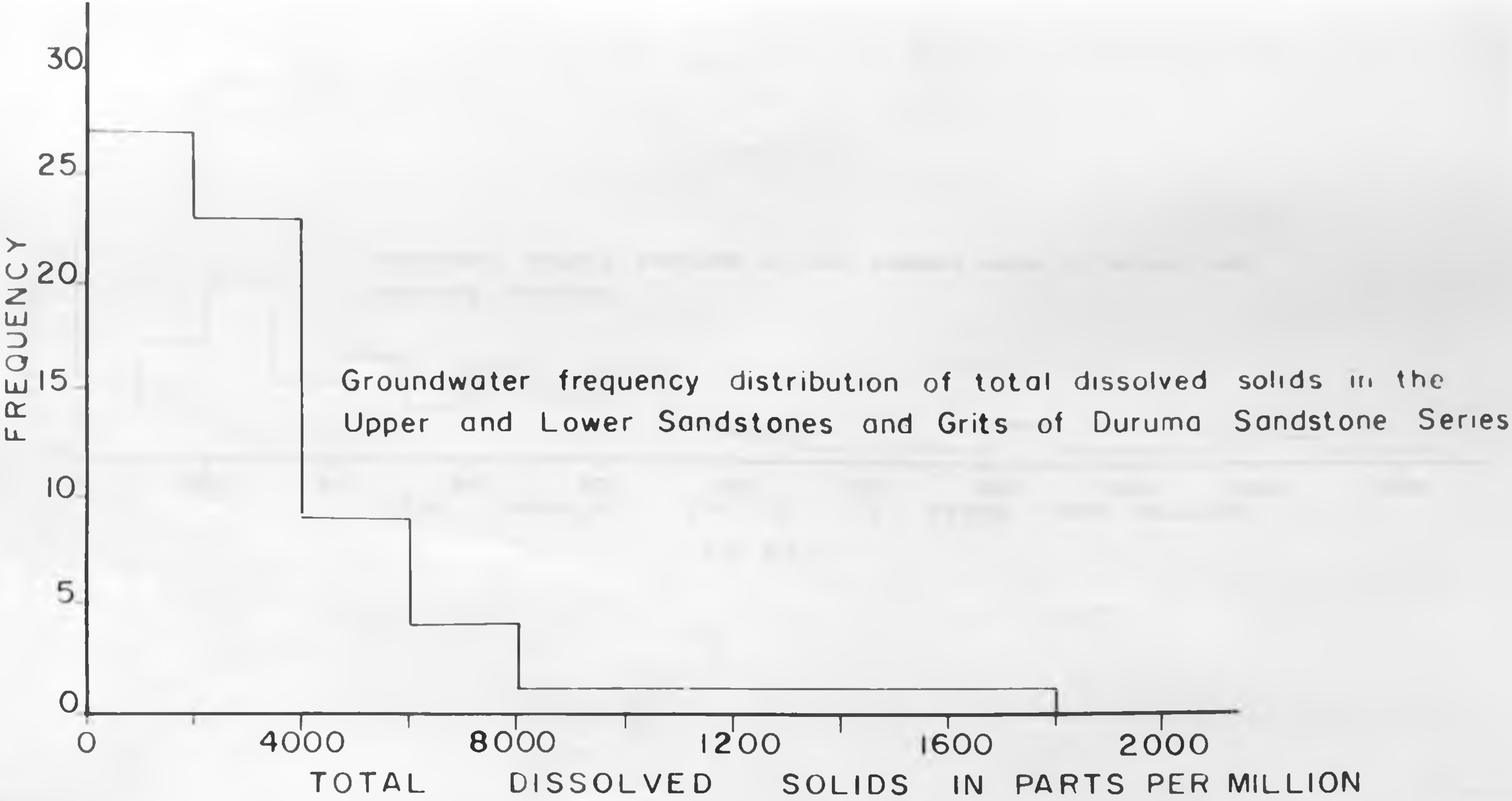

80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
FREQUENCY
Groundwater frequency distribution of Total Dissolved Solids in Quaternary Sediments.
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
TOTAL DISSOLVED SOLIDS IN PARTS PER MILLION

FIG 6 3



Groundwater frequency distribution of total dissolved solids in Pleistocene and Recent Coral Reef

FIG. 6.4



Groundwater frequency distribution of total dissolved solids in the Upper and Lower Sandstones and Grits of Duruma Sandstone Series

FIG. 6.5

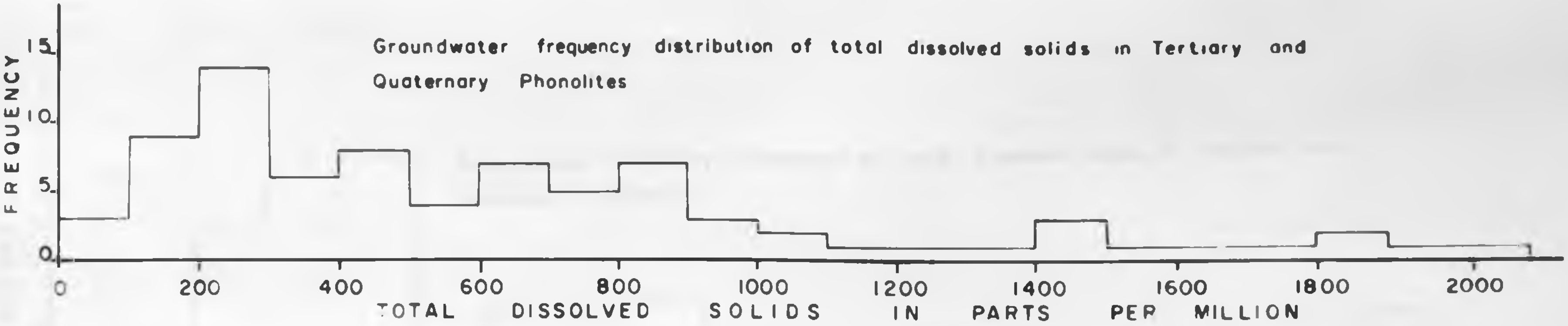
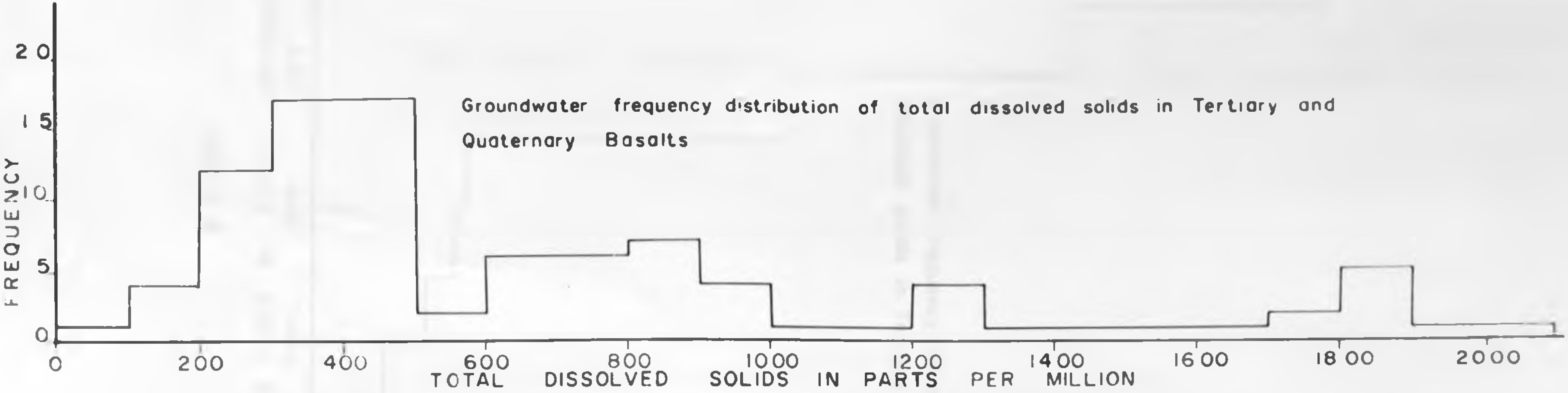

Groundwater frequency distribution of total dissolved solids in Tertiary and Quaternary Phonolites
FREQUENCY
15
10
5
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TOTAL DISSOLVED SOLIDS IN PARTS PER MILLION

FIG. 6.6



Groundwater frequency distribution of total dissolved solids in Tertiary and Quaternary Basalts

FIG 6.7

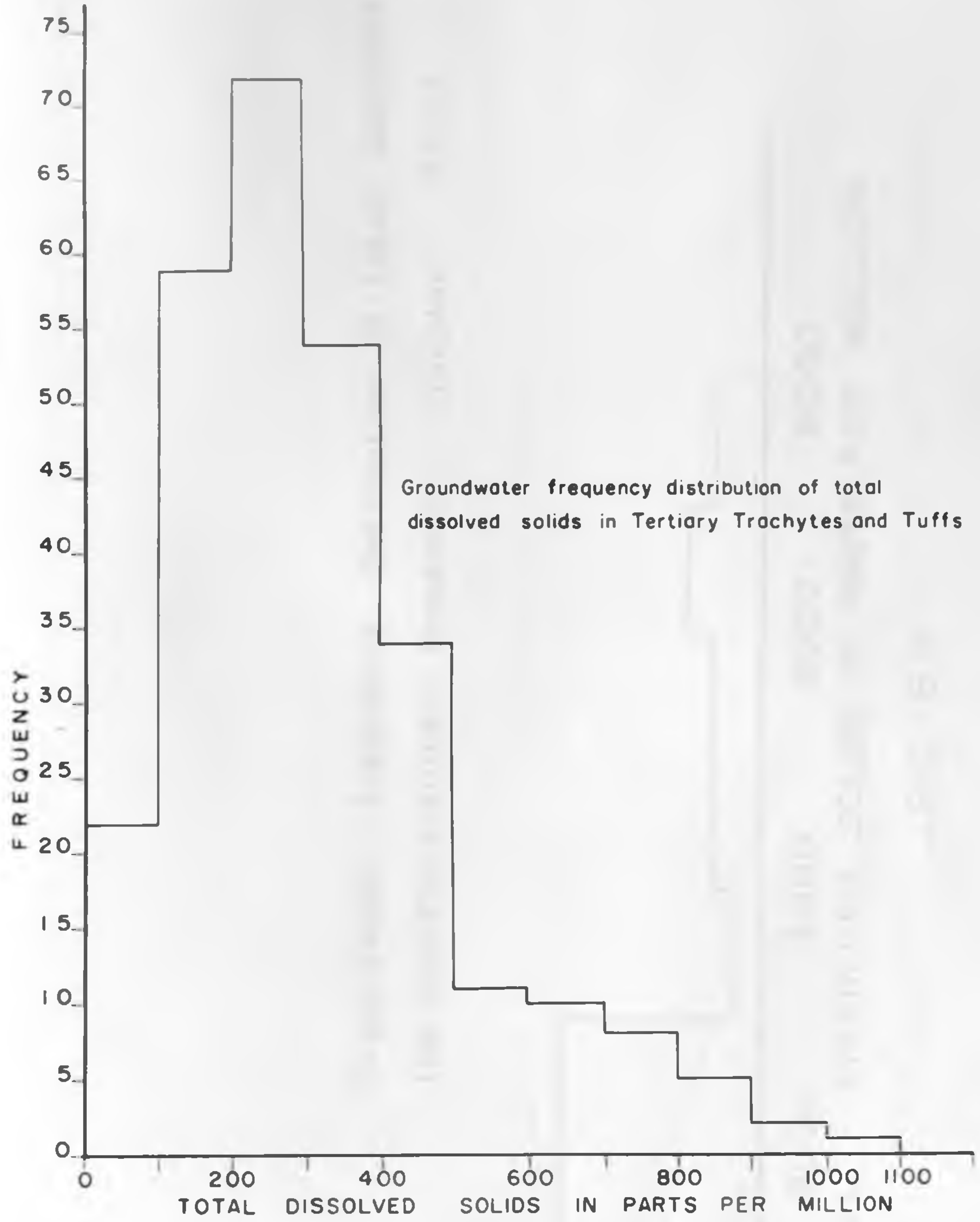
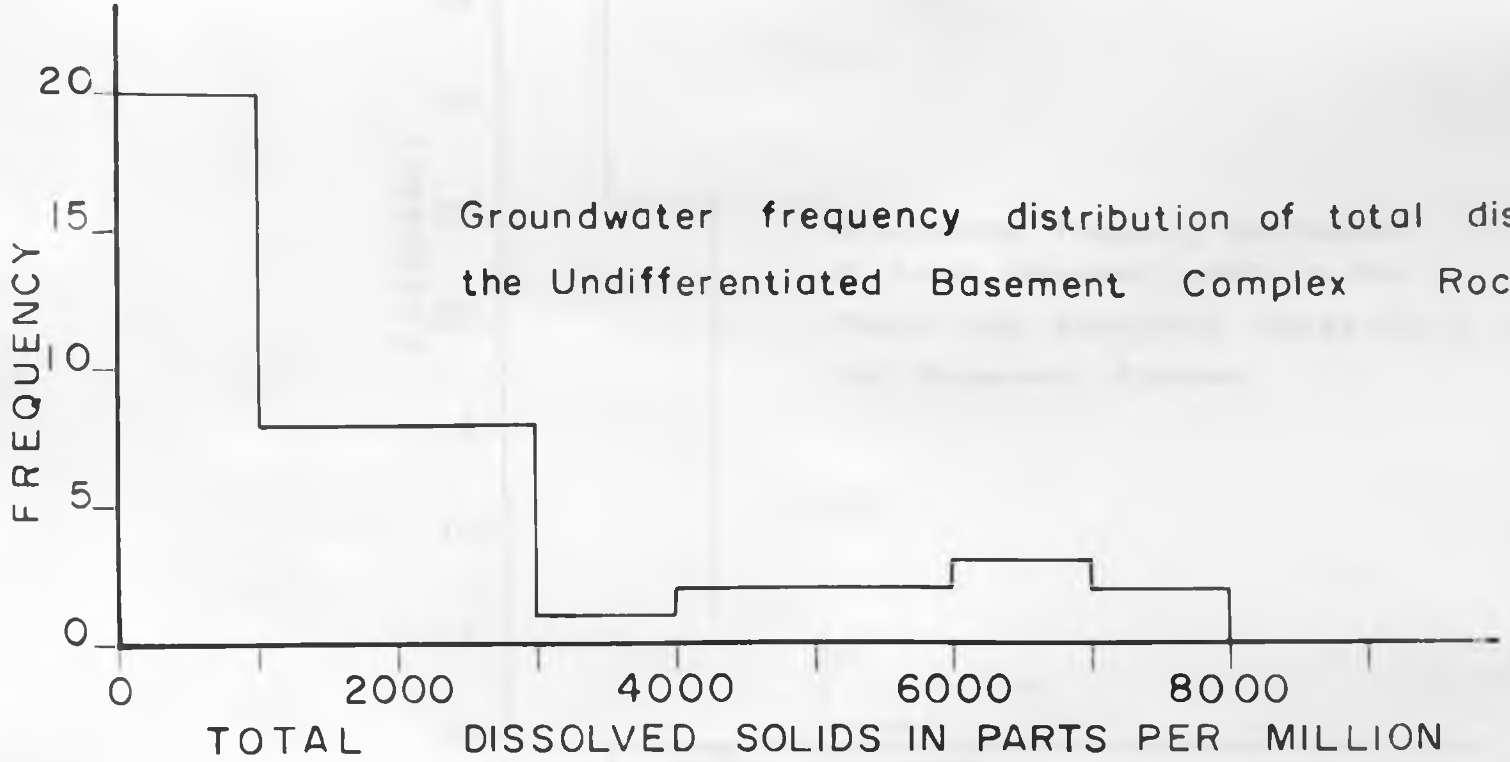
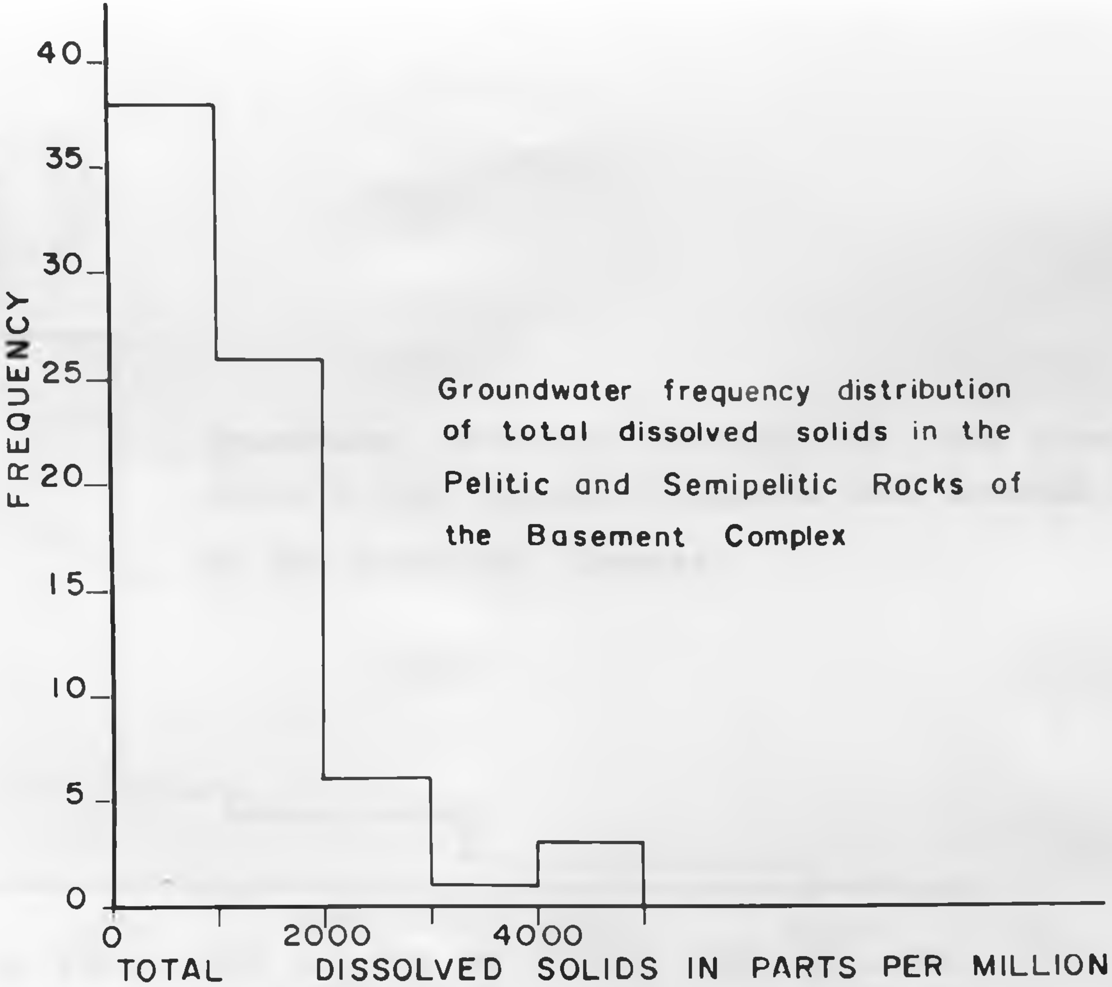

75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
FREQUENCY
0
200
400
600
800
1000
1100
TOTAL DISSOLVED SOLIDS IN PARTS PER MILLION
Groundwater frequency distribution of total dissolved solids in Tertiary Trachytes and Tuffs

FIG. 6.8



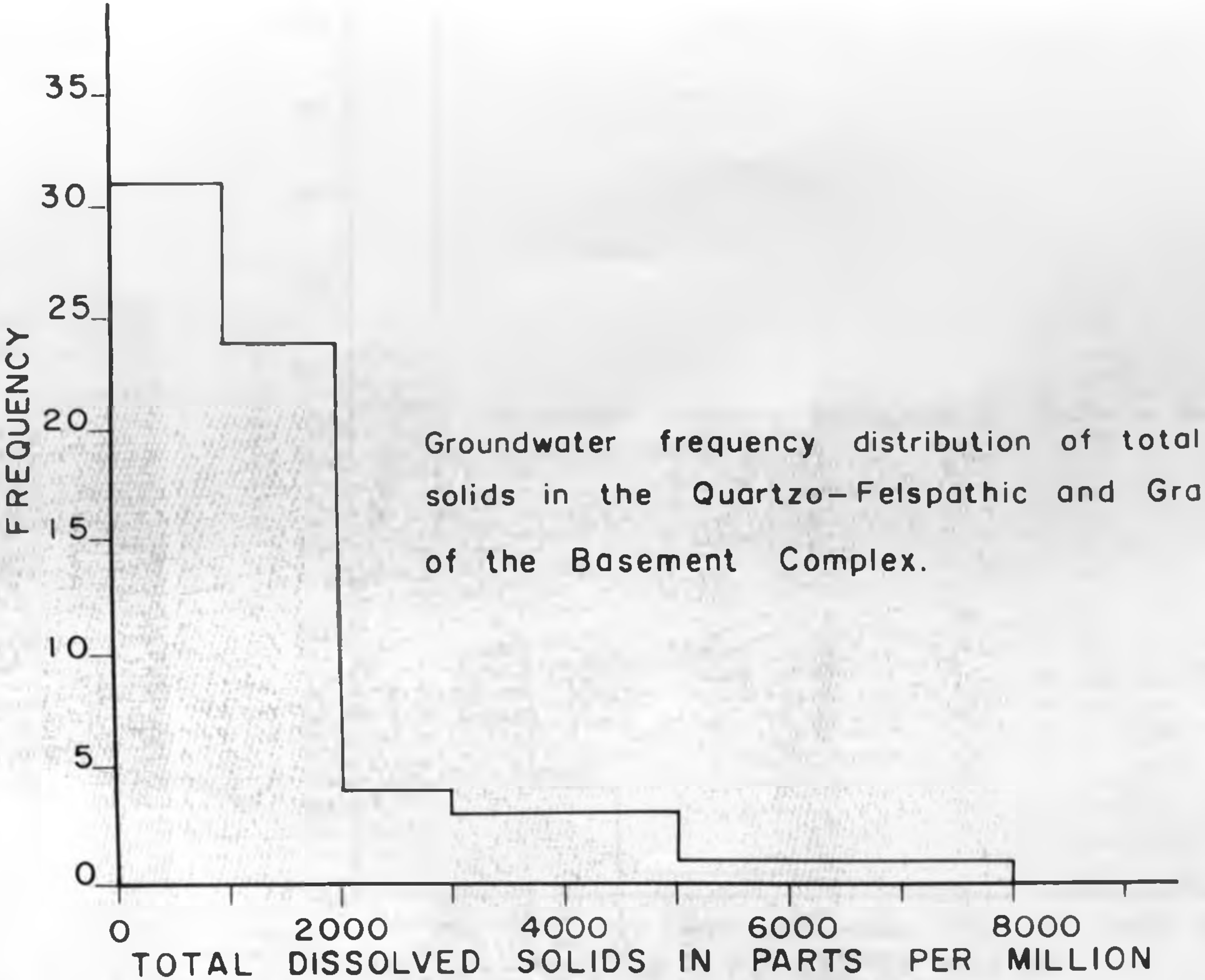
Groundwater frequency distribution of total dissolved solids in the Undifferentiated Basement Complex Rocks

FIG. 6.9



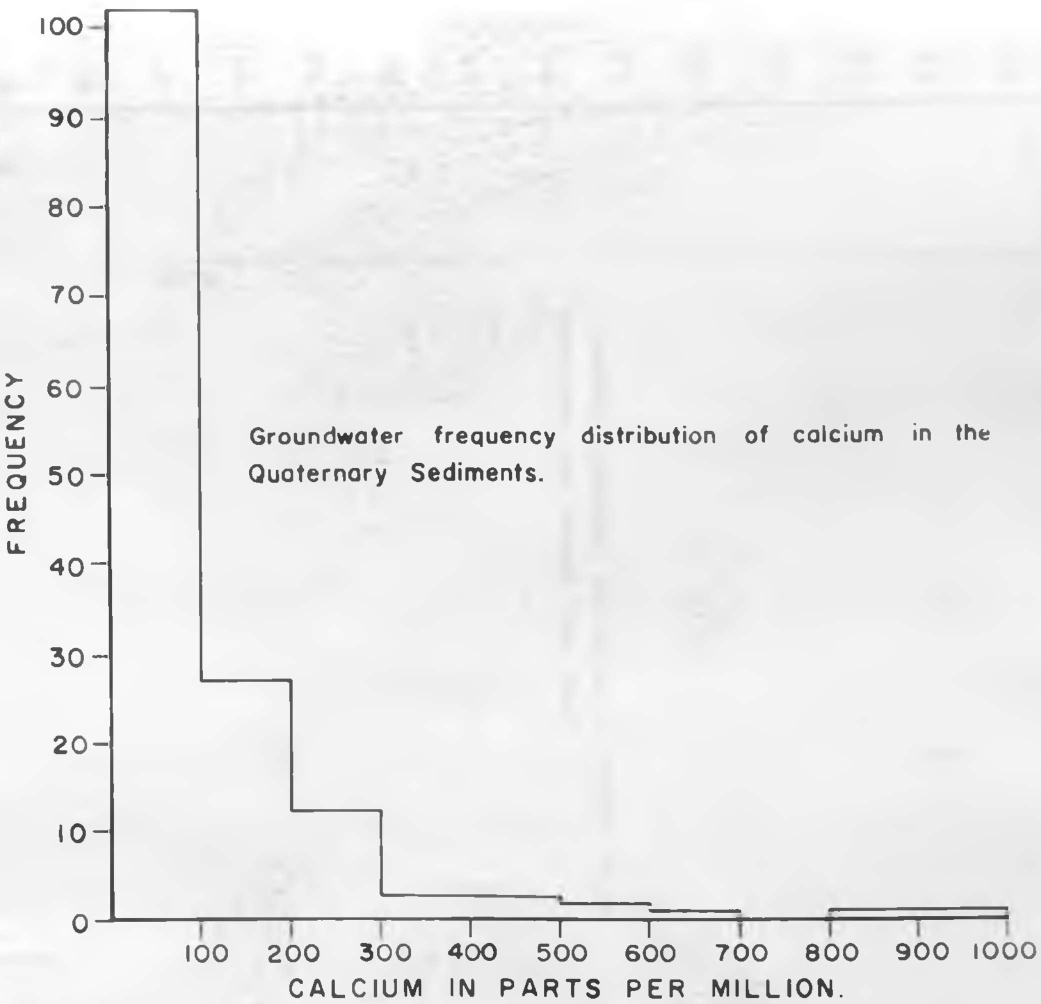
Groundwater frequency distribution of total dissolved solids in the Pelitic and Semipelitic Rocks of the Basement Complex

FIG. 6.10



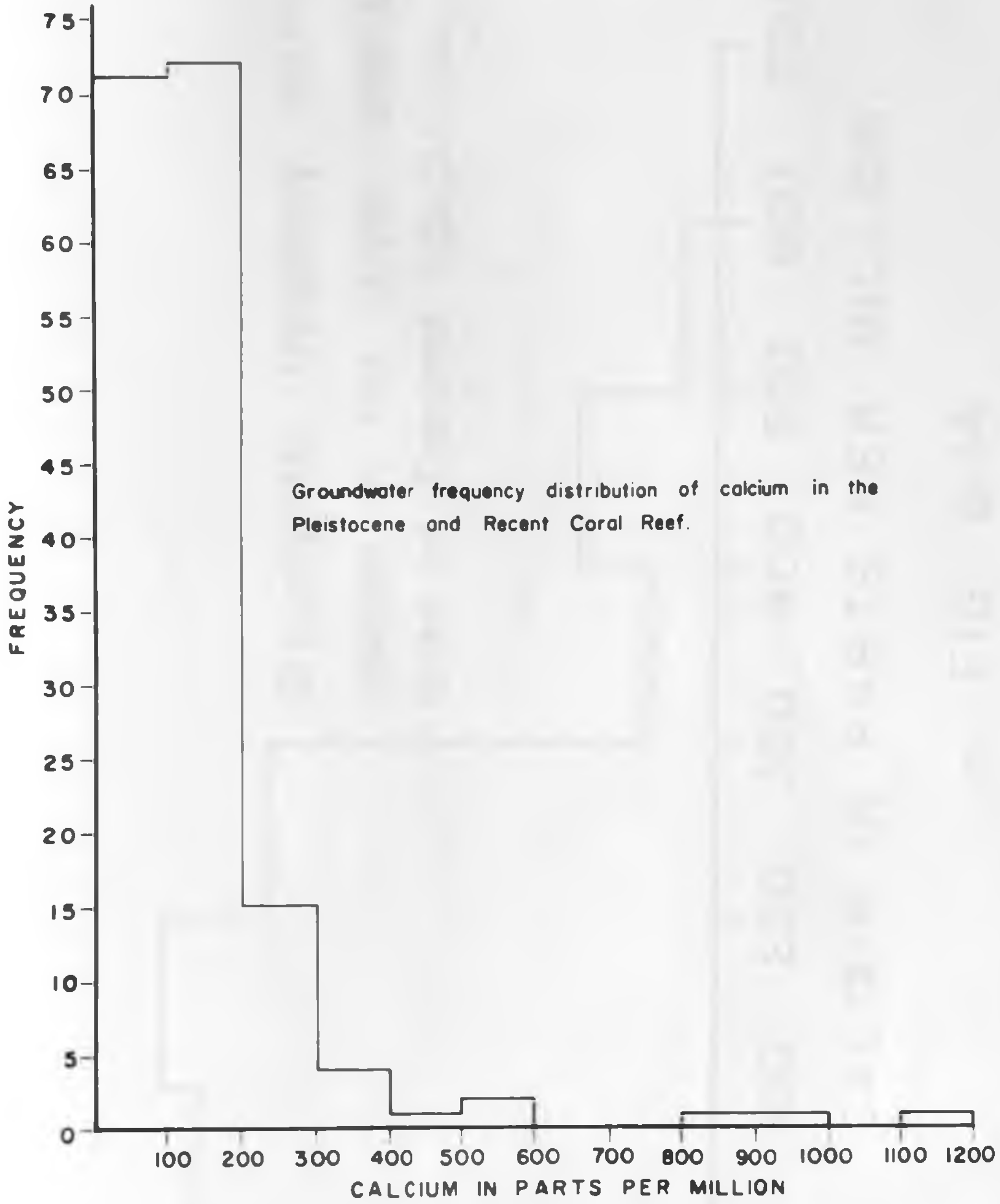
Groundwater frequency distribution of total dissolved solids in the Quartzo-Felspathic and Granitoid Rocks of the Basement Complex.

FIG. 6.11



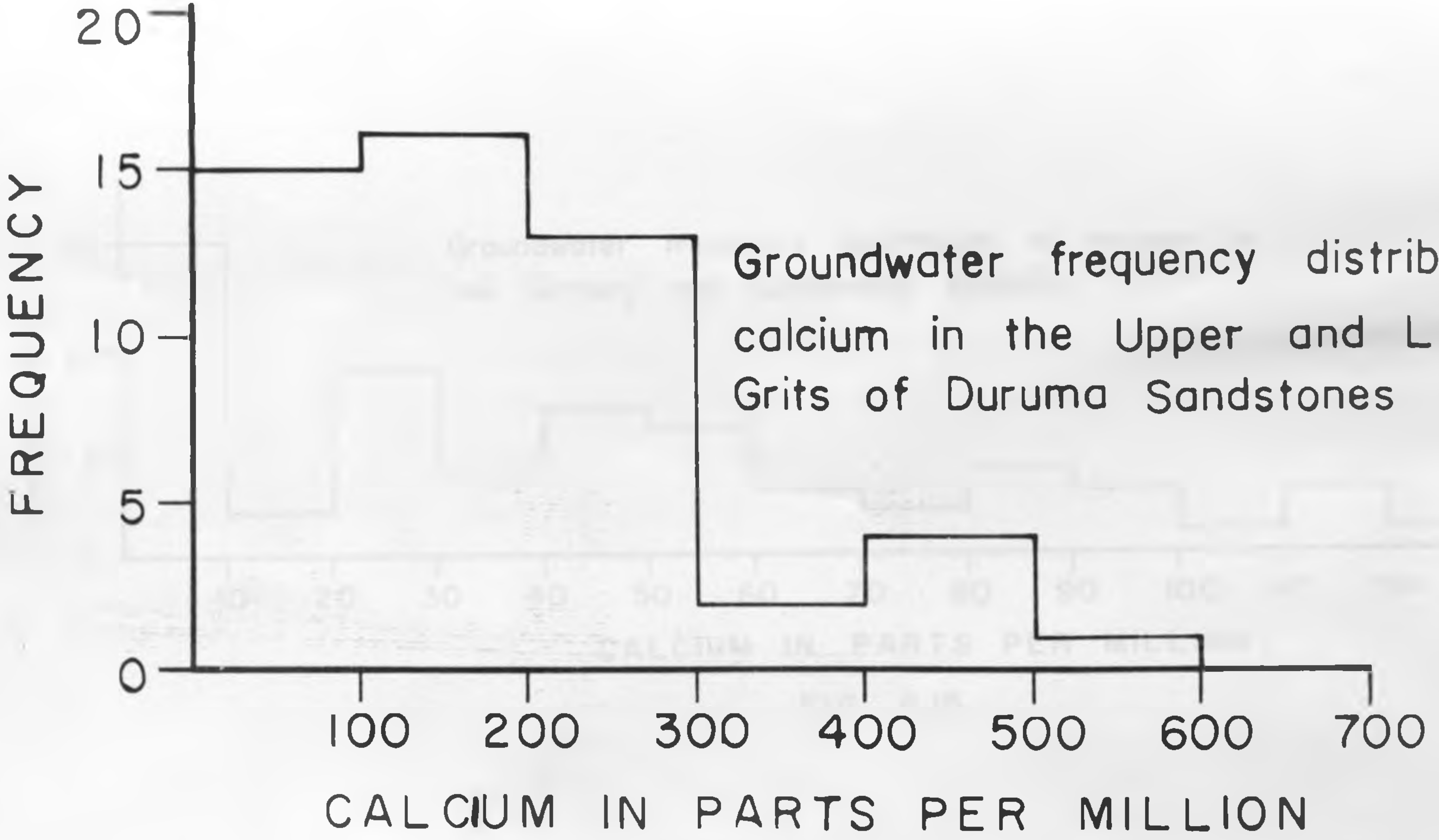
Groundwater frequency distribution of calcium in the Quaternary Sediments.

FIG. 6.12



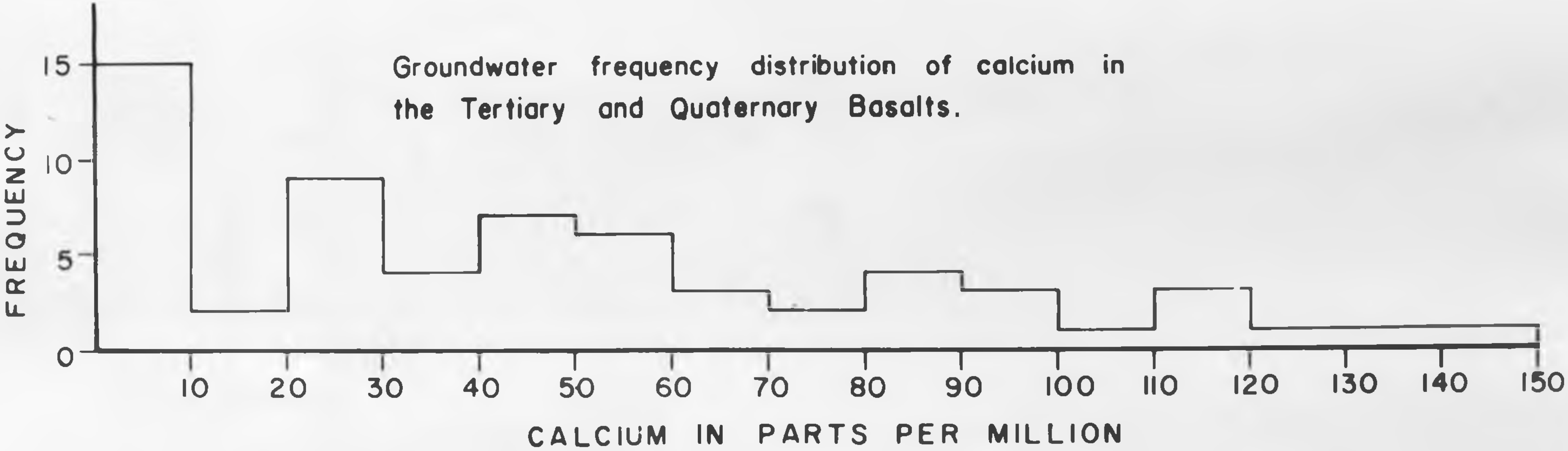
Groundwater frequency distribution of calcium in the Pleistocene and Recent Coral Reef.

FIG 6.13



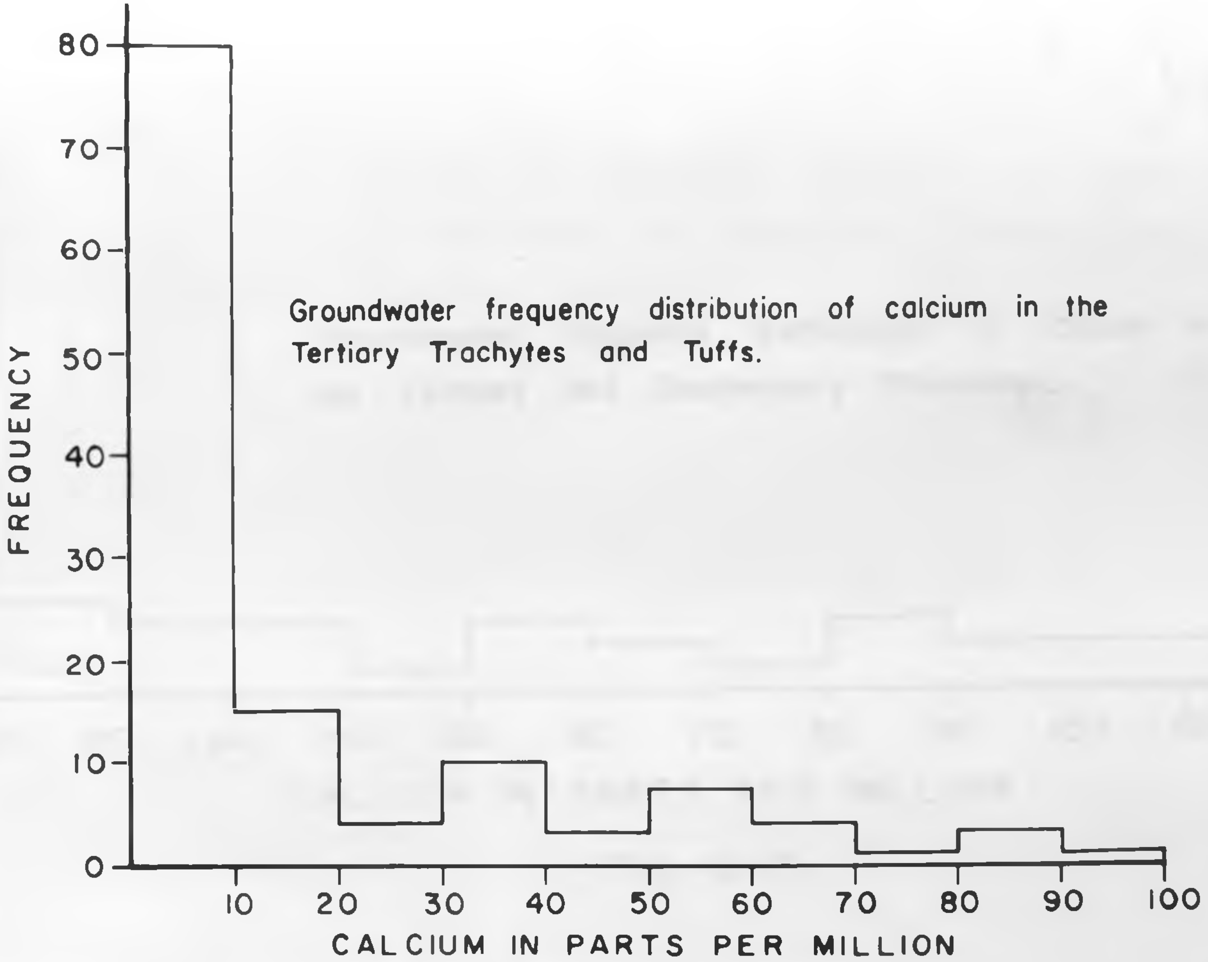
Groundwater frequency distribution of calcium in the Upper and Lower Stones Grits of Duruma Sandstones Series.

FIG. 6.14



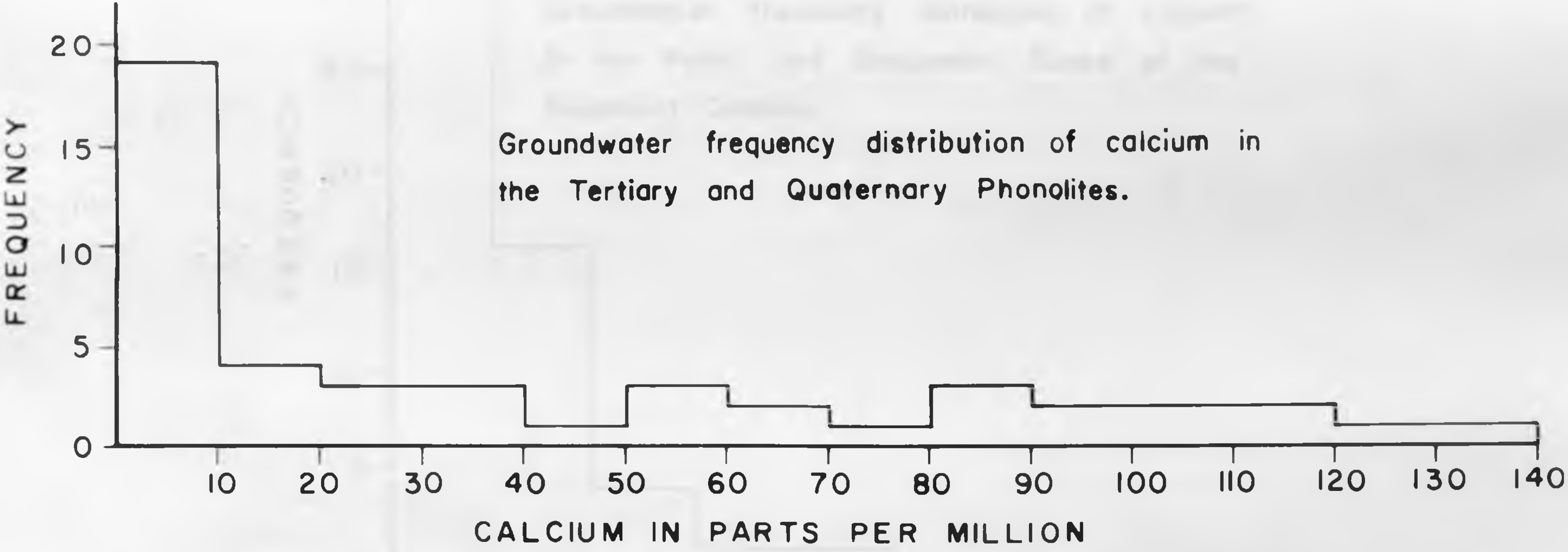
Groundwater frequency distribution of calcium in the Tertiary and Quaternary Basalts.

FIG. 6.15



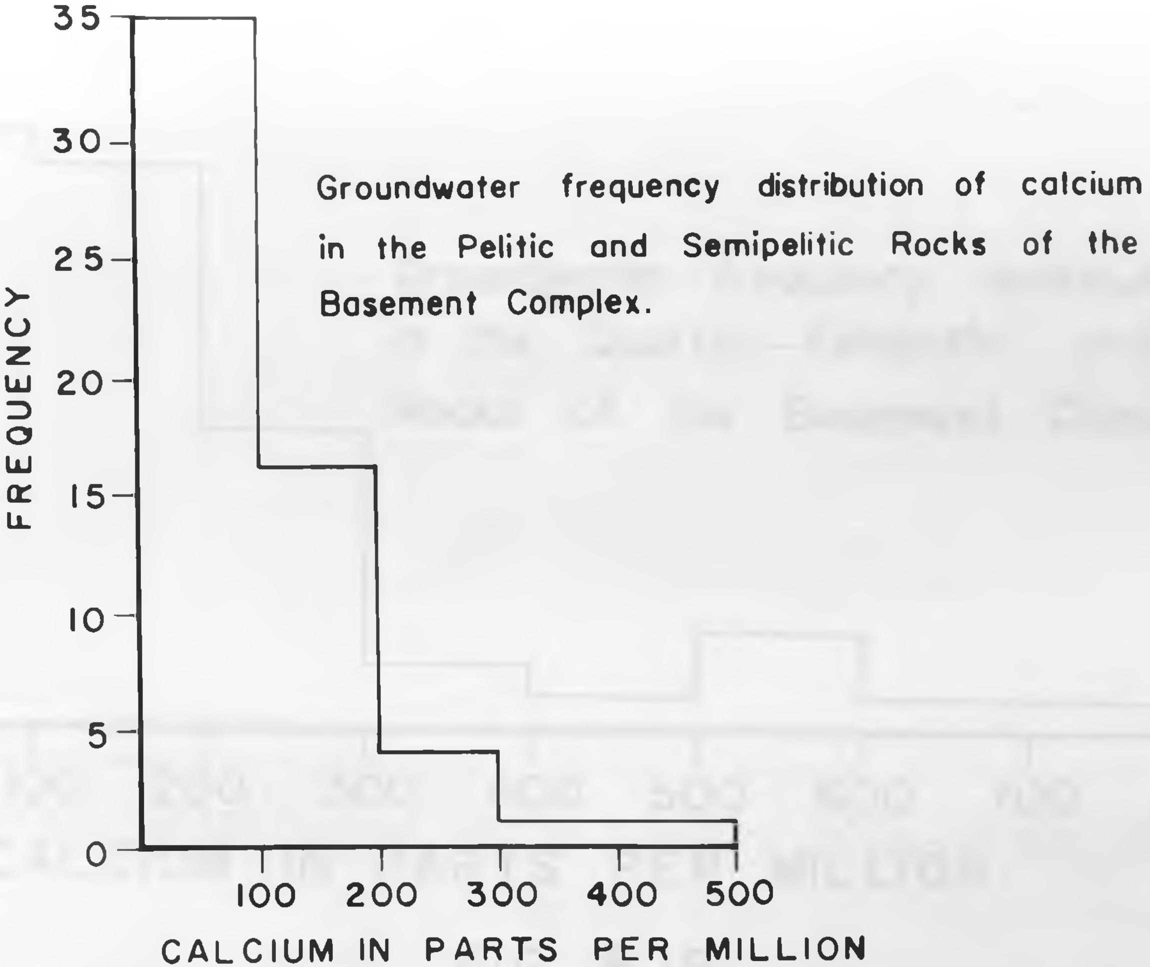
80
70
60
50
40
30
20
10
0
FREQUENCY
10
20
30
40
50
60
70
80
90
100
CALCIUM IN PARTS PER MILLION
Groundwater frequency distribution of calcium in the Tertiary Trachytes and Tuffs.

FIG. 6.16



Groundwater frequency distribution of calcium in the Tertiary and Quaternary Phonolites.

FIG. 6.17



Groundwater frequency distribution of calcium in the Pelitic and Semipelitic Rocks of the Basement Complex.

FIG. 6.18

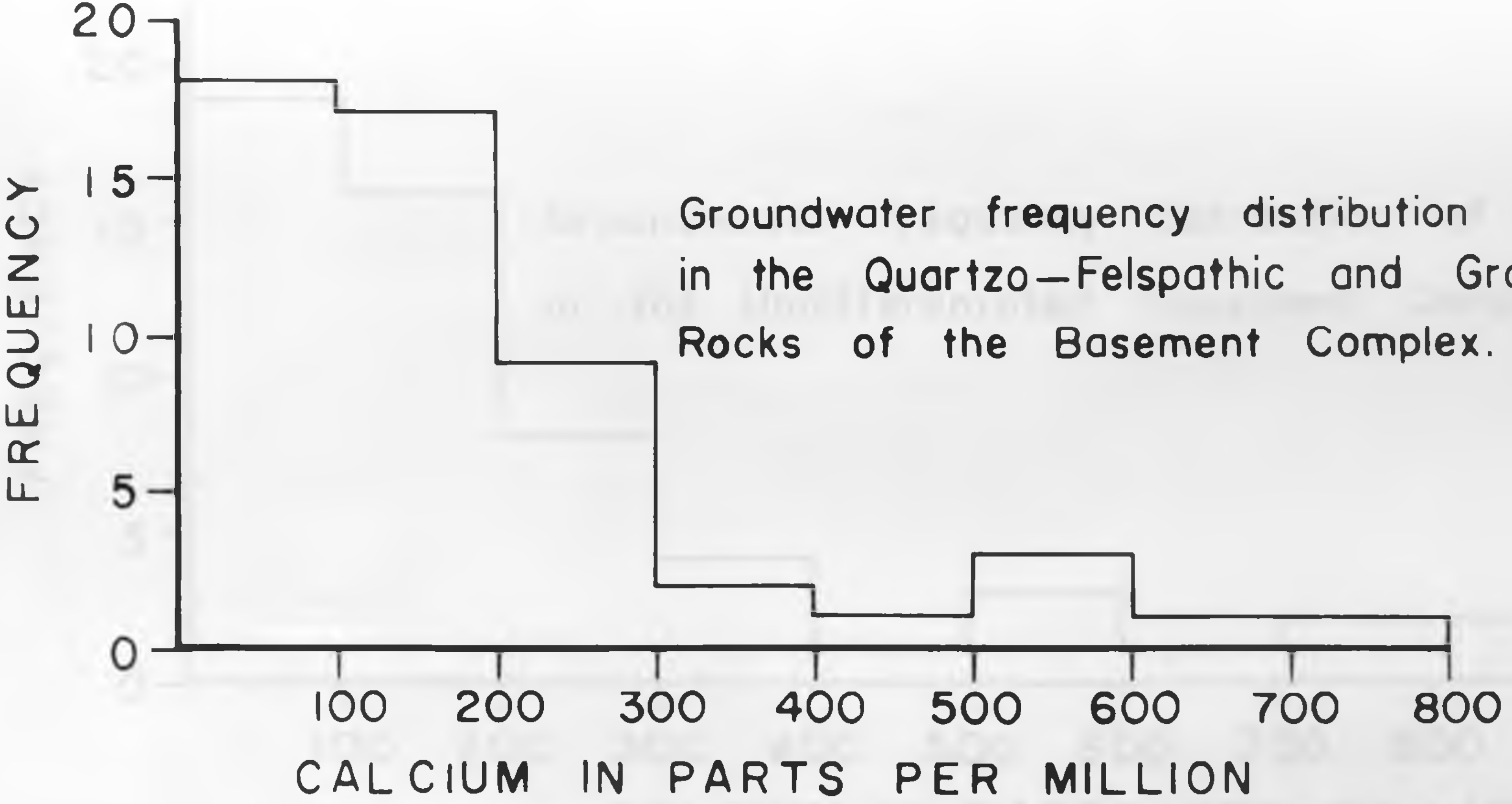

20
15
10
5
0
FREQUENCY
100
200
300
400
500
600
700
800
CALCIUM IN PARTS PER MILLION
Groundwater frequency distribution of calcium in the Quartzo–Felspathic and Granitoid Rocks of the Basement Complex.

FIG. 6.19

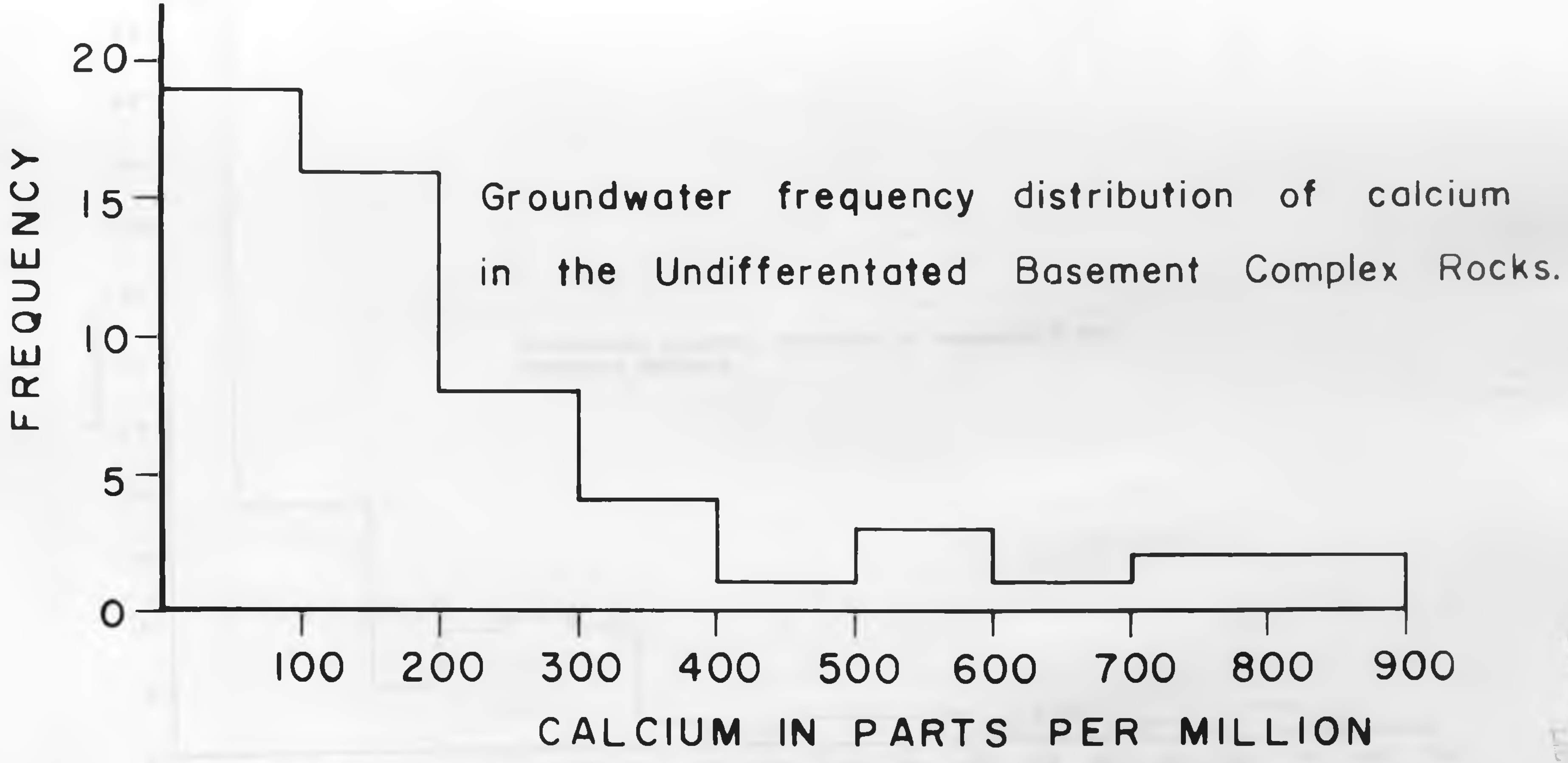

Groundwater frequency distribution of calcium in the Undifferentated Basement Complex Rocks.
FREQUENCY
20
15
10
5
0
100
200
300
400
500
600
700
800
900
CALCIUM IN PARTS PER MILLION

FIG. 6.20

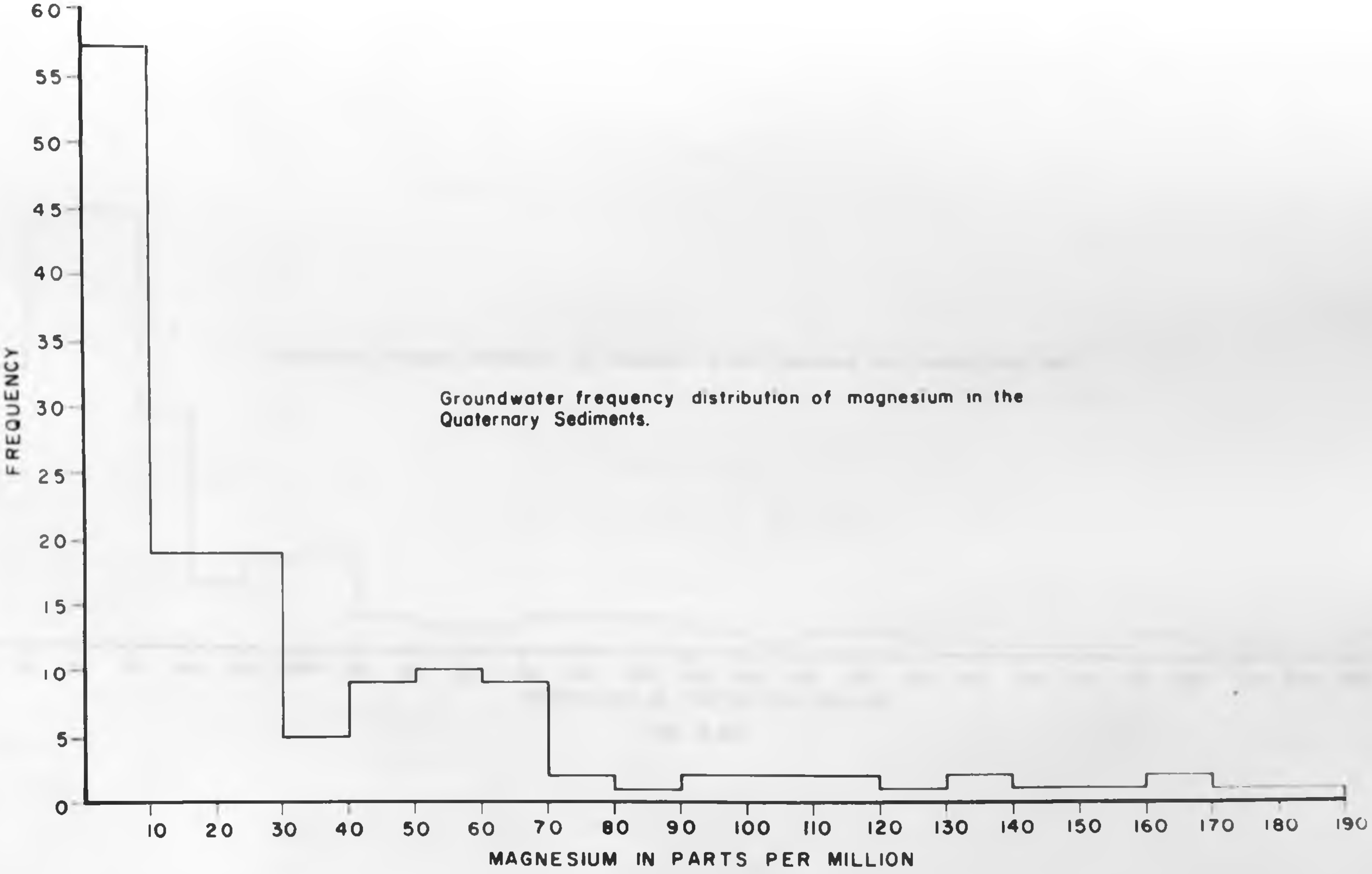
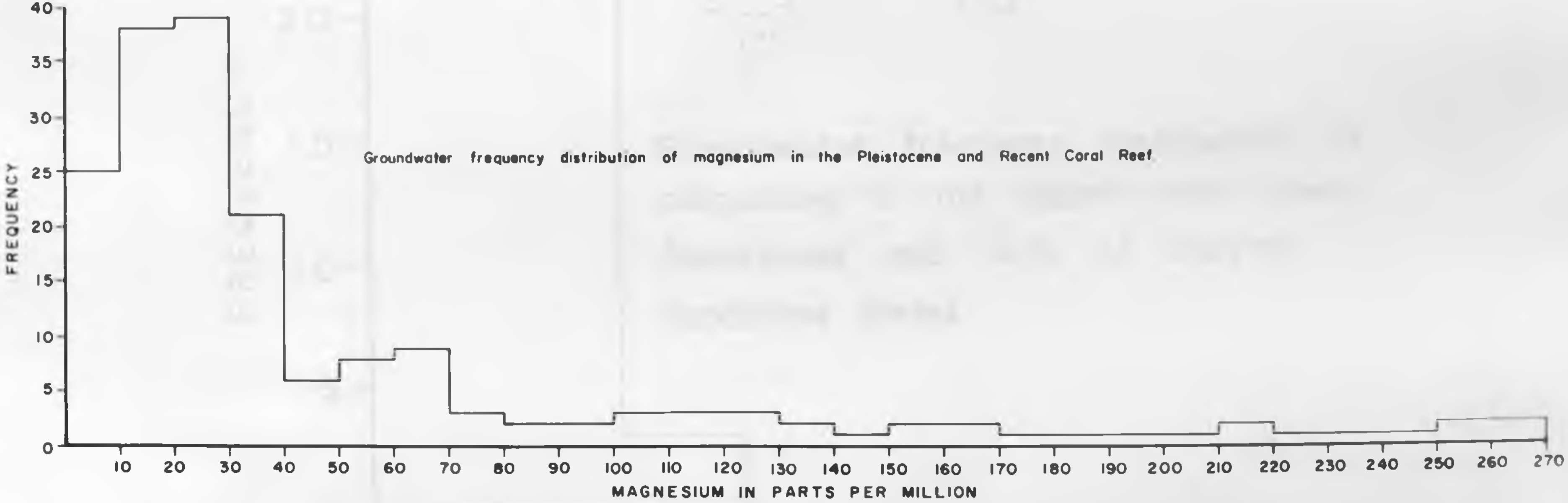
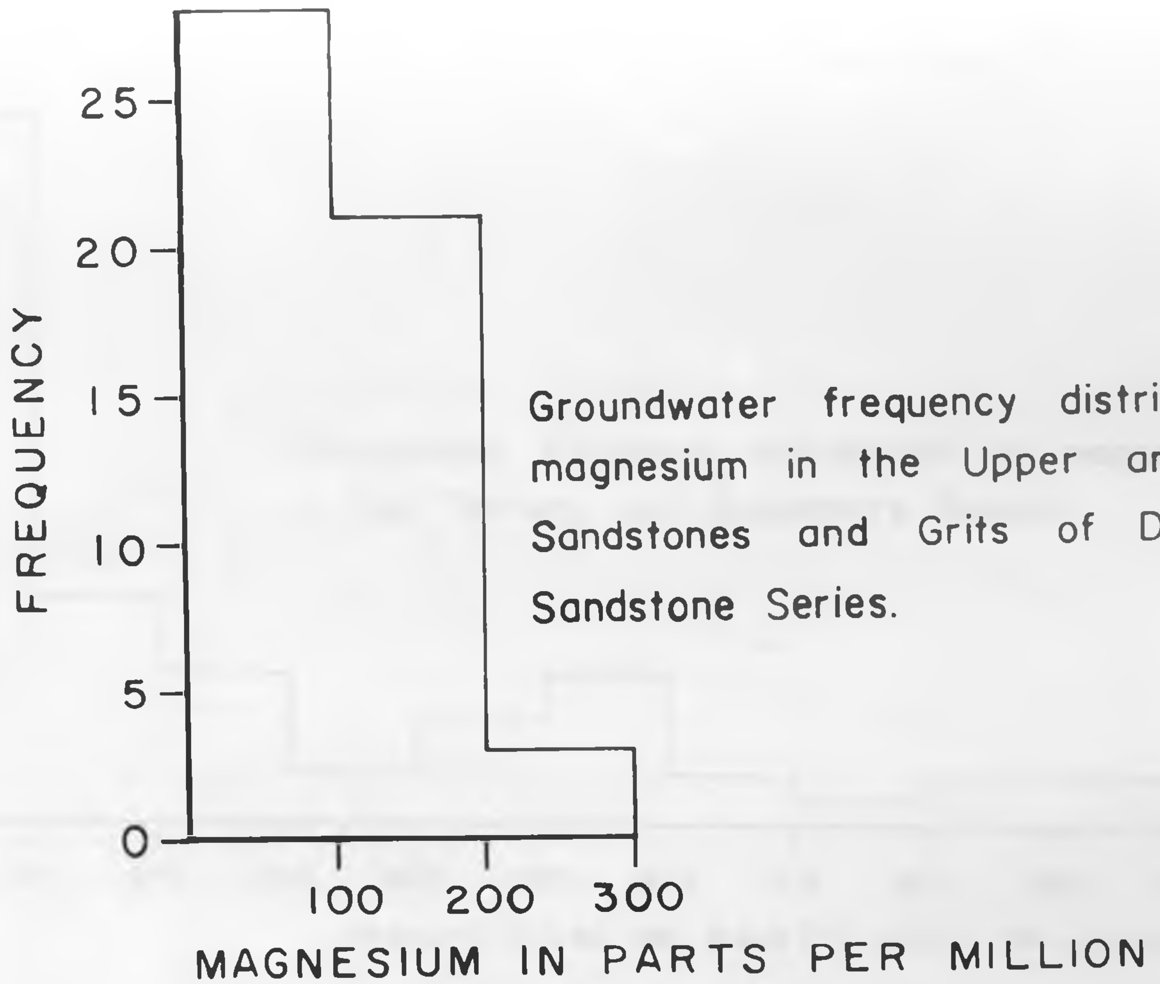

60
55
50
45
40
35
30
25
20
15
10
5
0
FREQUENCY
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
MAGNESIUM IN PARTS PER MILLION
Groundwater frequency distribution of magnesium in the Quaternary Sediments.

FIG 6.21



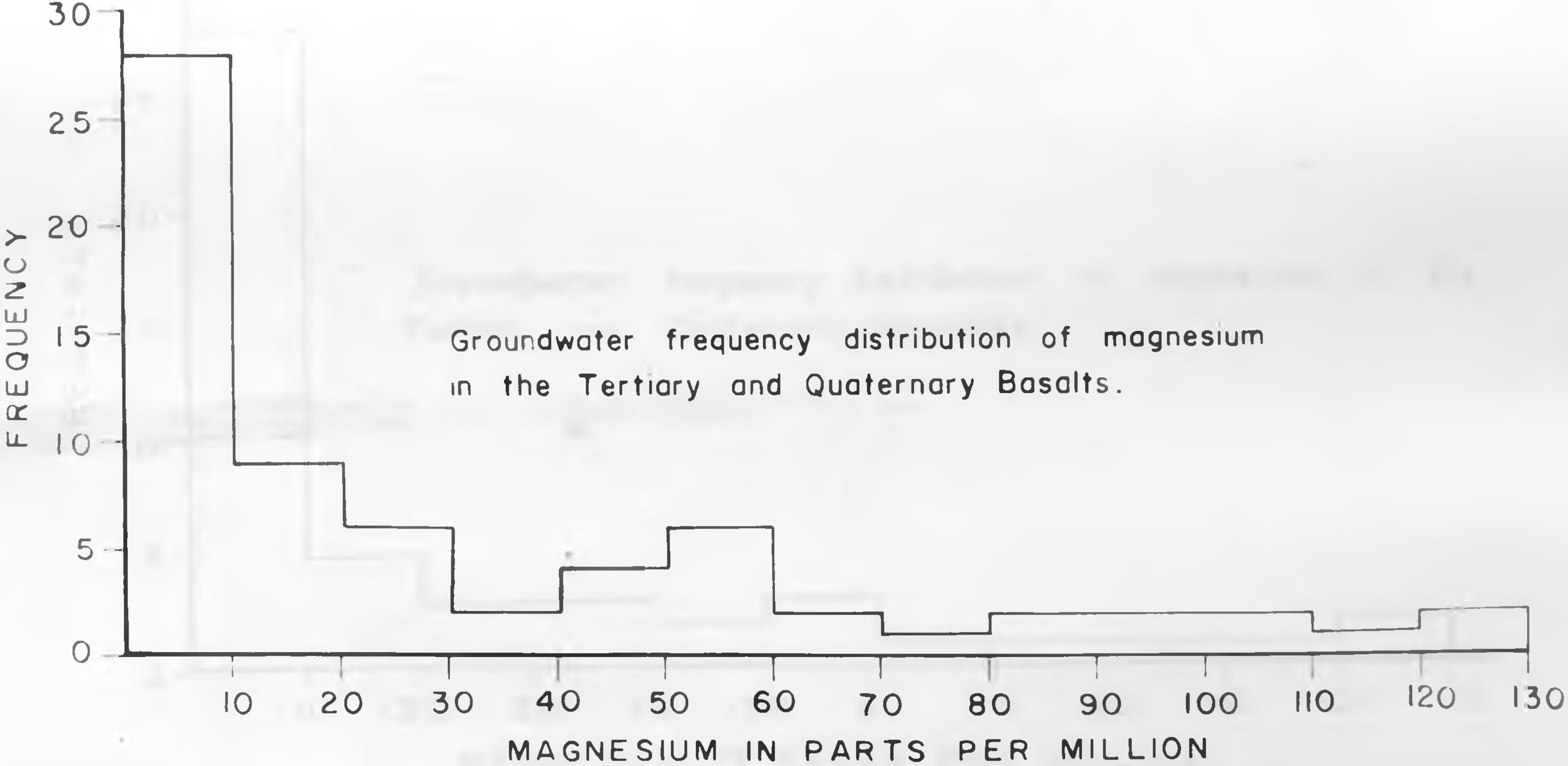
Groundwater frequency distribution of magnesium in the Pleistocene and Recent Coral Reef

FIG 6 22



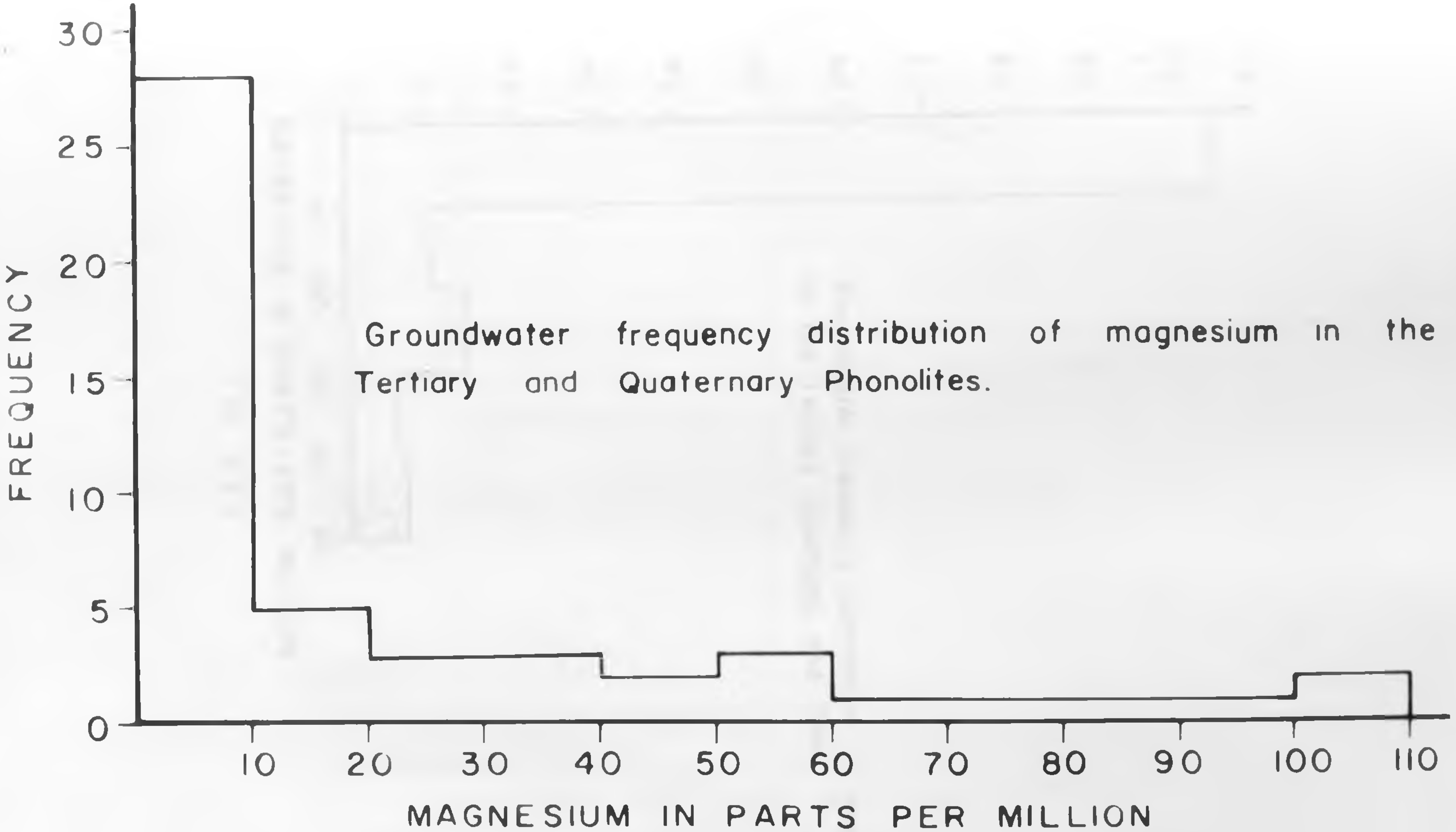
Groundwater frequency distribution of magnesium in the Upper and Lower Sandstones and Grits of Duruma Sandstone Series.

FIG. 6.23



Groundwater frequency distribution of magnesium in the Tertiary and Quaternary Basalts.

FIG. 6.24



Groundwater frequency distribution of magnesium in the Tertiary and Quaternary Phonolites.

FIG 6.25

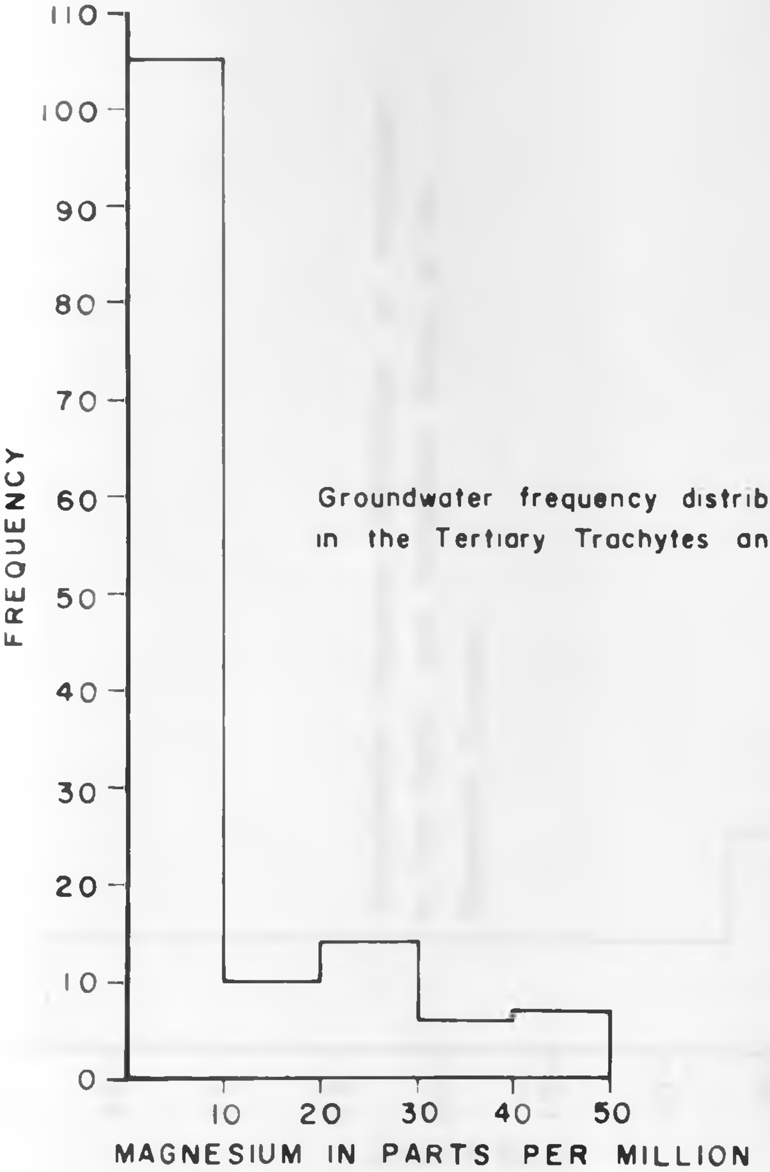
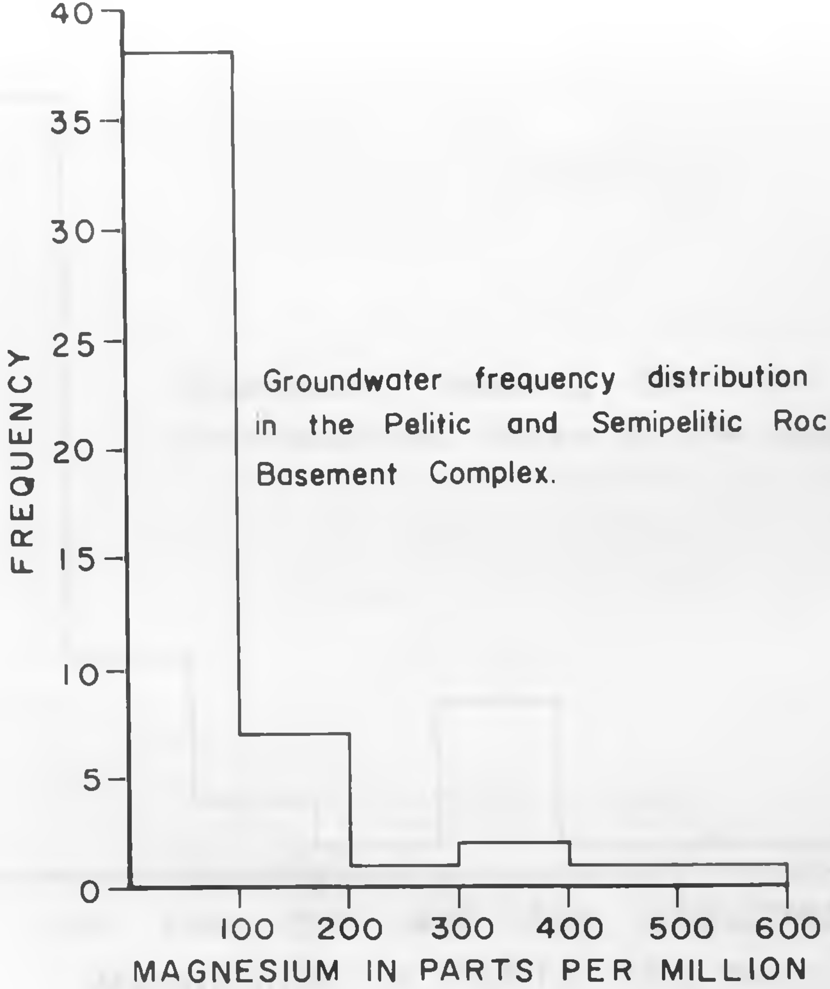
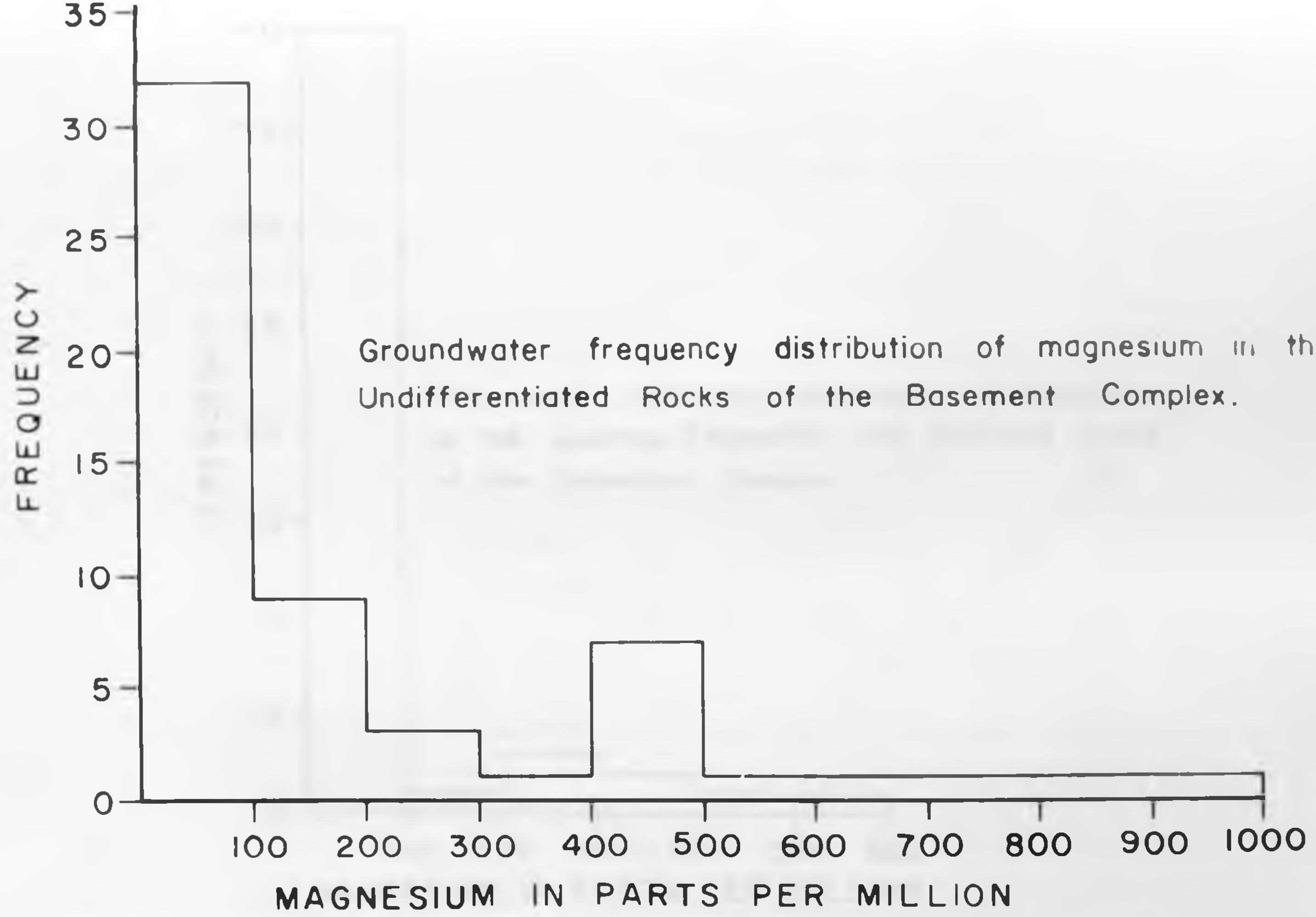

110
100
90
80
70
60
50
40
30
20
10
0
FREQUENCY
10
20
30
40
50
MAGNESIUM IN PARTS PER MILLION
Groundwater frequency distribution of magnesium
in the Tertiary Trachytes and Tuffs.

FIG. 6.26



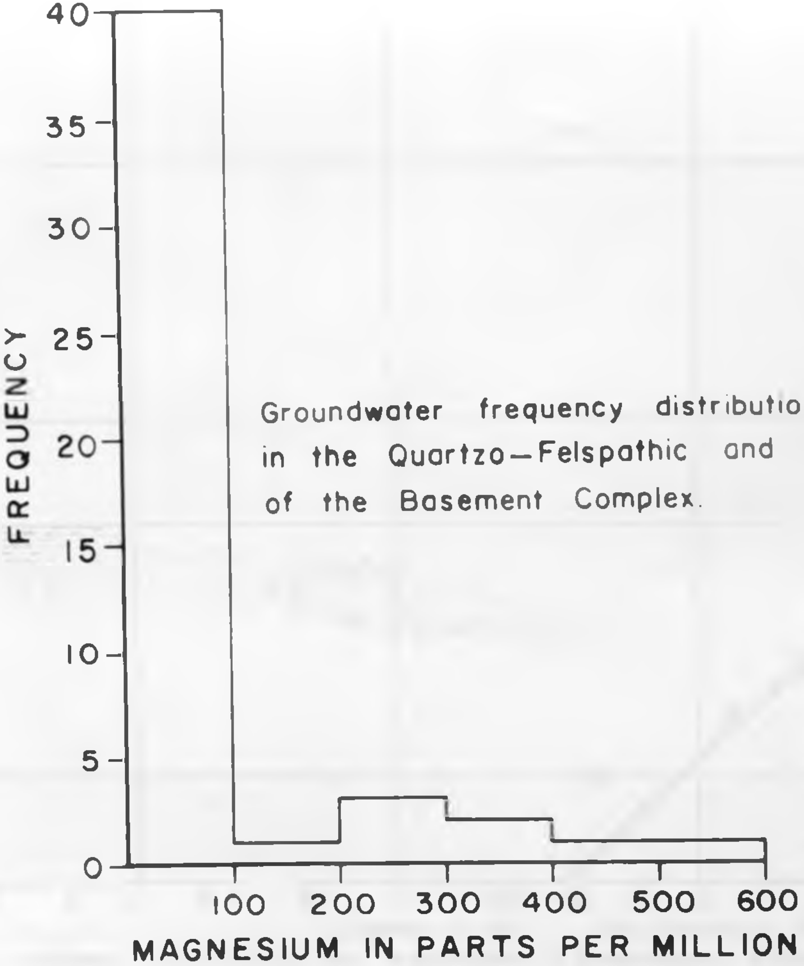
Groundwater frequency distribution of magnesium in the Pelitic and Semipelitic Rocks of the Basement Complex.

FIG. 6.27



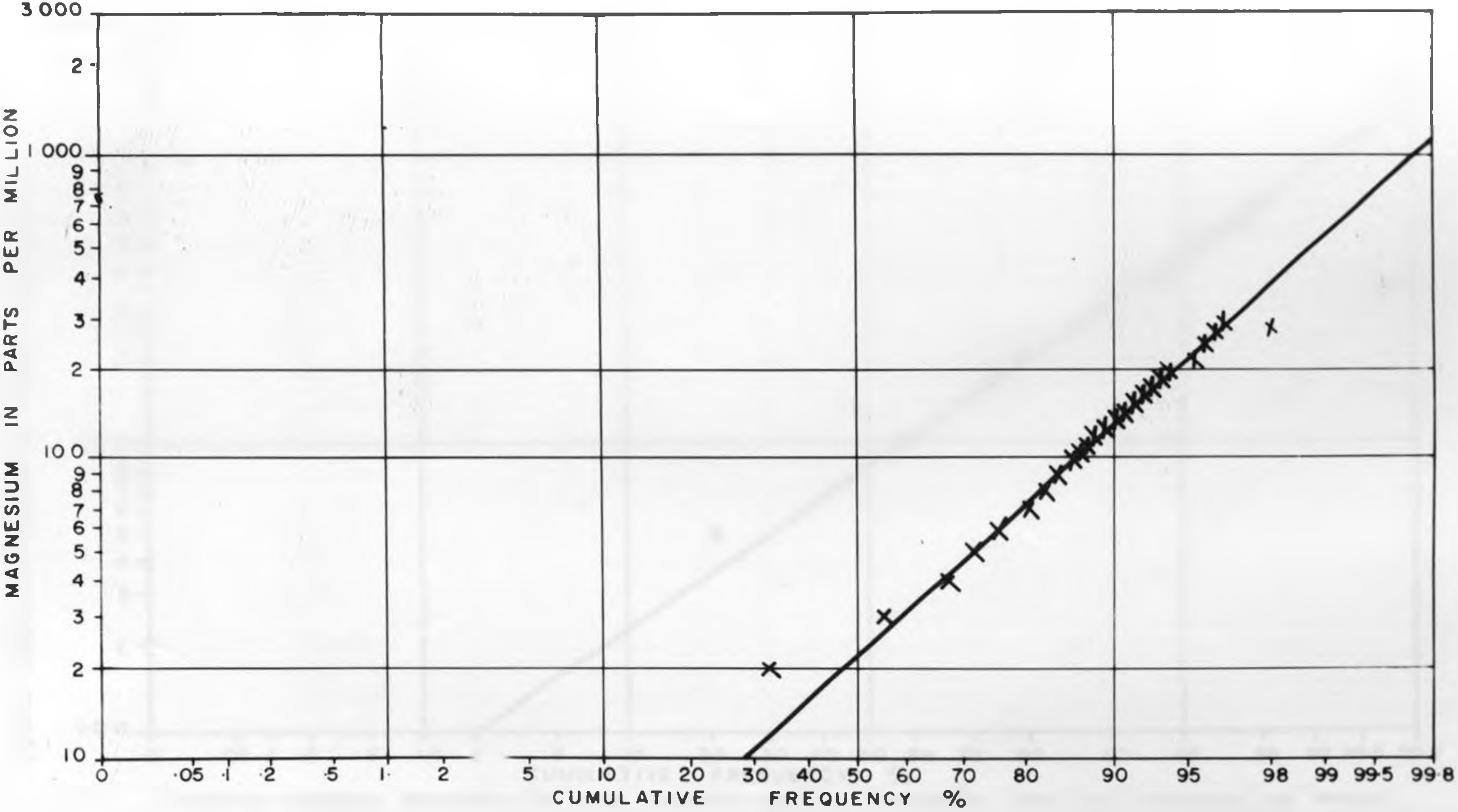
Groundwater frequency distribution of magnesium in the Undifferentiated Rocks of the Basement Complex.

FIG. 6.28



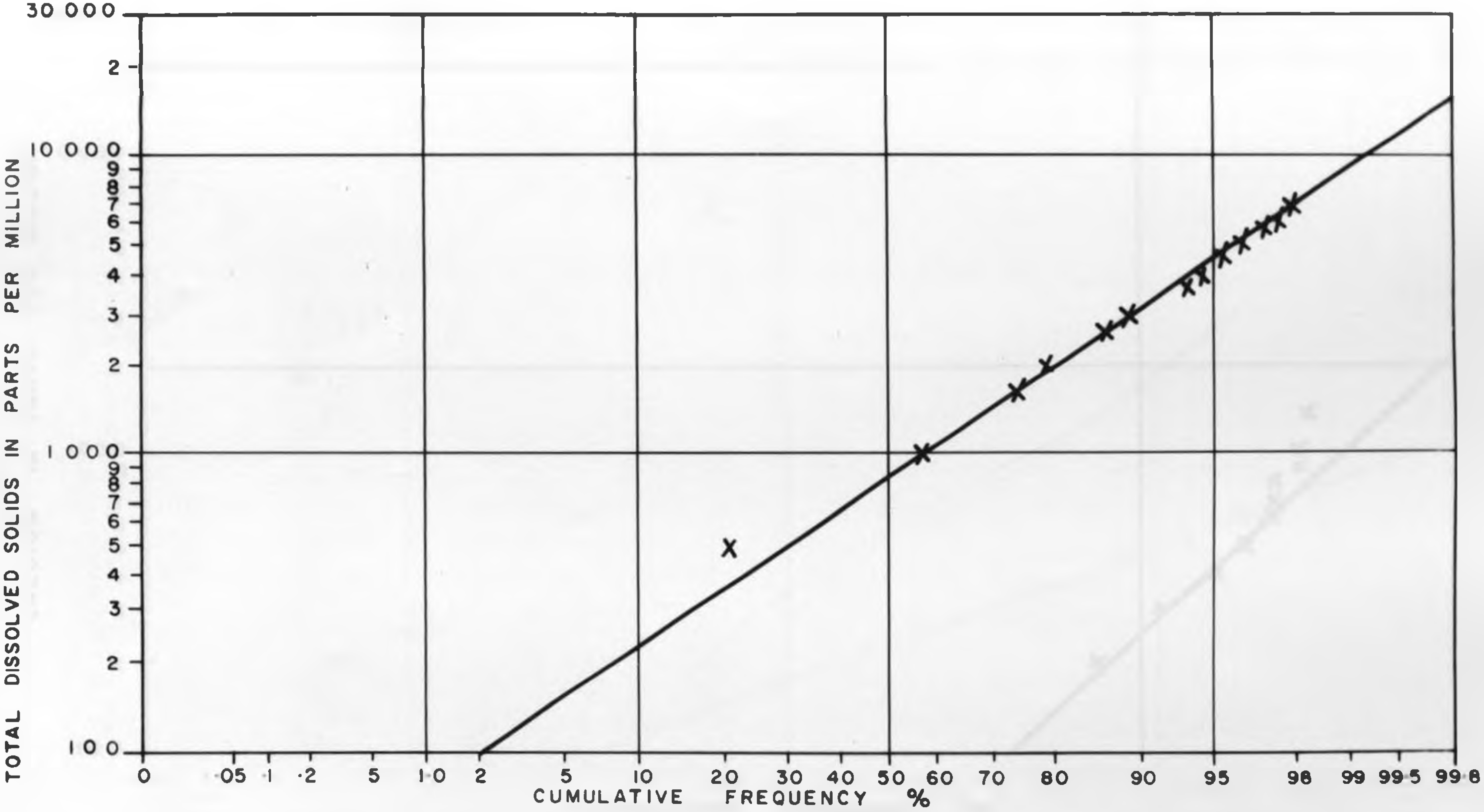
Groundwater frequency distribution of magnesium in the Quartzo–Felspathic and Granitoid Rocks of the Basement Complex.

FIG 6 29



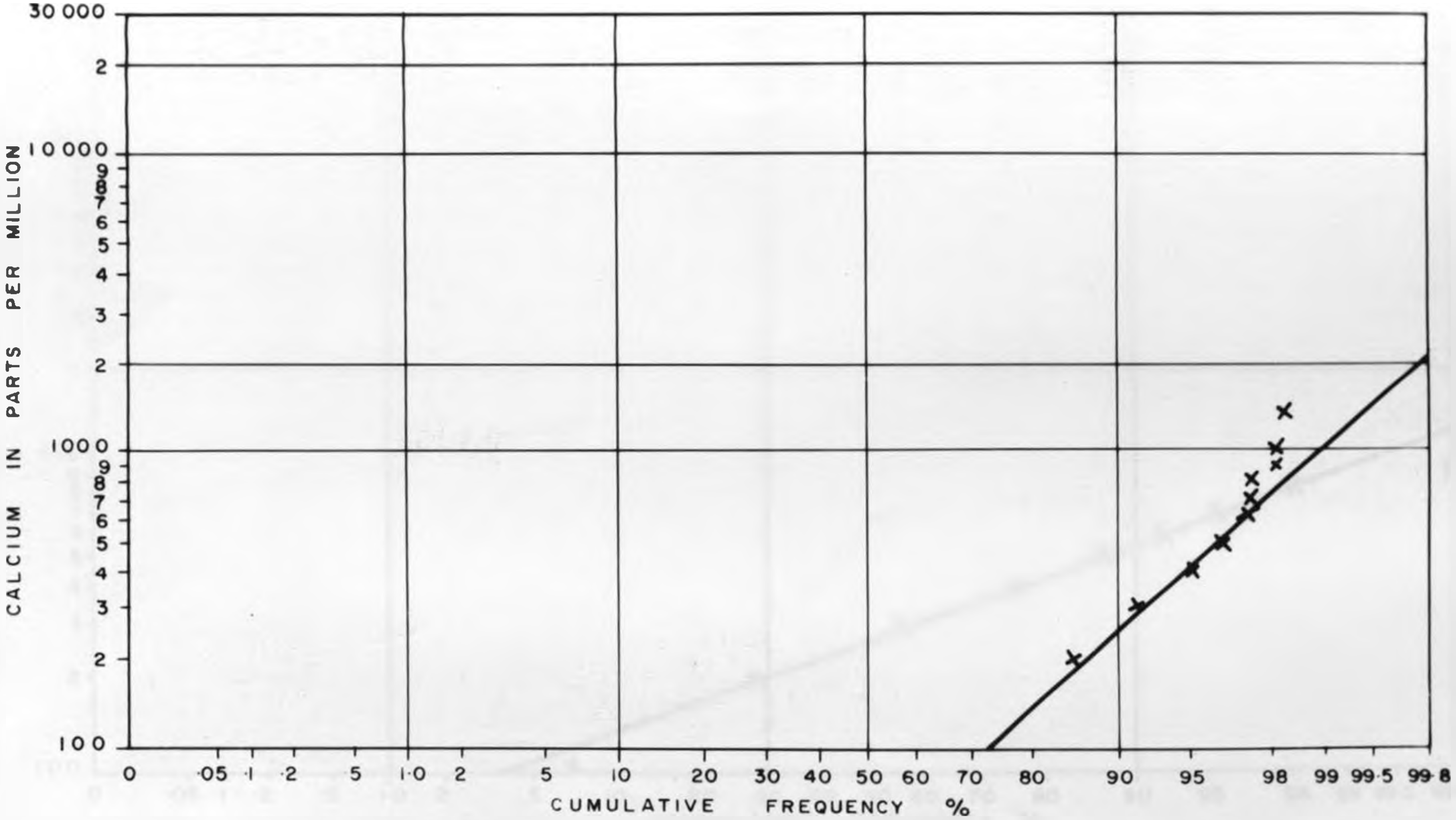
Cumulative frequency distribution for Magnesium in Groundwater within the Pleistocene and Recent Coral Reef

FIG. 6.30



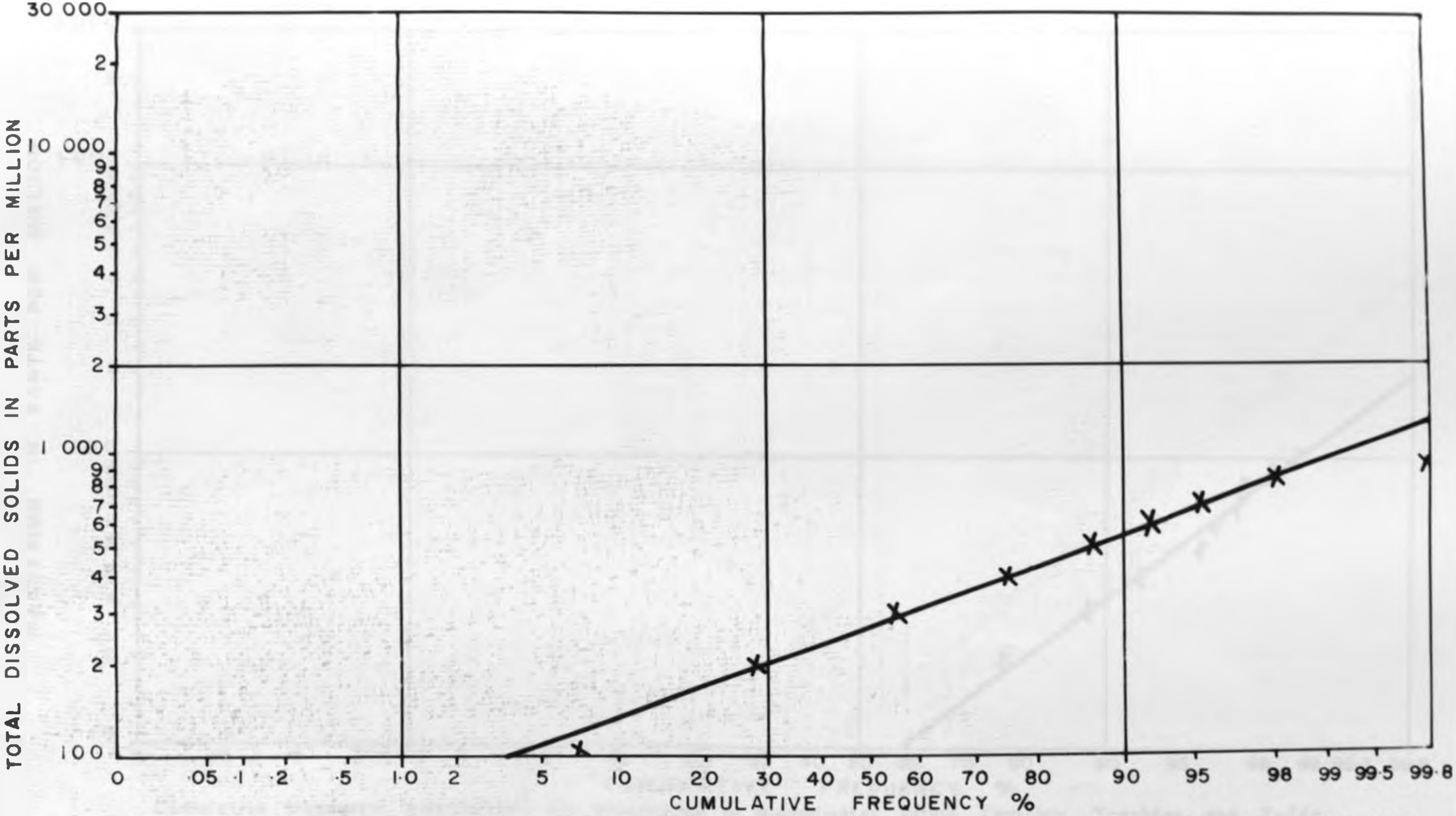
Cumulative frequency distribution for total dissolved solids in Groundwater within the Pleistocene and Recent Coral Reef.

FIG. 6 31



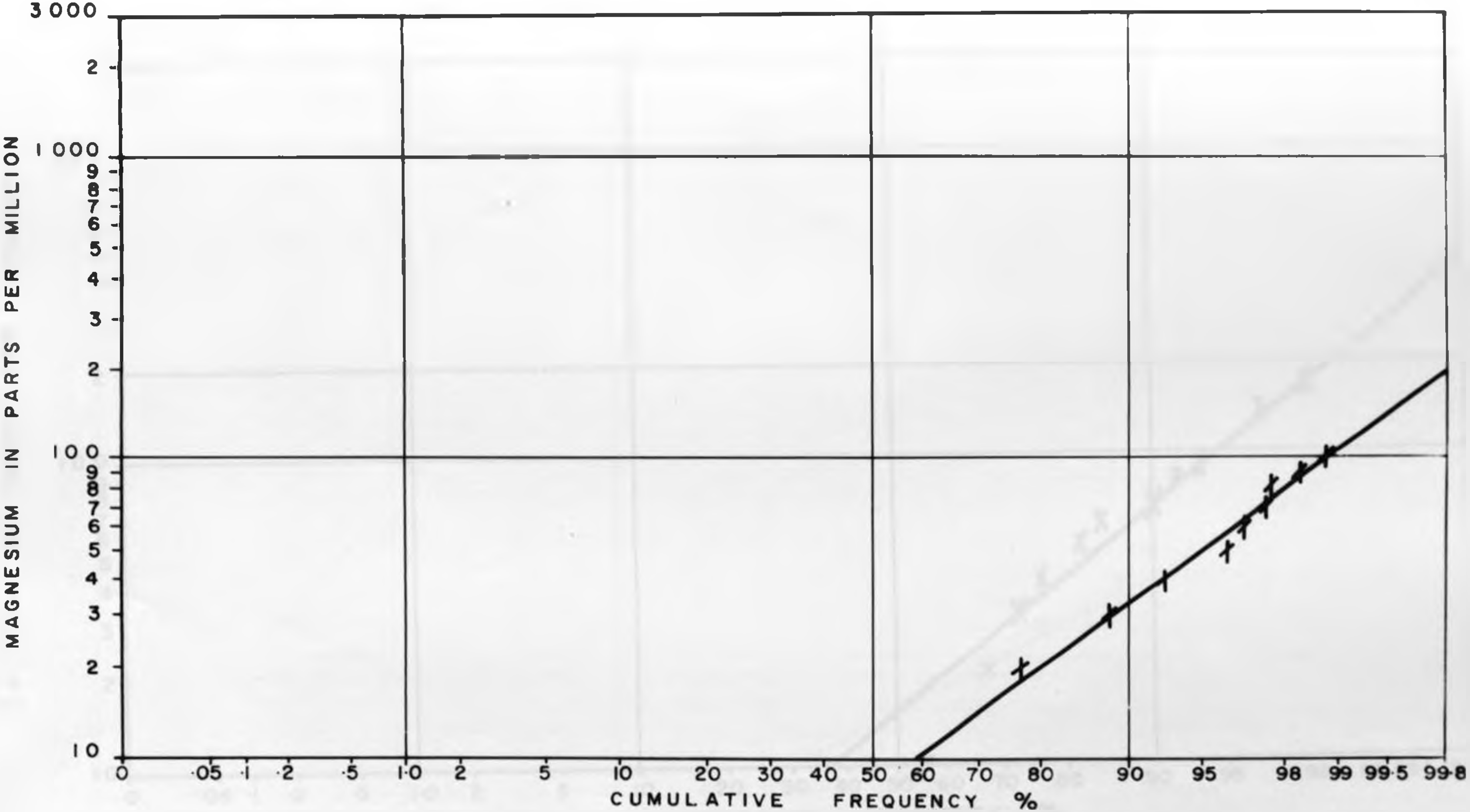
Cumulative frequency distribution of Calcium in Groundwater within the Pleistolene and Recent Coral Reef

FIG. 6.32



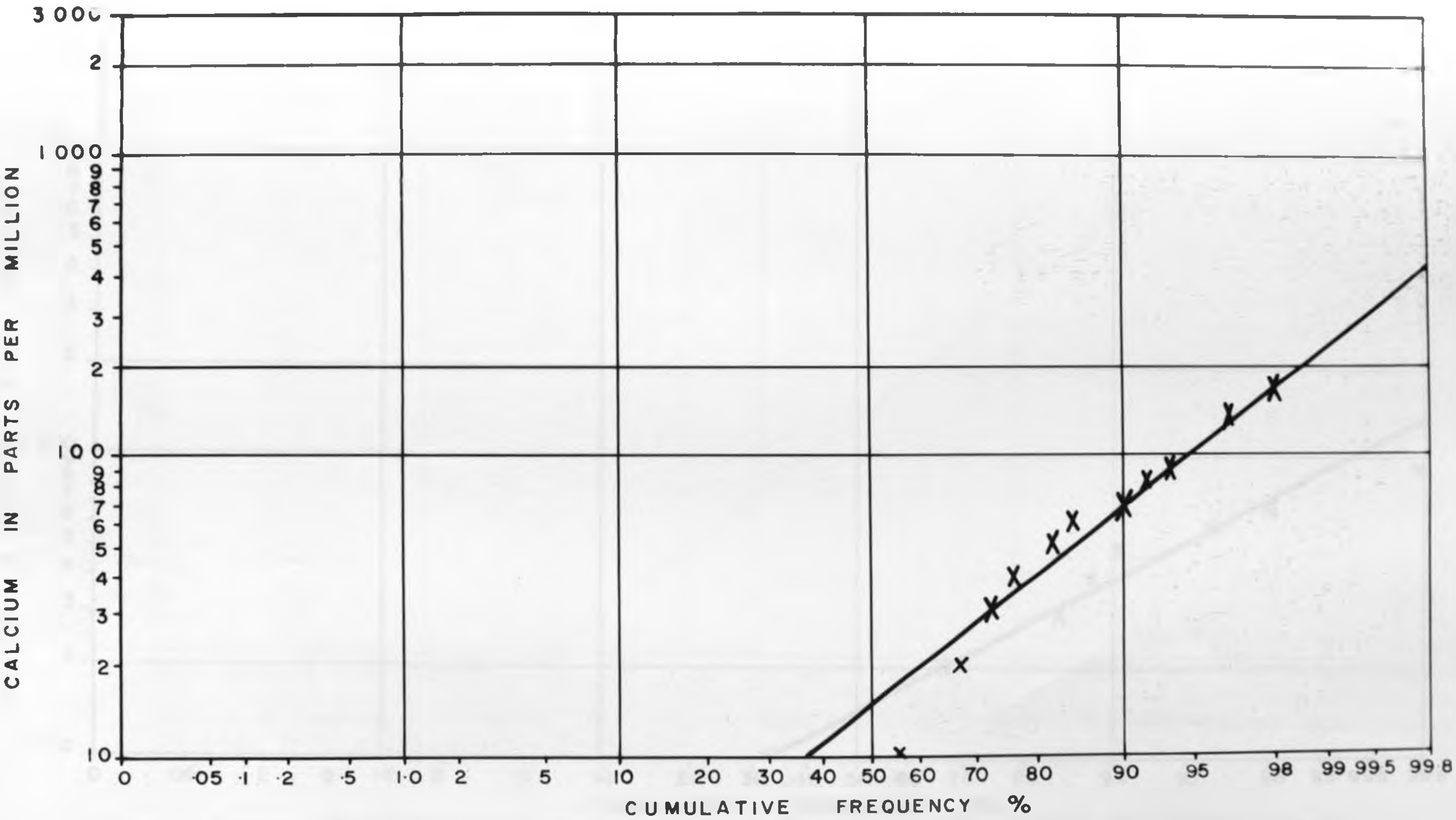
Cumulative frequency distribution for Total Dissolved Solids in Groundwater within the Tertriary Trachytes and Tuffs.

FIG. 6 33



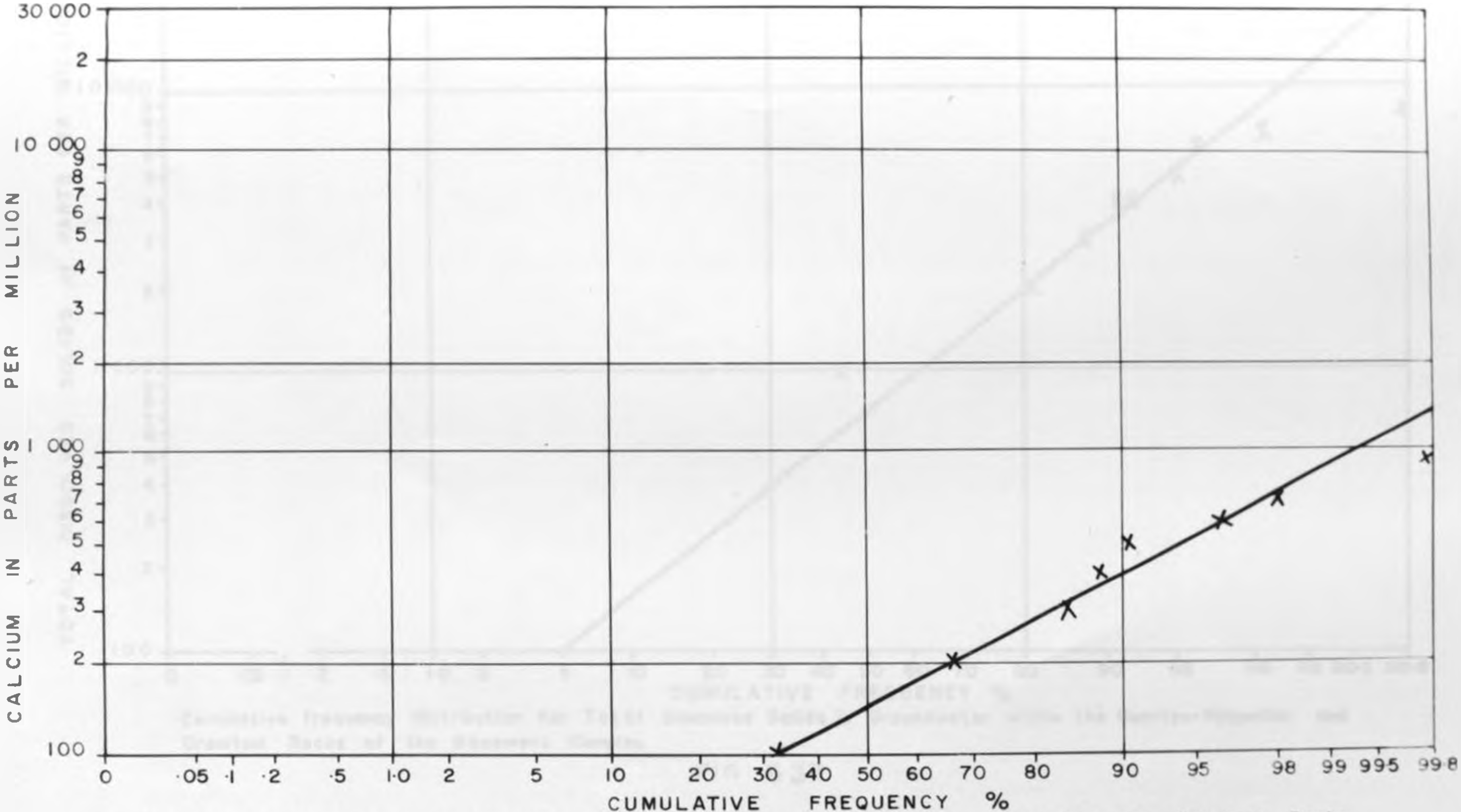
Cumulative frequency distribution for Magnesium in Groundwater within Tertiary Trachtes and Tuffs

FIG. 6.34



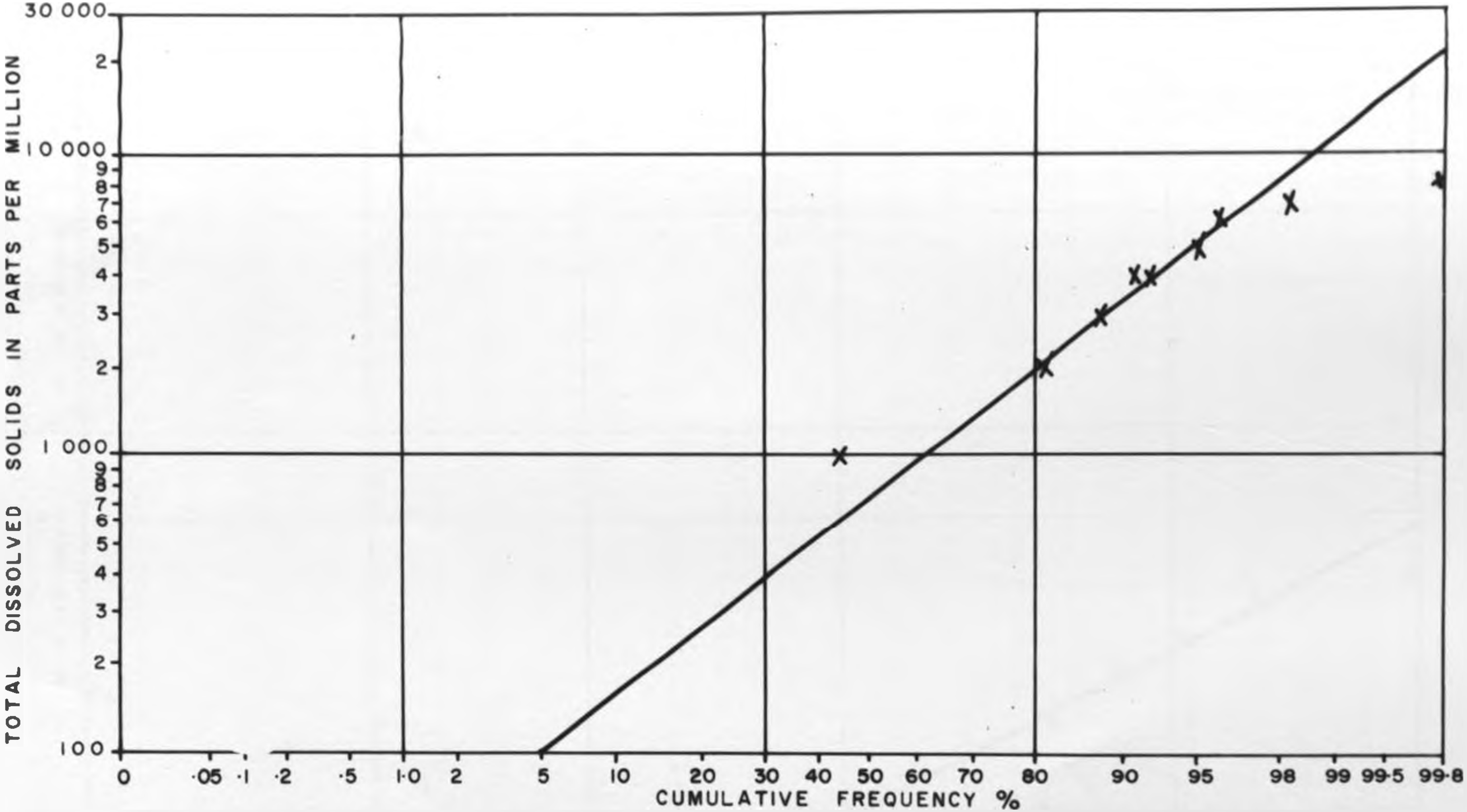
Cumulative frequency distribution of Calcium in Groundwater within the Tertiary Trachytes and Tuffs

FIG. 6.35



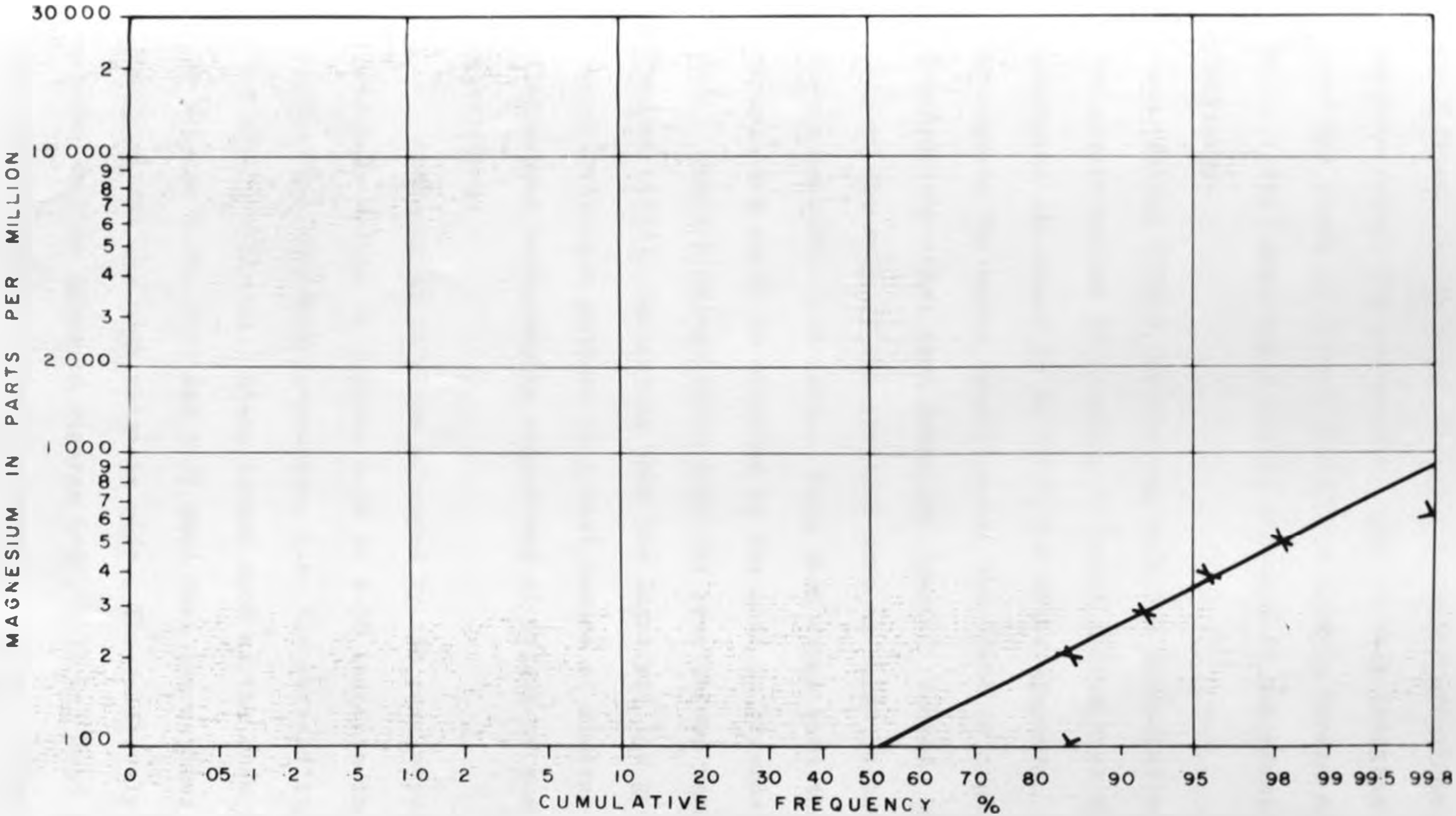
Cumulative frequency distribution for Calcium in Groundwater in the Quartzo-Felspathic and Granitoid Rocks of the Basement Complex

FIG. 6.36



Cumulative frequency distribution for Total Dissolved Solids in Groundwater within the Quartzo-Felspathic and Granitoid Rocks of the Basement Complex

FIG 6 37



Cumulative frequency distribution for Magnesium in Groundwater within the Quartzo-Felspathic and Granitoid Rocks of the Basement Complex

FIG. 6.38

dispersion of its concentration." Although it is assumed that Ahrens law is meant to apply to minor constituents in igneous rocks, the groundwater ions in this analysis suggest that the ideas of Ahrens, Vistelius (1960), Tenant and White (1959) and others can be extended to groundwater chemistry.

Aubrey (1954), in dealing with the distribution of the concentration of elements in rocks agrees that the lognormal law seems to be valid for minor elements. However, as regards the major constituents, the trend is towards lognormality other than normality itself. Indeed, this is true of the many of the chemical ions in Kenya groundwaters within specific rock units. This then means that the lognormal laws could be extended to the ions in groundwater as well. These findings agree with the conclusions reached by Cousins (1956), indicating that the lognormal law governs the distribution pattern of a vast number of diverse statistical measurements regardless of origin of such statistics.

Differences in slope potrayed by the cumulative frequency curves in Figures 6-30 to 6-38 indicate the different logarithmic standard deviations, i.e. the variability of the sample patterns. Steep slopes such as the ones potrayed by Figures 6-30, 6-35 and 6-37 show that the scatter of values about the mean value is wide. The relatively flatter slopes such as given in Figures 6-31, 6-33 and 6-36 show that the scatter about the mean is narrow. It must, however, be born in mind that the flatter curves have been affected by the differences in the size and class values of samples. Larger samples have shown a smaller variation of values and hence flatter curves. The similarity of these distribution patterns indicates that although the factors involved in groundwater chemistry are variable, there is some overall similarity in the frequency characteristics of each ion in groundwater.

In conclusion, it is necessary to note that satisfactory answers to the following questions must ultimately be sought: Why do given chemical concentrations of ions in groundwater follow the statistical patterns which they display? Why do these ions tend to follow this skewed log-normal type of distribution? Perhaps an answer to these questions lies in the processes of hydrogeochemical reactions that involve all the parameters that supply and extract given ions to and from the groundwaters. Another explanation remains to be found to explain the varying degrees of dispersion exhibited by the different ions and why dispersion of such ions may differ quite distinctly for different rock types.

N.B

B. Geographic Background of Groundwater Chemistry Variation in Kenya

Introduction

The geographic setting of Kenya has been examined in Chapter III. It is clear that Kenya's environment has been greatly modified by the geologic and geomorphological processes through time. These processes have given rise to diverse landforms which through the agencies of weathering differently affect the composition of groundwaters in the country. Landforms are quite important parameters in groundwater chemistry. The concentration of total dissolved solids in groundwater, for example, has been shown to decrease generally with altitude, with higher concentrations down at the coast and lowest concentrations in the highland and mountainous parts of the country. This finding agrees with Gorham (1961) who has shown that there is an inverse relationship between total salt concentration and height above sea level attributed to greater leaching at higher altitudes with greater precipitation.

It has been indicated earlier in this discussion that salts in groundwater depend upon the environment, movement and source of groundwater. Ordinarily, however, higher proportions of dissolved constituents are found in groundwater because of soluble materials present in geologic strata. This subsection is concerned mainly with precipitation and temperature, evapotranspiration and distance from water recharge points. Langbein (1949), from the data collected from United States drainage basins has devised a system for prediction of how runoff and sediment yields change with the mean annual temperatures and precipitation. Langbein and Dawdy (1964), have extended this idea to the prediction of total dissolved solids in streams as a function of runoff and therefore of precipitation and temperature. Okoth (1966), has shown that conductivity is always high in a place where water seeping downward can get in contact with shallow groundwater than in a place where the infiltration rate is low.

Effects of rainfall and temperature on Kenya's groundwater chemistry

The diversity of climatic and hydrologic parameters that have great influence on groundwater chemistry have been discussed in chapter five.

Rainfall affects groundwater chemistry in several ways:

(a) It contains some dissolved ions. However, these have an important effect upon groundwater chemistry only where the rocks are very resistant to chemical weathering and the groundwater is very dilute.

(b) It contains CO_2 which is responsible for much rock weathering. However, most of the CO_2 that gets into the groundwater comes from the soil air, where concentrations of CO_2 are many times greater than in the atmosphere. The soil CO_2 comes from the microbiological breakdown of organic matter from vegetation.

(c) Precipitation is also important because it controls the amount of vegetation produced over an area, andtherefore the amount that dies every year and breaks down to CO_2.

(d) Rainfall controls the amount of groundwater recharge, tending to increase the total rate of transport of ions out of a weathering zone but diluting their concentration.

Temperature is important in groundwater chemistry because, (a) high temperatures increase evapotranspiration and reduce recharge, thus making groundwater more concentrated but decrease total transport rate of dissolved solids out of groundwater; (b) it increases rates of chemical reaction; (c) decreases solubility of CO_2 and (d) it increases production of vegetation and therefore of CO_2 production in soils.

Penn (1971) has, for example, indicated that absolute amounts of rainfall over a basin are needed to determine the total amounts of water available for chemical weathering at the surface. The study of precipitation-runoff relationship such as has been shown in chapter five will provide an indication of the proportions that eventually become involved in the transfer of solutes into groundwater.

The effect of rainwater upon a rock or soil material may be looked at in the form of weathering steps. First, the rain partially dissolves the more soluble minerals with liberation of colloidal silica and the formation of carbonates containing iron, magnesium, calcium and the alkalies. The iron is almost instantly oxidized forming a visible rusty coating or precipitate of ferric oxide. The calcium, magnesium and alkali salts partly remain in solution, to be washed away together with much of the dissolved silica. The second step in this reaction is represented by the hydrolysis of the undissolved residues. The feldspars are transformed into kaolinite, the magnesian minerals into talc and/or serpentine and iron becomes limonite with little or no change in quartz grains. This double process of solution and hydrolysis is accompanied by an increase of volume which may or may not assist in effecting disintegration. By oxidation, solution and hydrolysis, a solid rock is converted into an aggregate of loose material which may remain in place as soil or be removed by running water.

Lastly, it must be noted that rain water is not the only chemical agent for affecting rock decomposition. Chemical reactions continue when water reaches the phreatic zone. The groundwater contains an accumulation of the salts formed during the earlier stages of the process. It is poorer in oxygen than the surface waters but richer in other substances and it may contain a large proportion of organic matter derived from the decay of vegetation. This organic matter often reverses the oxidation which had previously taken place, reducing ferric to ferrous compounds, and sulphates to sulphides. Furthermore the organic decomposition provides groundwater with large amounts of carbonic acid which increases its chemical activity.

On [illegible] 'weathering' horizon?

Figures 6-39? and 6-40? potray (sic!) the superimposition of the total dissolved solids concentration in groundwater upon the mean annual rainfall and mean maximum temperature maps of Kenya at the scale of 1:1 million respectively. This superimposition is strictly meant to show the relationship between the distribution of rainfall and temperature and the chemical variation of groundwater compositions in the country. These maps give a pictorial impression of the fact that groundwaters of low salinity are located in well-watered parts of the country which in most cases also have low temperatures. It is important to note that groundwaters

GIS analysis

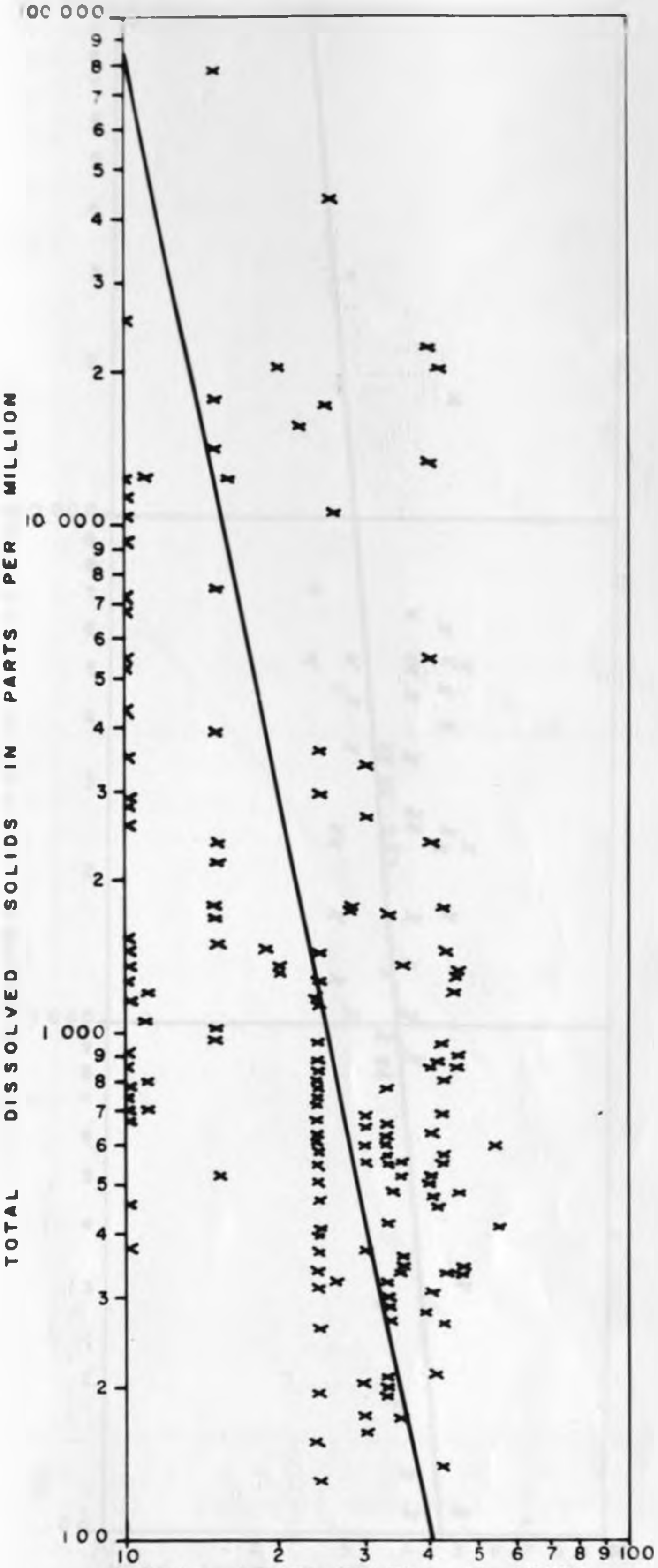
with generally less than 500 parts per million of total dissolved solids are situated in the wetter and lower temperature zones of the regions already discussed, namely ① the Rift Valley, Lake Victoria basin and Central Province. Since there is sufficient and readily available water providing for recharge and dilution of salts in these areas, the water is leached through the aquifers quite rapidly and does not have enough time to come into equilibrium with its surrounding soil and rock minerals. The rates of evaporation from the water table are lower than elsewhere. The rainfall amounts in these zones are above 40 inches and the mean maximum temperatures are less than 26°C.

② Parts of the eastern half of the Central, North-eastern and the Rift Valley regions form an intermediate groundwater zone. These are areas receiving about 30 inches of rainfall with temperatures of less than 30°C. They have relatively higher rates of evaporation, low amounts of rainfall and higher temperatures. This then means that the less the water available for groundwater recharge and dilution of salts , the longer the time in contact with the surrounding minerals forming the aquifer. Higher evaporation rates and the removal of this water from areas providing for groundwater recharge and the already mentioned available time contribute to groundwaters in these areas with well over 3,000 parts per million of total dissolved solids.

③ The Mandera-Garissa and Lake ~~Rudolf~~ zones, forming the north-eastern and north-western half of the country, generally experience rainfall of less than 15 inches and temperatures of more than 30°C. In these low rainfall and high temperature zones there is little leaching process activity, suggesting that the waters have sufficient time to come into equilibrium with minerals forming the aquifer. The high evaporation rates and low groundwater recharge mean that there is not sufficient water percolating into the ground to flush away the soluble salts from the groundwater aquifer. These and the time factor give groundwaters containing up to 8,000 parts per million in these areas. Todd (1959), confirms this fact when he notes that high salinities are found in soils and groundwaters of arid climates, where leaching by rain is not effective in diluting the salt solutions. He continues to indicate that poorly drained areas have also high salt concentrations.

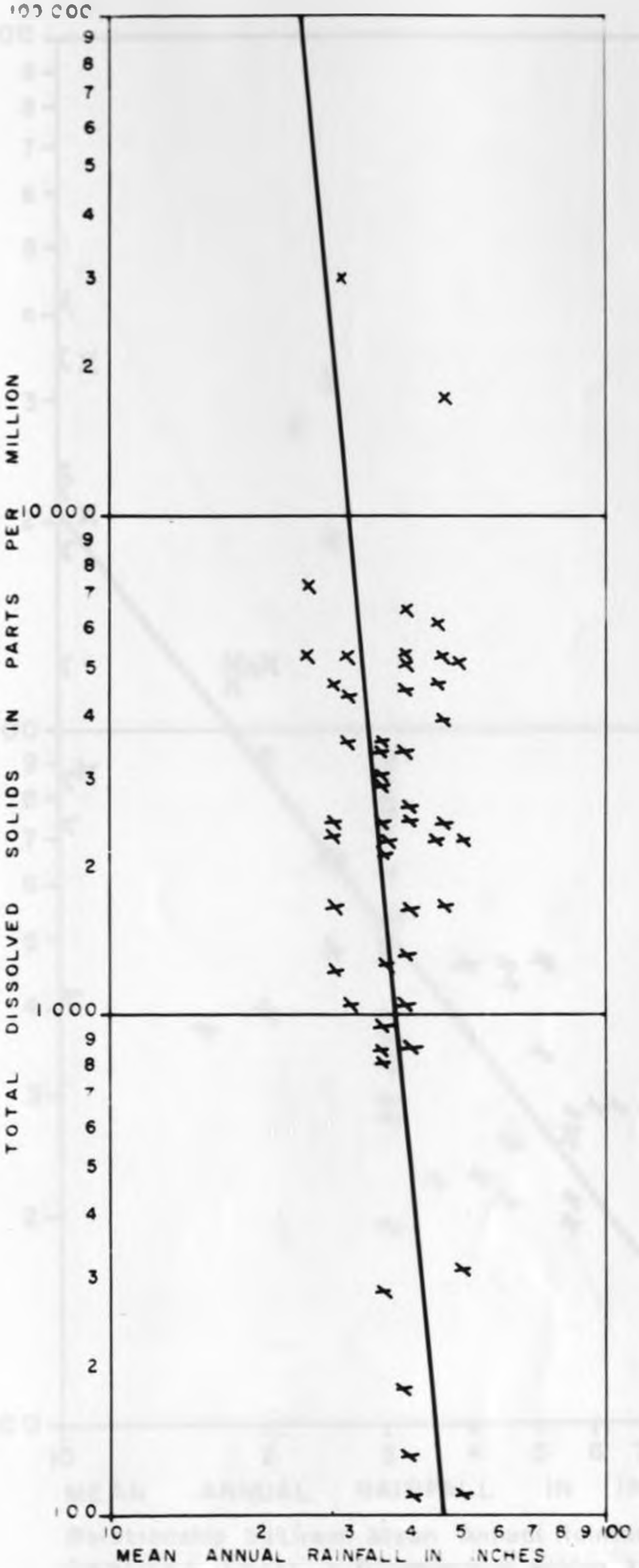
④ The Coastal zone with rainfall amounts of well over 40 inches and temperatures of about 35°C is an area comparable to the already mentioned Lake and Rift Valley regions in terms of rainfall amounts. The striking fact is that despite this comparable relationships, groundwaters of up to 20,000 parts per million of total dissolved solids have been recorded. These groundwaters have been affected by the intrusion and infiltration of salt waters from the adjacent Indian Ocean. Also important is the fact that in some places, the groundwaters are in Jurassic, Triassic and Quaternary Marine Sediments which are saline.

From the observations made above, and especially as indicated in Figures 6-39 and 6-40, there is a relationship between rainfall and temperature and the concentration of total dissolved solids. To confirm the relationship, amounts of rainfall for given areas for given geologic units have been plotted against respective amounts of total dissolved solids in groundwater. These relationships have been illustrated in Figures 6-41, 6-42, 6-43, 6-44, 6-45 and 6-46. These figures show an inverse relationship between the mean annual rainfall and total dissolved solids in groundwater. This relationship, which is not simple, is variable with respect to rock types. This would, of course, be expected for different geologic materials will respond differently to the amounts of rainfall and other weathering agents which would in turn influence amounts of salts in groundwater. These findings agree with those of Gorham (1961) who has shown that the precipitation-evaporation ratio is of great importance in water chemistry for if precipitation exceeds evaporation there will be loss of ions in the drainage waters but if evaporation is in excess, there will be accumulation of salts within the surface and sub-surface waters as is the case with the groundwaters of the arid and semi-arid parts of Kenya. Todd (1959) concurs with Gorham when he notes that evaporation, temperature and precipitation affect the quality of water. For example, in arid areas where the rate of evaporation exceeds the rate of inflow from streams and direct precipitation, there is an increase of total dissolved solids in lakes and reservoirs. He continues to direct attention to the fact that storm runoff can also have a marked effect on water quality.



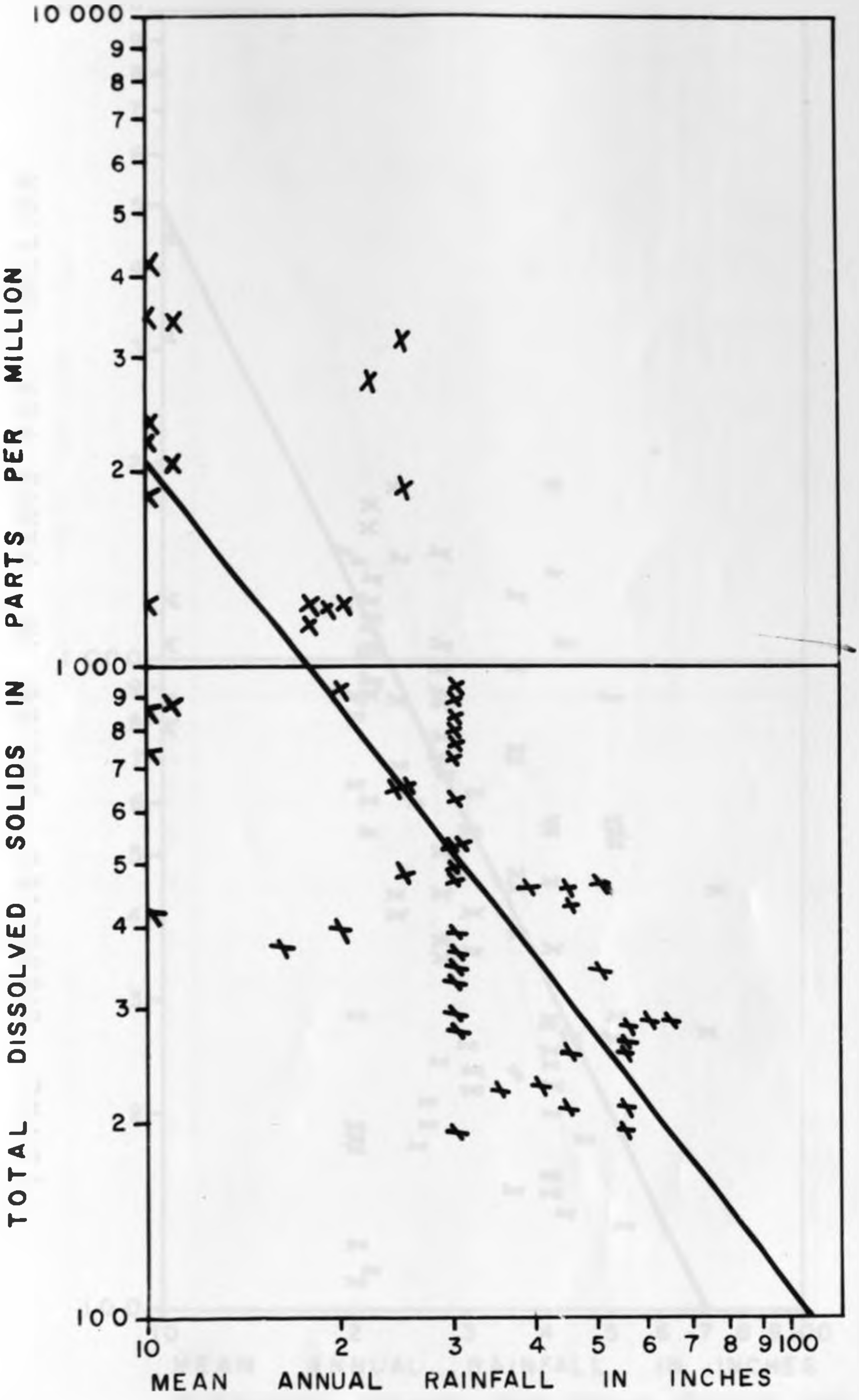
Relationship between Mean Annual Rainfall and Total Dissolved Solids in Groundwater within the Quaternary Sediments

FIG 6 41



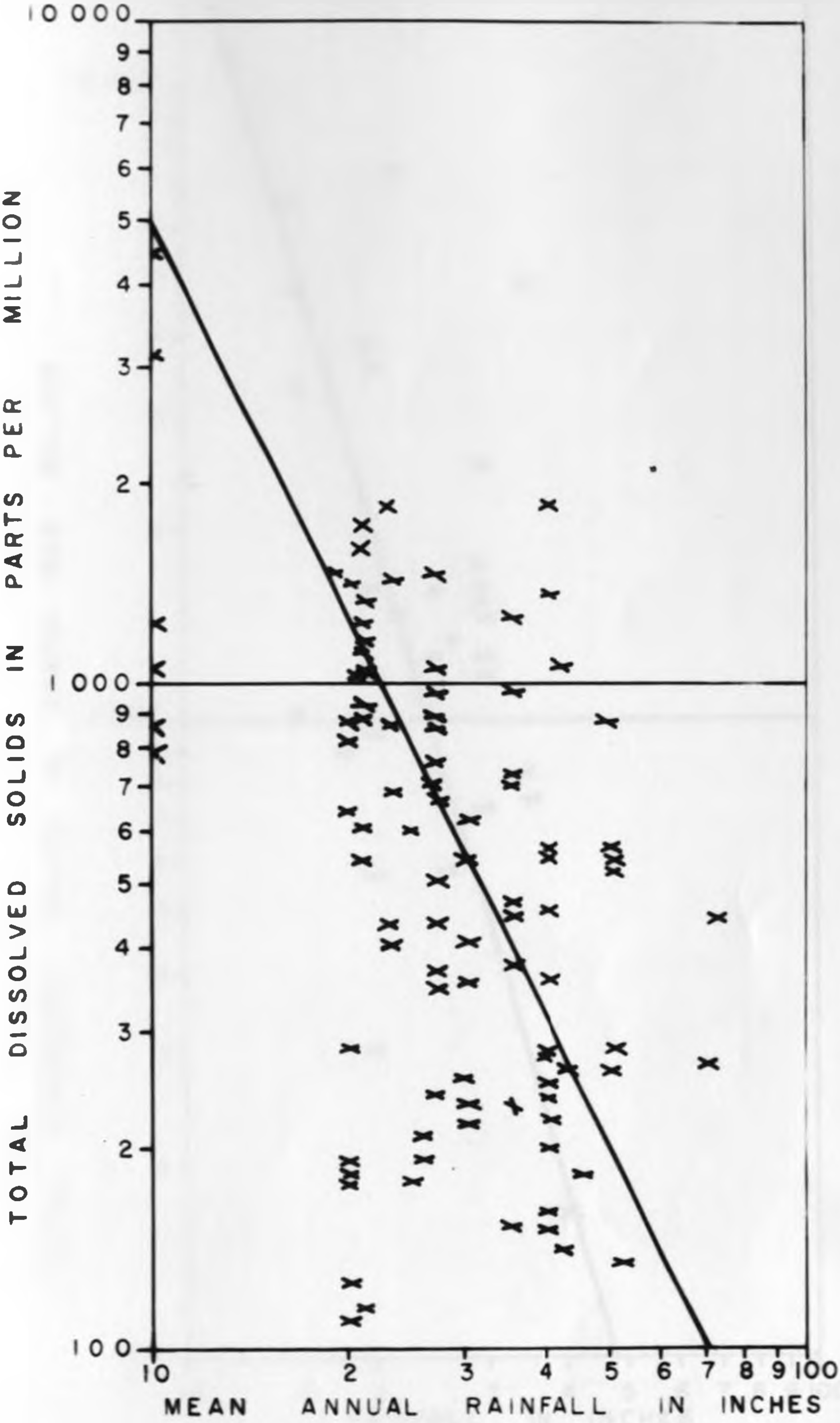
Relationship between Mean Annual Rainfall and Total Dissolved Solids in Groundwater within the Upper and Lower Sandstones and Grits of the Duruma Sandstone Series

FIG 6 42



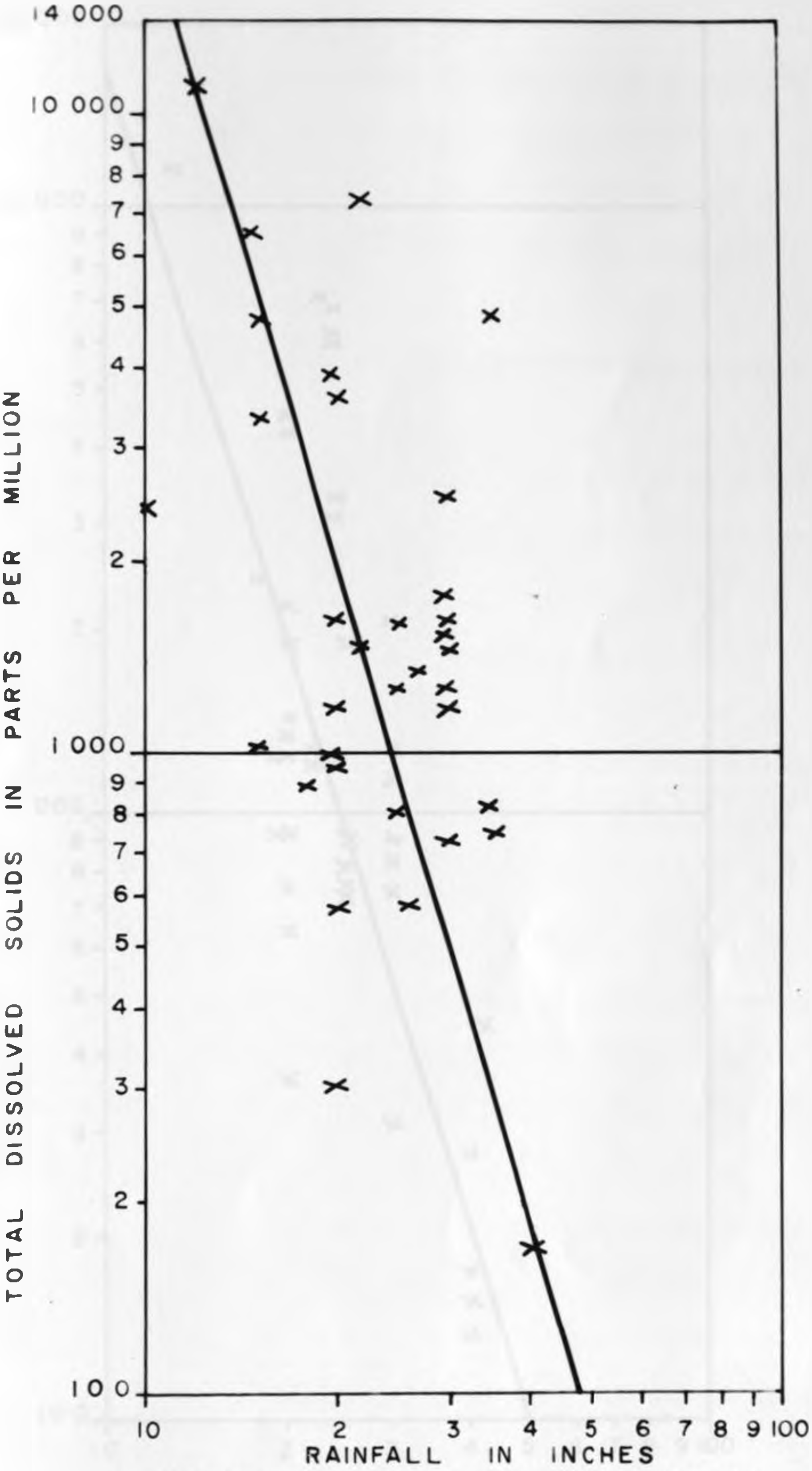
Relationship between Mean Annual Rainfall and Total Dissolved Solids in Groundwater within the Tertiary and Quaternary Basalts

FIG. 6.43



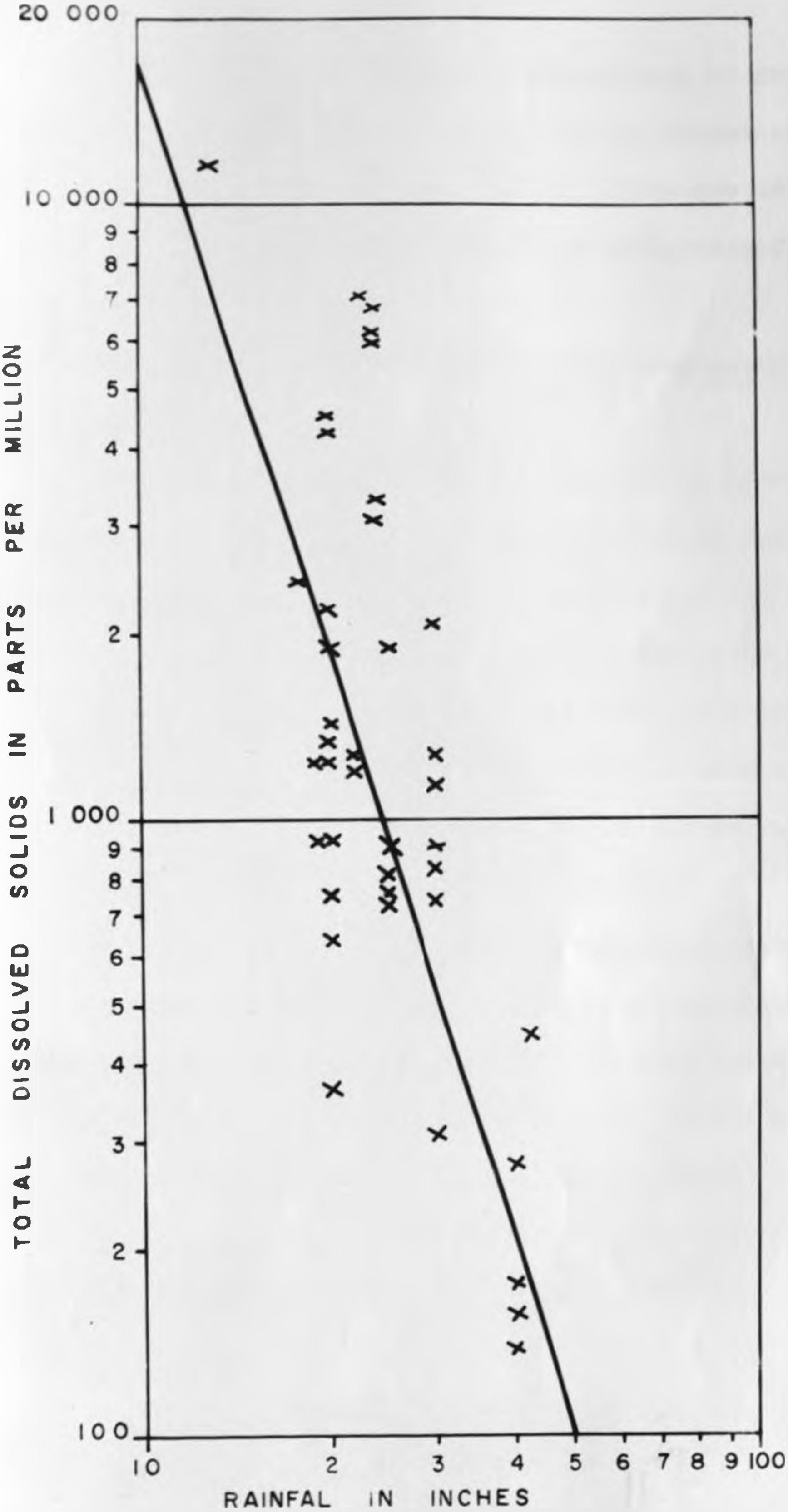
Relationship between Mean Annual Rainfall and Total Dissolved Solids in Groundwater within the Tertiary and Quarternary Phonolites

FIG. 6.44



Relationship between Mean Annual Rainfall and Total Dissolved Solids in Groundwater within the Quartzo- Felspathic and Granitoid Rocks of the Basement Complex

FIG. 6 45



Relationship between Mean Annual Rainfall and Total Dissolved Solids in Groundwater within the Undifferentiated Basement Complex Rocks

FIG 6 46

Since changes in the chemical composition of groundwater are caused by solution, precipitation, oxidation, reduction and ion exchange, the amounts and nature of water available and temperatures are important parameters for hydrogeochemical reactions.

From the above observations the following conclusions may be drawn:-

① (a) The high rainfall and low temperature areas have groundwaters with relatively low amounts of total dissolved solids. In these zones the rates of evaporation are low and there is sufficient water which is readily available for groundwater dilution. Furthermore, the water is leached through the aquifer quite rapidly such that it does not have sufficient time to come to equilibrium with the surrounding minerals of the materials forming the aquifer.

(b) The relatively low rainfall and high temperature zones experience waters with intermediate concentrations of total dissolved solids. Here the rates of evaporation from the water table is relatively higher and the waters are far removed from areas providing for groundwater recharge.

(c) The extremely low rainfall and high temperature zones have groundwaters with quite high concentrations of total dissolved solids. The high evaporation rates, low rainfall and distance from areas providing water for groundwater recharge are partly responsible for these high concentrations. It must also be appreciated that the leaching rates are quite low and the water stays in contact with its surrounding rocks or soil minerals for quite a long time.

(d) The Coastal zone has waters with the highest amounts of total dissolved solids. The influence of the adjoining Indian Ocean, has played an increasingly active role in the provision of salts to groundwaters situated in this zone. Another important fact is that these waters occur in some of the salt-bearing marine sediments of coastal Kenya. calcareous rocks

(e) There is a modification of groundwater chemistry down the gradient along profiles of groundwater flow due to the changing parameters of the environment and the water itself.

C. Geologic Background of Groundwater Chemistry in Kenya

The chemical components of groundwater are a result of various geologic factors which include the chemical-mineralogical composition, structure and texture of specific rock types or units. The geological formations and their spatial distribution in Kenya have been discussed in Chapter III.

Seaber (1965), in discussing the chemical character of water within the English town Formation, New Jersey, has noted that water chemistry, within a particular aquifer is related to the lithologic and topographic framework of the coastal plain of the United States and to the pattern of groundwater movement within the Plain. As has been indicated earlier, Todd (1959) also showed that concentration of salts in water depend upon the environment, movement and source of groundwater. He has further indicated that the supply of ions in groundwater is provided by the solution of the rocks or soils through which the water has travelled.

Table VI-1 gives the average composition of the crustal rocks of the earth. From this table it may be noted that the crustal rocks of the earth are composed of different elements of varying amounts. These compositions are important for, as indicated before, the ions in groundwater will be supplied by these rocks. This is a further indication that because of the differing nature of crustal rocks, the groundwaters obtained from these rocks will be equally variable in terms of chemical composition.

Hem (1959) has shown that there is a general relationship between mineral composition of a natural water and that of the solid minerals with which the water has been in contact. He has further observed that such a relationship could be relatively simple and uncomplicated as in the case of an aquifer receiving direct recharge by rainfall and from which water is discharged without contacting any other aquifer or other water. Conversely, the situation may be rendered very complex by influence of one or more interconnected aquifer of different composition, mixing of unlike waters, chemical reactions such as base exchange, absorption of dissolved ions and other factors. This is indeed the case with many of the Kenya groundwaters. Furthermore, differences in climatic or other environmental influences on the weathering processes can produce very different types of water from essentially similar rocks. This is certainly the problem with the waters being examined in this study and the importance of such modifications cannot be overlooked.

TABLE VI-1

AVERAGE COMPOSITION OF CRUSTAL ROCKS

(after V.M. Goldschmidt and Bryan Mason)

	In terms of elements			In terms of oxides	
NAME	FORMULAAND VALENCY	PERCENTAGE	NAME	FORMULA	PERCENTAGE
Oxygen	O^{-2}	46.60	Silica	SiO_2	59.26
Silicon	Si^{++}	27.72	Alumina	Al_2O_3	15.35
Alumina	Al^{3+}	8.13	Iron (Ferric oxide	Fe_2O_3	3.14
Iron	(Fe^{3+}	5.00	(Ferrous oxide	FeO	3.74
	(Fe^{2+} (				
Calcium	Ca^{2+}	3.63	Lime	CaO	5.08
Sodium	Na+	2.83	Soda	Na_2O	3.81
Potassium	K+	2.59	Potash	K_2O	3.12
Magnesium	Mg^{2+}	2.09	Magnesia	MgO	3.46
Titanin		0.44	Titanio	TiO_2	0.73
Hydrogen	H^+	0.14	Water	H_2O	1.26
Phosphorous	P^{5+}	0.12	Phosphorous Pentoxide	P_2O_5	0.28

Clarke (1924), has shown that practically all minerals, certainly the important ones, are attacked by water and carbonic acid. He has shown that in the case of silicate minerals, the pyroxenes and amphiboles yield most readily to water, then follow the plagioclase feldspars, then orthoclase and micas, with muscovite the most resistant of all. Further observations show that even quartz is not quite insoluble and corrosion of quartz pebbles in conglomerates has been noted by several scholars of sedimentation. Among the commoner accessory minerals, apatite and pyrite are most easily decomposed. Magnetite is less attacked and such minerals as zircon, corundum, chlorite and ilmenite tend to accumulate with little alteration in sandy rock residues. These minerals are not absolutely incorrodible but they are nearly so. Corundum, for example, slowly undergoes hydration and is converted at least superficially into gibbsite or diaspore. The relative solubility of various minerals in water as determined by Hoffmann (1882), and illustrated by Clarke (1924), are given in Table VI-2. Hoffmann's method of solubility determination consisted of a system of allowing water to percolate through the powdered mineral material for two months and measuring the loss of weight. He did not, however, consider the possibility of gain by hydration. The excessive solubility shown for talc and muscovite has been greatly questioned by Clarke (1924). The materials extracted from minerals by carbonated water as given by Clarke (1924) have been shown in Table VI-3.

It is clear in Table VI-2 and VI-3 that different

TABLE VI-2

RELATIVE SOLUBILITY OF VARIOUS MINERALS IN WATER

	GRAMS TAKEN	LOSS OF WEIGHT
Vesuvianite $Ca_{10}(Mg,Fe)_2Al_4(Si_2O_2)(SiO_4)_5(OH,F)_4$	4.109	0.064
Epidote $CaFe^{+3}Al_2O.OH(Si_2O_7)(SiO_4)$	3.353	0.052
Olivine $(MgFe)_2(SiO_2)$	3.506	0.078
Chlorite $(MgAlFe)_{12}\ (Si,Al)_8O_{20}\ (OH)_{16}$	2.591	0.094
Talc $Mg_6(Si_8O_{20})(OH)_4$	1.1245	0.105
Muscovite $K_2Al_4(Si_6Al_2O_{20})(OH,F)_4$	0.5058	0.056
Biotite $K_2(MgFe^{+2})_{6-4}(Fe^{+3}Al\ Ti)_{0-2}$ $(Si_{6-5}Al_{2-3}O20)(OH,F)_4$	.9736	0.035

TABLE VI-3

MATERIALS EXTRACTED FROM MINERALS BY CARBONATED WATER

	SiO_2	Al_2O_3	K_2O	Na_2O	MgO	CaO	P_2O_5	FeO	SUM
Adularia	0.1552	0.1368	1.3527	-	-	-	-	Trace	0.328
Oligoclase	0.237	9.1713	-	2.367	-	3.43	-	Trace	0.533
Hornblende	0.419	Trace	Trace	-	-	8.528	-	4.829	1.536
Magnetite	-	-	-	-	-	-	-	0.942	0.307
Magnetite	Trace	-	-	-	-	-	-	2.428	1.821
Apatite	-	-	-	-	-	1.696	1.417	-	1.529
Apatite	-	-	-	-	-	2.168	1.822	-	2.018
Apatite	-	-	-	-	-	1.946	2.12	Trace	1.976
Olivine	0.873	Trace	-	-	1.291	-	-	8.733	2.111
Serpentine	0.354	-	-	-	2.649	-	-	1.527	1.211

geologic materials will respond differently to agents of weathering such as rain water. This subsection is largely concerned with the effects of weathering products from these geologic materials on the groundwater chemistry. As indicated earlier, the interpretation is based on values of total dissolved solids concentration in groundwater. These values have been superimposed on the compiled and simplified geological map of Kenya at the scale of 1:1 million (see

From this map it is evident that the three main rock groups, namely sedimentary, igneous (mainly volcanic) and metamorphic rocks, have further been subdivided into various rock units on the basis of age and lithology. This particular map is meant strictly for interpretation purposes only. It should be pointed out that the "X" and "C" which appear in the map, but are unfortunately omitted from the main key, refer to the undifferentiated Basement complex rocks and carbonatites respectively.

EFFECTS OF GEOLOGY ON KENYA'S GROUNDWATER CHEMISTRY

Groundwater associated with Sedimentary Formations in Kenya

The nature and distribution of sedimentary rocks in Kenya has been discussed in Chapter III. From Figure 6-2 it is evident that groundwaters with total dissolved solids of up to and above 15,000 parts per million are associated with the sedimentary rocks of Coastal Kenya. Groundwaters in the Pleistocene and Recent coral reef show concentrations of total dissolved solids generally of up to 2,000 parts per million. Apart from the contribution of salts, received from the much soluble coral limestones with high amounts of calcium carbonate, the greater proportion of the salts is a contribution from the intrusion of sea water from the adjoining Indian Ocean. Indeed this is quite in agreement with other findings elsewhere. For example, Ward (1967), has indicated that in normal free groundwater conditions, with a water table sloping towards sea level at the coast, the groundwater body takes the form of a lens of fresh water floating on more saline water beneath. The increase of salinity with depth in these coastal waters is a reflection of this finding. Furthermore, the spray of ions from the sea by wind action is also another contribution.

The Quarternary Sediments of the coast exhibit groundwater with more or less the same degree of salinity as groundwaters in the Pleistocene and Recent Coral reef. But unlike these sediments, the Quaternary sediments of the arid and semi-arid north-eastern part of the country, contain groundwaters having a total dissolved solids concentration of up to 8,000 parts per million. One must, however, be appreciative of the fact that localized environmental factors, such as the situation of the Lorian Swamp will give rise to the variable nature of these waters. In general, it is appropriate to suggest that the shelly limestones, óolitic limestones, shales, sands and the carbonate cementing material of the sediments are quite soluble and hence provide a higher concentration of salts to groundwater. Far more important, however, is the fact that due to extremely low rainfall and marked temperatures, there is considerable evaporation of water from the water table. With extremely low leaching activity and low amounts of water to provide for groundwater recharge and dilution of their salts, and considering the fact that these waters stay for quite a long time within their enclosing rock or soil minerals, these waters are highly charged with salts. Because of local variations in the environmental factors, water within the other Quaternary Sediments occurring elsewhere have a concentration of total dissolved solids of less than 500 parts per million. This is particularly noticeable in areas within the Rift Valley and Lake Victoria regions.

Groundwater within the Post-Miocene sediments which consist of sands, clays, pebble beds and lenses of limestones exhibit total dissolved solids concentrations comparable to that exhibited by the Quaternary sediments of the Coastal Kenya and parts of North-eastern Province. Perhaps these high concentrations are not only derived from these rocks, but are also contributed by groundwater flow. These waters are situated far from areas providing water for groundwater recharge. Furthermore there is relatively high rate of evaporation in this zone as explained earlier on. Amounts of total dissolved solids in groundwater within the sediments of this eastern part of the country range up to 3,000 parts per million. But sediments of similar age in parts of the Rift Valley region have waters of less than 1,000 parts per million of total dissolved solids.

Groundwaters within the saline Jurassic sediments of marine origin, mainly composed of the highly soluble limestones and the relatively impermeable shales generally have a total dissolved solids concentration of up to 5,000 parts per million. The less soluble Cretaceous sediments mainly composed of sands, contain groundwaters with less than 3,000 parts per million of total dissolved solids.

Groundwater associated with the Duruma Sandstone Series, mainly composed of sandstones, shales, grits with carbonate as the main cementing material have a higher concentration of total dissolved solids, generally well over 5,000 parts per million. Because of the impervious nature of these rocks the water gets in contact with its surrounding rock minerals for quite a considerable period of time and hence the higher concentrations.

From the observations above, it is evident that the sedimentary rocks, because of their area of location and high solubility rates have high concentrations of soluble constituents. Sodium and calcium are the common cations, while bicarbonate, carbonate and sulphate are the corresponding common anions. It is true that there is also a characteristically high concentration of chloride in these waters.

Groundwater Associated with Volcanic Rocks in Kenya

The volcanic rocks forming the extrusive representatives of the Igneous rocks as shown in Chapter III may be considered with respect to their mineralogical composition, as forming a continuous series, members of which grade into each other successively.

At one end of the scale of igneous rocks are member groups which consist largely of alkali feldspars and quartz. Further on in the series are rocks such as diorite which consist of mixtures of alkali and plagioclase (calcic and sodic) feldspars with quartz. Still further, on in the scale are rocks like gabbro and basalt which contain mostly plagioclase feldspar and ferromagnesian minerals with no quartz and at the very end of the scale are rocks which contain ferromagnesian minerals only.

It is obvious, therefore, that Igneous rocks are in general composed of silica and silicate minerals. Siever (1957), has noted that the primary source of silica in solution is the chemical weathering of silicate minerals formed at higher temperatures and pressures. He has further indicated that most natural waters are undersaturated with respect to amorphous silica and much of the ocean is undersaturated with respect to quartz. The silica cycle starts with the weathering of silicate minerals, gets through the stages of transportation, precipitation and metamorphism and finally comes back to reconstituted silicate minerals.

Groundwaters associated with the Tertiary and Quaternary basalts which are relatively low in silica but containing appreciable amounts of silicate minerals, such as pyroxenes, micas and feldspars, occurring in the intensive leaching zone have concentrations of total dissolved solids generally less than 600 parts per million. Those occurring in the arid, northern parts of the rift valley have groundwater with concentrations of up to 1,000 parts per million.

The undersaturated Tertiary and Quaternary phonolites, mainly composed of such silicate minerals as orthoclase of the Sanidine Variety, nepheline and other feldspathoids occurring in high rainfall and low temperature humid areas have groundwaters with less than 300 parts per million of total dissolved solids, while those occurring in less rainfall and high temperature areas have groundwaters with up to 500 parts per million of total dissolved solids.

The trachytes, which are rich in potassic and sodic feldspars, biotite hornblende and olivine for the certain classes of trachytes, contain groundwaters having less than 500 parts per million of total dissolved solids. Those occurring in a less humid area seem to contain water with a total dissolved solids concentration of up to 700 parts per million.

The Tertiary and Quaternary ryolites which are quite rich in the insoluble silica, have groundwaters with extremely low concentrations of total dissolved solids, generally of the order of up to 100 parts per million, although in some less humid areas concentrations of up to 150 parts per million are not uncommon. Rhyolites of the Nyanzian system exhibit groundwaters with comparable amounts of total dissolved solids.

The Tertiary and Quaternary pyroclastics, tuffs and nephelinites which have less appreciable amounts of silica have groundwaters having less than 300 parts per million but those occurring in the less rainfall and high temperature zones have waters of up to 400 parts per million of total dissolved solids.

Because the silicate minerals which compose the rocks examined above differ considerably with respect to the amounts of silica released to respective groundwaters, there is a variation not only of the amounts of silica in the groundwater but also the sum total concentration of dissolved constituents in groundwater. For example, the decomposition of the alkali feldspars which form the dominant minerals of the rhyolites and other acid volcanics can occur in several different ways depending upon conditions of weathering and the same is true of other constituent silicate minerals. Due to the complex mixing of the constituent silicate minerals which make up the volcanic rocks, and since the solubility of these rocks is different, it is difficult to make any close prediction as to the amounts of silica that will be released to groundwater by these rocks. Hem (1959), has for example, indicated that calcium feldspar, anorthite, could decompose to kaolinite and calcium carbonate with no release of silica at all. Olivine, a major constituent of basic rocks such as basalts and gabbro may yield only one molecule of silica for each four magnesium ions released during the formation of serpentine. Pyroxenes such as augite may also be converted to serpentine by a similar process involving action of water and carbon dioxide.

These reactions indicate that silicates rich in alkali are likely to release more silica in the weathering process in proportion to the cations released than the ferromagnesian silicates or those containing much calcium. Although not all the silica released may be dissolved, this relationship may help to explain why in some of these volcanic rocks soft waters high in pH and in silica concentrations are found. Tables giving silica values for different waters are given in Chapter VII.

In drawing conclusions from the observations above, it is realized that the volcanics which are mainly composed of silicate minerals are situated in a humid area with intensive weathering. Because of the high leaching rates, the percolating water does not have sufficient time to come into equilibrium with its surrounding rock and soil minerals and hence the relatively low concentrations of total dissolved solids. The volcanics located in the arid and semi-arid regions have, however, groundwaters with higher concentrations of total dissolved solids. Another factor which needs mention is the relative solubility of the minerals forming these rocks.

Groundwater Associated with Metamorphic Rocks in Kenya

From the examination of the geology of Kenya in Chapter III, it is quite clear that any kind of rock may be altered or metamorphosed. All degrees of alteration which exist are from minor chemical or physical change to complete change and reassemblage of the minerals. Heat and pressure are the most important metamorphic agents.

The metamorphosed rocks are of Precambrian age and as shown in Figure Map? 6-2, occupy the eastern half and parts of western portions of the country. These rocks are mainly located in a rather unfavourable environment, generally in areas receiving less than 30 inches of rainfall and temperatures of above 30°C. These are places which are far removed from areas providing for groundwater recharge.

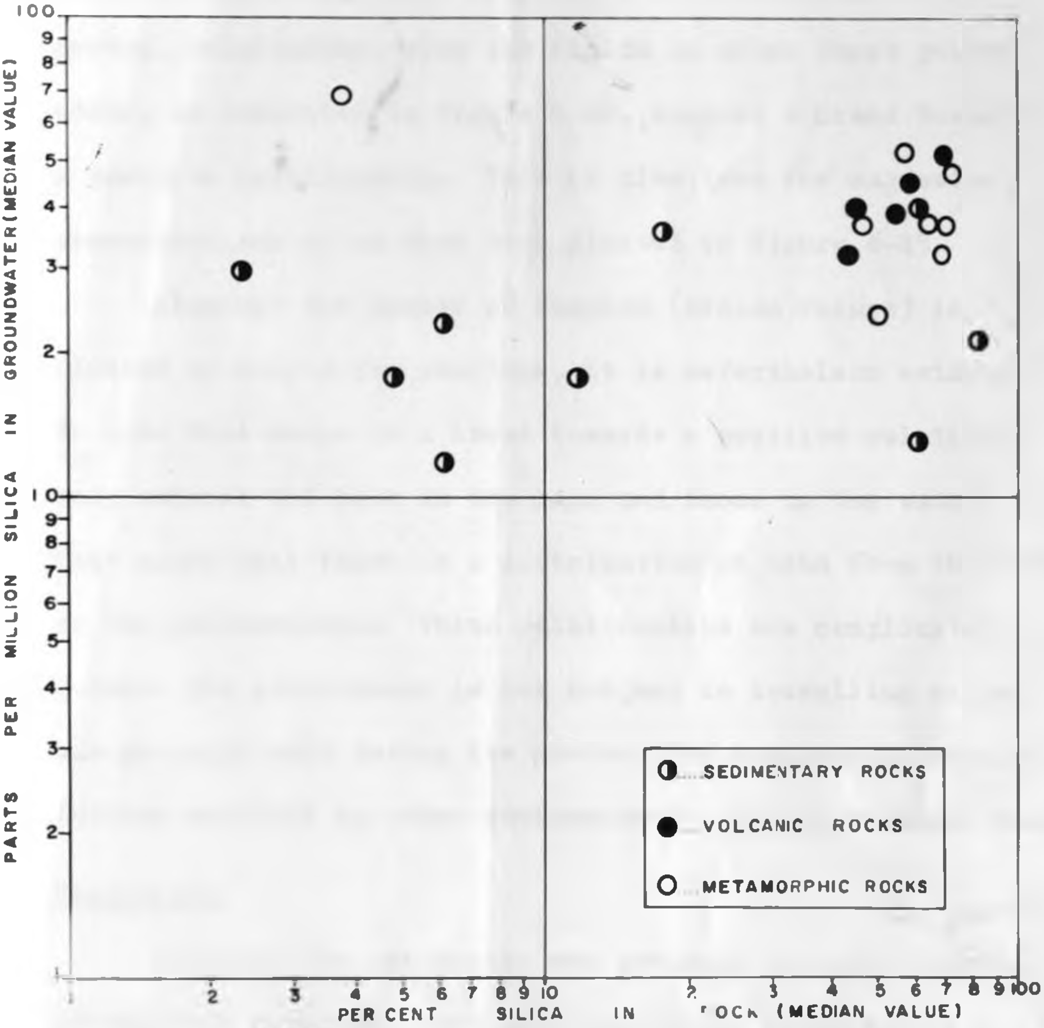
In the pelitic and semi-pelitic rocks where the movement of groundwater is restricted by the overburden of silicate minerals and other materials of low solubility and permeability the amount of total dissolved solids is in the order of up to 5,000 parts per million. Those occurring in the wetter portions of the western part of the country exhibit groundwater with total dissolved solids of less than 1,000 parts per million. These waters, as shown in Figure 6-39 and ? 6-40,? are located in relatively low rainfall and high temperature zones and hence higher evaporation rates from the water table. Groundwaters within the calcareous metasediments which range from pure marbles and ophicalcite to the more complicated lime-silicate rocks, show appreciable amounts of total dissolved solids but generally less than 4,000 parts per million. The ones occurring in a much more humid environment show concentrations of up to 2,000 parts per million. The soluble nature of these rocks and the other environmental factors examined earlier are responsible for these high amounts of total dissolved solids.

The quartzo-feldspathic rocks and migmatites which are mainly composed of the relatively insoluble silica and silicate minerals exhibit groundwaters with total dissolved solids concentration well below 2,000 parts per million. Those that occur in humid areas have groundwaters of less than 1,000 parts per million of total dissolved solids. It is interesting to note that the granites which are extremely rich in silica contain waters of very low concentrations of total dissolved solids, generally well below 500 parts per million.

The undifferentiated Basement Complex rocks which comprise of migmatites, gneisses, schists and other metamorphics have waters with extremely high amounts of total dissolved solids generally well up to and over 5,000 parts per million. Those located in humid areas have groundwaters with less amounts of total dissolved solids.

Nyanzian acid to basic volcanics and the relatively unmetamorphosed sediments of the Kavirondian and Bukoban systems are located in areas where the rates of leaching are high and where there is adequate water for groundwater recharge. These rocks contain groundwater very much comparable with groundwater in the Tertiary and Quaternary volcanics examined earlier and the concentration of total dissolved solids is well below 500 parts per million.

Median values of silica in groundwater in parts per million, plotted against median values of silica in percentages in respective rock units are shown in Figure 6-47. This indicates that despite the scarce number of samples involved, there appears to be a general relationship between the amounts of silica in groundwater and in given rock types. These median values, do not only seem to fall within one field but also give a trend towards a positive linear relationship. This is particularly the case with the metamorphic and volcanic rocks. It is difficult from this diagram to draw any distinct line between the metamorphics and volcanics. This may be attributed largely to the mineralogical and chemical composition of the rocks forming both types of rocks. The relationship with sedimentary rocks is much more confusing generally because of the different environments from which



Relationship between Silica Content in Groundwater and in respective Rock Types

FIG. 6.47

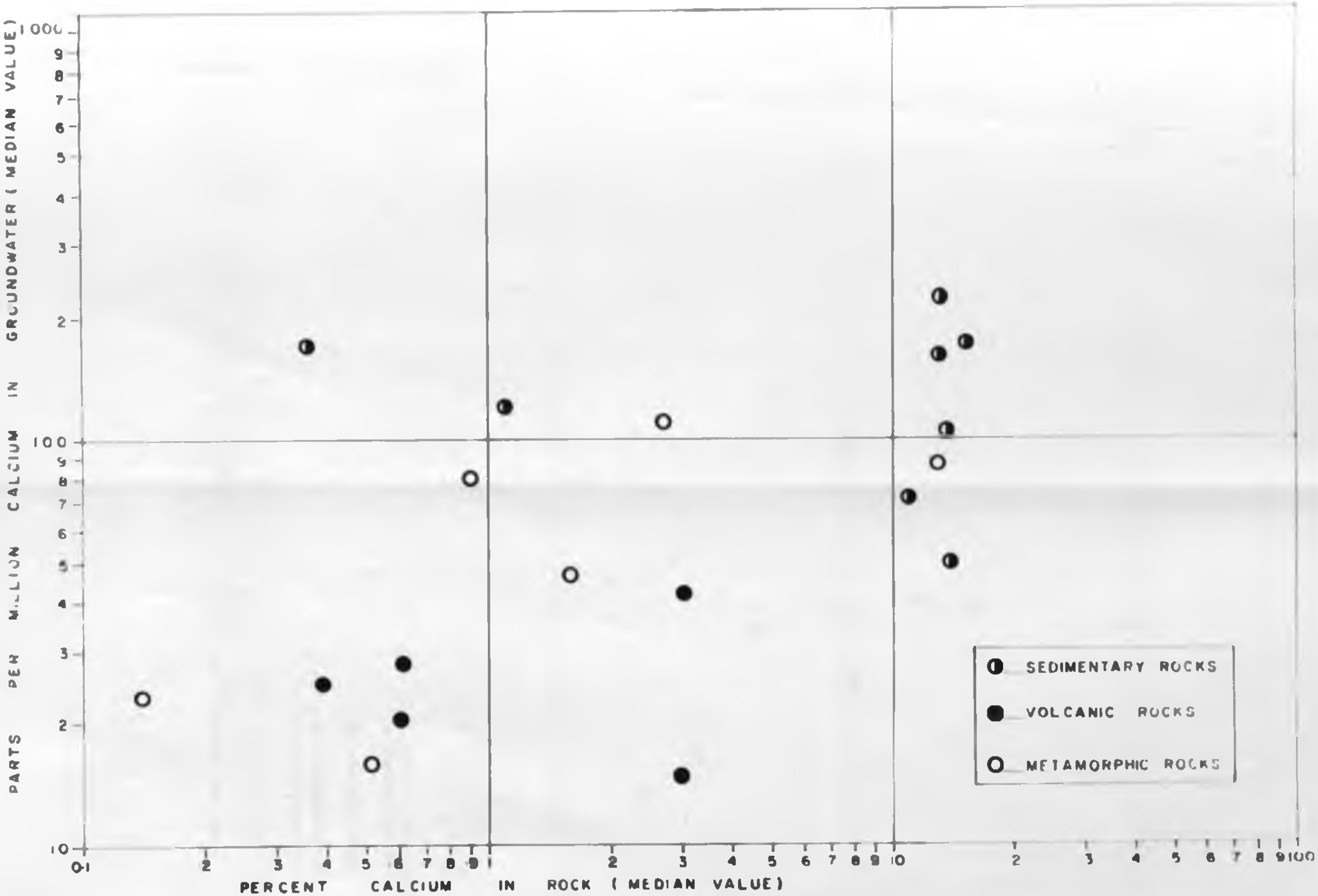
these samples were drawn.

Plotting of the median values for calcium in the groundwater, against concentrations of the same cation in the respective rock units give a relationship which is more or less the same as above. Again, the difference between volcanic and metamorphic rocks is a bit obscured, but the general relationship plus the fields in which these points occur, as indicated in Figure 6-48, suggest a trend towards a positive relationship. This is also true for magnesium concentrations which have been plotted in Figure 6-49.

Although the number of samples (median values) is limited to only a few readings, it is nevertheless evident to note that there is a trend towards a positive relationship between the ions in the rock and those in the water. This means that there is a contribution of ions from the rocks to the groundwaters. These relationships are complicated because the groundwater is not subject to travelling within one geologic unit during its cycle. The groundwater is also further modified by other environmental factors examined earlier.

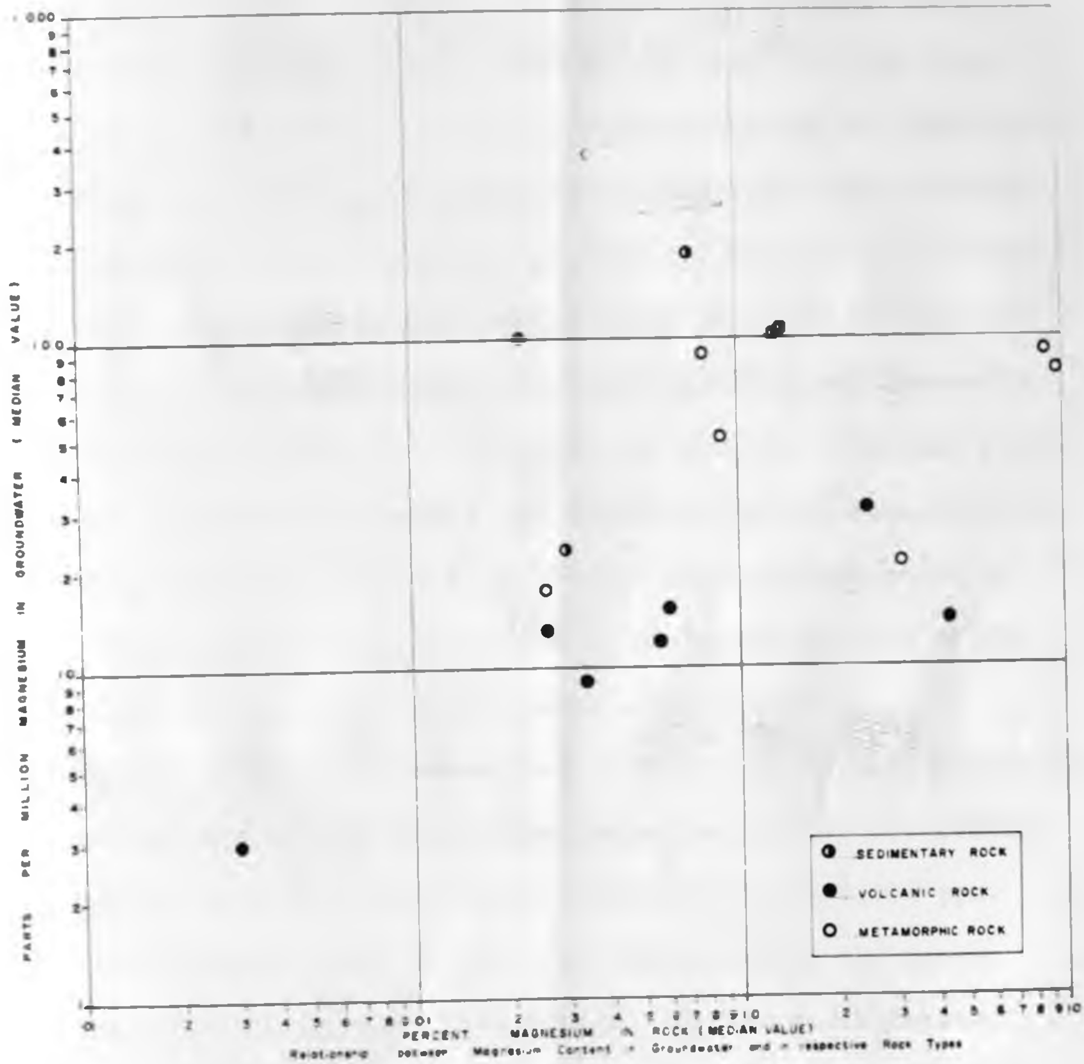
Conclusion

Although the geographic and geologic factors affecting groundwater chemistry have been dealt with under separate sections in this chapter, it must be realized that they are interdependent. These factors include the climatic and hydrologic parameters such as rainfall, temperature, evapotranspiration and topographic parameters such as aspect and area, geologic factors such as the structure, chemistry and mineralogical composition of the rocks and the hydrogeological



Relationship between Calcium Content in Groundwater and in respective Rock Types

FIG. 6 48



Relationship between Magnesium Content in Groundwater and in respective Rock Types

FIG 6 49

factors such as groundwater flow, circulation and groundwater recharge. This does not, however, mean that these are the only factors influencing the groundwater chemistry for, as Rainwater and Thatcher (1960) and Lohr and Love (1952) have noted, the chemical quality of water is the resultant action of the geologic, hydrologic, biologic and cultural environment of water and varies from time to time and from place to place. However, the following conclusions may be drawn with respect to the significance of the geographic and geologic factors in the variation of groundwater chemistry in Kenya:-

(i) The highly soluble sedimentary rocks of the coastal Kenya contain groundwaters of very high salinity generally well up to and above 8,000 parts per million. In some places the groundwaters have a total dissolved solids concentration of up to 20,000 parts per million. This concentration is partly derived from the intruding sea water and the saline marine sediments in which these waters occur.

(ii) Groundwaters associated with the sedimentary formations of the semi-arid and arid North-eastern part of the country have a total dissolved concentration of up to 8,000 ppm. This is largely due to the high solubility of the rock-minerals that contain this water. Another contributing factor is the high evaporation rates with very low amounts of rainfall that provide water for groundwater recharge.

(iii) Groundwater in the Tertiary and Quaternary volcanics as well as those of the Basement complex, Nyanzian and Kavirondian rocks situated in western and south-western Kenya have very low amounts of total dissolved solids, generally of the order of 500 ppm. This can be attributed to the high leaching rates in this high rainfall and low temperature area and the relative solubility of the rock and soil minerals containing this water.

(iv) The metamorphic formations provide groundwater of intermediate amounts of total dissolved solids of well up to 5,000 ppm. These rocks which mainly consist of silica and silicate minerals are situated in comparatively drier areas and are far removed from points providing the groundwater recharge.

(v) There is a close relationship between groundwater chemistry on one hand and the environmental factors of geology, hydrology and geography on the other hand and hence the significance of the examined geologic and geographic factors in the variation of groundwater chemistry.

CHAPTER VII

WATER RESOURCE PLANNING AND DEVELOPMENT

This chapter forms the conclusion to this thesis and examines the following items:-

1. Water quality criteria and international standards of water for various uses.
2. Systematic description of the variation of groundwater chemistry in Kenya.
3. Suggested groundwater zones and the suitability of groundwater resources of Kenya for various uses.
4. Areas for further research.

In planning for water resource development, it is necessary to have information regarding the quality of the water. This will provide a base for effective water usage and management. Unlike the previous chapter which dealt with the relationship of the major environmental factors and water chemistry, this chapter examines the distribution of the chemical constituents in groundwater which forms the basis upon which evaluation of the groundwater quality in Kenya is attempted. The groundwater samples examined in this analysis were derived from boreholes and wells only. This study does not involve the thermal and alkaline spring waters mainly associated with the volcanic activity in the Rift Zone.

According to Dixey (1946), boreholes are very important sources of rural water supplies in many African countries. The boreholes are usually 6 inches feet in diameter and most of them are 100-250 feet in depth. In drier parts of Africa, however, deep boreholes in the order of 200-300 feet in depth drilled in metamorphic and other rocks have given steady yields. He continues to indicate that excavated wells constructed by various government and other organisations are usually about four feet in diameter. They are linked with concrete and are fitted with a concrete head surrounded by an apron and drain. The depth range is of the order of 30 to 70 feet but they also rarely exceed 100 feet. Boreholes and wells examined in Kenya are less than 500 feet in depth and the description given by Dixey (1946), could also apply to them.

1. Water Quality Criteria and International Standard of Water for Various Uses

The criteria of water quality will be determined by the purpose and use of given water but as Davis and De Weist (1966) have indicated, the chemical and biological characteristics of the water determine its usefulness for industry, agriculture or the home.

(a) Water quality criteria for domestic and drinking purposes

Drinking water standards are based on two main criteria:-

(i) The presence of objectionable tastes, odours or colours.

(ii) The presence of substances with adverse physiologic effects.

On the basis of these criteria, the United States

TABLE VII-1

U.S. PUBLIC HEALTH SERVICE DRINKING WATER STANDARDS, 1962

Ionic Concentrations in Milligrams per Litre

	CHARACTERISTIC	SUGGESTED LIMIT THAT SHOULD NOT BE EXCEEDED	CAUSE FOR REJECTION
PHYSICAL	Colour	15 units	
	Taste	Unobjectionable	
	Threshold Odour number	3	
	Turbidity	5 units	
CHEMICAL	Alkyl benezene sulfonate	0.5	
	Arsenic	0.01	0.05
	Barium	-	1.0
	Cadmium	-	0.01
	Chloride	250	-
	Chromium (hexavalent)	-	0.05
	Copper	1	
	Carbon chloroform extract[1]	0.2	-
	Cynide	0.01	0.2
	Fluoride[2]	0.7-1.2	1.4-2.4
	Iron	0.3	
	Lead		0.05
	Manganese	0.05	
	Nitrate	45	
	Phenols	0.001	
	Selenium		0.01
	Silver		0.05
	Sulfate	250	
	Total dissolved solids	500	
	Zinc	5	

[1] Organic contaminants

[2] The concentration of fluoride may be between 0.6 and 1.7 mg/l, depending on the listed annual average maximum air temperature.

Public Health Service (1962), has given drinking water standards and these are shown in Table VII-1.

Gorrel (1958), has classified water on the basis of Sodium Chloride content into the classes shown in Table VII-2. The fresh water group includes those waters containing a maximum of approximately three times the sodium chloride content generally accepted as the limit for drinking water. The division between brackish water and salty water is placed at approximately one-third of the sodium chloride content of sea water. The division between salty water and brine is approximately three times the sodium chloride of sea water or one-third of the salt content of a saturated solution of Sodium Chloride at normal temperatures and pressures. Davis and De Weist (1966) have used the same classification but instead of sodium chloride content, they have used the concentration of total dissolved solids. They have further given water quality criteria for various uses and this is shown in Table VII-3. Of the ions appearing in this table, the limits of lead, fluoride, arsenic, sulphate, sodium, chloride, nitrate, selenium and chromium are based on adverse physiological effects.

TABLE VII-2 WATER CLASSIFICATION ON THE BASIS OF SODIUM CHLORIDE CONTENT

Class	NaCl Content in ppm	Name of Water
1	0-1,000	Fresh water
2	1,000-10,000	Brackish water
3	10,000-100,000	Salty water
4	over 100,000	Brine

TABLE VII-3 WATER QUALITY CRITERIA FOR VARIOUS USES IN MAXIMUM RECOMMENDED CONCENTRATIONS IN PARTS PER MILLION.

ION	DRINKING	GENERAL HOUSEHOLD USE		IRRIGATION		FOOD PROCESSING	BOILER WATER	
		GOOD	POOR	GOOD	POOR		HIGH PRESSURE	LOW PRESSURE
Antimony	0.05	-	-	-	-	0.05	-	-
Arsenic	0.05^{x}	-	-	-	-	0.05	-	-
Barium	1.00^{x}	-	-	-	-	1.00	-	-
Bicarbonate	500	150	500	200	500	300	5	50
Boron	20	-	-	0.3	3.0	-	-	-
Cadmium	0.01^{x}	-	-	-	-	0.01	-	-
Calcium	200	40	100	-	-	80	1	40
Chloride	250	-	-	100	300	300	-	-
Chromium	0.05^{x}	-	-	-	-	0.05	-	-
Copper	1.0	0.5	3.0	-	-	3.0	-	-
Cyanide	0.2^{x}	-	-	-	-	0.2	-	-
Fluoride	1.5	-	-	-	-	1.5	-	-
Hydrogen Sulfide	1.0	0.05	2.0	-	-	0.5	-	5
Iron	1.0	0.2	0.5	-	-	0.2	-	-
Lead	0.05^{x}	-	-	-	-	0.05	-	-
Magnesium	125	20	100	-	-	40	1	20
Manganese	0.05	0.05	0.3	-	-	0.1	-	-
Nitrate	20	-	-	-	-	20	-	-
Phenol	0.001	-	-	-	-	0.001	-	-
Selenium	0.01^{x}	-	-	-	-	0.01	-	-
Silica	-	10	50	-	-	50	1	30
Silver	0.05^{x}	-	-	-	-	0.05	-	-
Sodium	200	100	300	50	300	300	-	50
Sulfate	250	100	300	200	500	-	-	-
Synthetic detergents	0.5	0.2	1.0	-	-	0.5	-	-
Total solids	1,500	300	2,000	500	3,000	1,000	100	2,000
Zinc	5	-	-	-	-	5-	-	-

x Mandatory limits of the U.S. Public Health Service for water used on interstate public transportation facilities.

The exact optimum limits for all ions are actually controlled by the health, size and age of the individual as well as by his eating and drinking habits. Limits of water for general household purpose are established to prevent objectionable odours, stains and deposits as well as to prevent waste of soap owing to high hardness values.

Steel (1966), has defined potable water as that which is safe to drink, pleasant to taste and usable for domestic purposes. Contaminated water is that which contains micro-organisms, chemicals, industrial or other wastes or sewage so that it is unfit for its intended use. The term polluted water, according to him, is synonymous with contaminated water. He has further given common impurities and wastes known to occur in water and their effects. These are shown in Table VII-4.

The World Health Organization (1971), has given the international standards for the acceptability of drinking water and these are summarized in Table VII-5. They have also shown the effects of certain high concentrations of given ions in water.

Although these standards are widely quoted for drinking water, they are not directly applicable to every situation. As an example, ocean water is clearly unsuitable for domestic purposes. Nevertheless, if fresh water is too expensive, sea water can be used for washing, cooking, recreation and fire protection. Davis and De Weist (1966), have noted that in some parts of North Africa, Australia and other arid regions, many people drink water with total dissolved solids of more than twice the generally recommended limit.

TABLE VII-4 THE COMMON INPURITIES IN WATER AND THEIR EFFECTS

	IMPURITIES			EFFECTS
SUSPENDED IMPURITIES	Bacteria			Some cause disease
	Algae, protozoa			odour, colour, turbidity
	Silt			Murkiness or turbidity
DISSOLVED IMPURITIES	SALTS[1]	Calcium and Magnesium	bicarbonate	alkalinity, hardness
			Carbonate	alkalinity, hardness
			sulfate	hardness
			chloride	hardness, corrosive to boilers
		Sodium	bicarbonate	alkalinity, has softening effect
			carbonate	alkalinity, has softening effect
			sulfate	foaming in steam boilers
			fluoride	mottled enamel of teeth
			chloride	taste
	Iron Oxide			taste, red water, corrosive to metals, hardness.
	Manganese			black or brown water
	Vegetable dyes			colour[2], acidity
	GASSES		Oxygen	corrosive to metals
			carbon dioxide	corrosive to metals, acidity
			Hydrogen sulfide	rotten-egg odour, acidity, corrosive to metals.
			Nitrogen	

[1] Salts cause tastes if present in large amounts

[2] strictly colour is caused by material in a colloidal state.

TABLE VII-5 SUBSTANCES AND CHARACTERISTICS AFFECTING THE ACCEPTIBILITY OF WATER FOR DOMESTIC USE

Substance or characteristic	Undesirable effect that may be produced	Highest desirable level	Maximum permissible level
Substances causing discoloration	Discoloration	5 units	50 units
Substances causing odours	Odours	Unobjectionable	Unobjectionable
Substances causing tastes	Tastes	Unobjectionable	Unobjectionable
Suspended matter	Turbidity. Possibly gastrointestinal irritation	5 units	25 units
Total solids	Taste. Gastrointestinal irritation	500mg/l	1500mg/l
pH range	Taste. Corrosion	7.0 to 8.5	6.5 to 9.2
Anionic detergents	Taste and foaming	0.2mg/l	1.0mg/l
Mineral oil	Taste and odour after chlorination	0.01mg/l	0.30mg/l
Phenolic compounds (as phenol)	Taste, particularly in chlorinated water	0.001mg/l	0.002mg/l
Total hardness	Excessive scale formation	2mEq/l (100mg/l $CaCO_3$)	10mEq/l (500mg/l $CaCO_3$)
Calcium	Excessive scale formation	75mg/l	200mg/l
Chloride (as Cl)	Taste; corrosion in hot-water systems	200mg/l	600mg/l
Copper (as Cu)	Astringent taste; discoloration and corrosion of pipes, fittings and utensils	0.05mg/l	1.5mg/l
Iron (total as Fe)	Taste; discoloration; deposits and growth of iron bacteria; turbidity.	0.1mg/l	1.0mg/l
Magnesium (as Mg)	Hardness; taste; gastrointestinal irritation in the presence of sulfate.	Not more than 30mg/l if there are 250mg/l of sulfate; if there is less sulfate, magnesium up to 150 mg/l may be allowed	150mg/l
Manganese (as Mn)	Taste; discoloration; deposits in pipes; turbidity.	0.05mg/l	0.5mg/l
Sulfate (as SO_4)	Gastrointestinal irritation when magnesium or sodium are present.	200mg/l	400mg/l
Zinc (as Zn)	Astringent taste; opalescence and sand-like deposits.	5.0mg/l	15mg/l

As far as can be determined, most of these people have suffered no injurious effects. Hem (1959), concurs with these conclusions when he indicates that in some sections of the United States, the quality of water available for most individual domestic supplies and some public supplies does not meet the standards in one or more respects. Nevertheless, many people in such areas have used these waters for entire life-time and although detailed medical data are not available, it would appear that the poor quality of their water supply, so far as dissolved solids are concerned, has had little visible effect.

(b) Water Quality Criteria for Agricultural Purposes

The use of water on the farm for non-domestic purposes includes the water consumed by livestock, the irrigation of crops and the operation of machinery.

Quality of Irrigation Water

The concentration and composition of dissolved constituents in water determine its quality for irrigation purposes. The quality of water is an important consideration in any appraisal of salinity or alkali conditions in an irrigated area. Whether particular water may be used successfully for irrigation depends on many factors not directly associated with water composition. Among these factors is the nature and composition of the soil, topography, amount and method of water applied, types of crops to be grown, climate and other environmental considerations. For example, salts may harm plant growth physically by limiting the uptake of water through modification of osmotic

? Cause a state of plasmolysis = cell flaccidity.

processes or chemically by metabolic reactions, such as caused by toxic substances. Effects of salts on soils causing changes in soil structure, permeability and aeration indirectly affect plant growth. Specific limits of permissible salt concentrations for irrigation purposes is variable with different degrees of salt tolerances of given plants. Todd (1959), gives the relative tolerances of crops to salt concentrations (Table VII-6). He has expressed the salt content in terms of electrical conductivity measured in micromhos per centimetre cubed. He has further shown that certain crops including most deciduous fruits, trees, navy beans are sensitive to Boron. He has given the relative tolerances of plants to Boron and these are shown in Table VII-7. From this table, it is apparent that Boron is necessary in very small quantities for normal growth of all plants but in larger concentrations it becomes toxic. The amount of Boron required vary with the crop type. Sensitive crops require minimum amounts, whereas tolerant crops require higher amounts. Hem (1959), as shown in Table VII-8, has given the rating of irrigation water for crops on the basis of Boron concentrations. Davis and De Weist (1966) have also given water quality criteria for good and poor irrigation water (Table VII-3).

Richards (1954), has stated that the characteristics of an irrigation water that appear to be most important in determining its quality are as follows:-

1. Total concentration of soluble salts.
2. Relative proportion of sodium to other cations.

TABLE VII-6 **RELATIVE TOLERANCES OF CROPS TO SALT CONCENTRATIONS**

(Electrical Conductivity Values represent levels at which a 50 percent decrease in yield may be expected as compared to yields on non-saline soil under comparable growing conditions)

Crop Division	Low Salt Tolerance	Medium Salt Tolerance	High Salt Tolerance
Fruit Crops	Avocado	Cantaloupe	Date palm
	Lemon	Date	
	Strawberry	Olive	
	Peach	Fig	
	Apricot	Pomegranate	
	Almond		
	Plum		
	Prune		
	Grapefruit		
	Orange		
	Apple		
	Pear		
Vegetable Crops	EC X 10^3 = 3	EC X 10^3 = 4	EC X 10^3 = 10
	Green beans	Cucumber	Spinach
	Celery	Squash	Asparagus
	Radish	Peas	Kale
	EC X 10^3 = 4	Onion	Garden beets
		Carrot	EC X 10^3 = 12
		Potatoes	
		Sweet Corn	
		Lettuce	
		Cauliflower	
		Bell pepper	
		Cabbage	
		Broccoli	
		Tomato	
		EC X 10^3 = 10	
Forage Crops	EC X 10^3 = 2	EC X 10^3 = 4	EC X 10^3 = 12
	Burnet	Sickle milkvetch	Bird's-foot trefoil
	Ladino clover	Sour clover	Barley (hay)
	Red clover	Cicer milkvetch	Western wheat grass
	Alsike clover	Tall meadow oatgrass	Canada wild rye
	Meadow foxtail	Smooth brome	Rescue grass
	White Dutch clover	Big trefoil	Rhodes grass
			Bermuda grass
Field Crops	EC X 10^3 = 4	EC X 10^3 = 6	EC X 10^3 = 10
	Field beans	Castorbeans	Cotton
		Sunflower	Rape
		Flax	Sugar beet
		Corn (field)	Barley (grain)
		Sorghum (grain)	EC X 10^3 = 16
		Rice	
		Oats (grain)	
		Wheat (grain)	
		Rye (grain)	
		EC X 10^3 = 10	

TABLE VII-7

RELATIVE TOLERANCES OF PLANTS TO BORON, LISTED IN ORDER OF INCREASING TOLERANCE

Sensitive	Semi-Tolerant	Tolerant
Lemon	Lima bean	Carrot
Grape fruit	Sweet potato	Lettuce
Avocado	Bell pepper	Cabbage
Orange	Pumpkin	Turnip
Thornless blackberry	Zinnia	Onion
Apricot	Oat	Broad bean
Peach	Milo	Gladiolus
Cherry	Corn	Alfalfa
Persimmon	Wheat	Garden beet
Kadota fig	Barley	Mangel
Grape	Olive	Sugar beet
Apple	Ragged Robin rose	Date palm
Pear	Field pea	Palm
Plum	Radish	Asparagus
American elm	Sweetpea	Athel
Navy bean	Tomato	
Jerusalem artichoke	Cotton	
English walnut	Potato	
Black walnut	Sunflower	
Pecan		

TABLE VII-8

RATING OF IRRIGATION WATER FOR VARIOUS CROPS ON THE BASIS OF BORON CONCENTRATION IN THE WATER

Classes of Water		Sensitive Crops ppm	Semi-tolerant Crops ppm	Tolerant Crops ppm
Rating	Grade			
1	Excellent	0.33	0.67	1.00
2	Good	0.33 to 0.67	0.67 to 1.33	1.00 to 2.00
3	Permissible	0.67 to 1.00	1.33 to 2.00	2.00 to 3.00
4	Doubtful	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
5	Unsuitable	1.25	2.50	3.75

3. Concentration of Boron or other element that may be toxic.

4. Under some conditions, the bicarbonate concentration of Calcium and Magnesium.

The United States Salinity Staff Laboratory (1954), have given a diagram for the classification of irrigation waters. This diagram is shown in Figure 7-1. According to this diagram they have drawn the following conclusions:

(a) Conductivity

1. Low salinity water (C1) is of less than 250 Micromhos/cm (EC X 10^6) at 25°C of conductivity and can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop.

2. Medium salinity water (C2) generally consists of less than 750 Micromhos/cm (EC X 10^6) at 25°C of conductivity and can be used for plants with moderate salt tolerances (see Table VII-7).

3. High salinity water (C3) has conductivity of up to 2250 Micromhos/cm (EC X 10^6) at 25°C and is suitable only for good salt tolerant plants.

4. The very high salty water (C4) with conductivity of more than 2250 Micromhos/cm can only be used under very special circumstances, for example, the soils must be adequate, irrigation water must be applied in excess to provide considerable leaching. Extremely high salt-tolerant plants will be able to survive.

(b) Sodium

Sodium or alkali hazard is usually expressed in terms

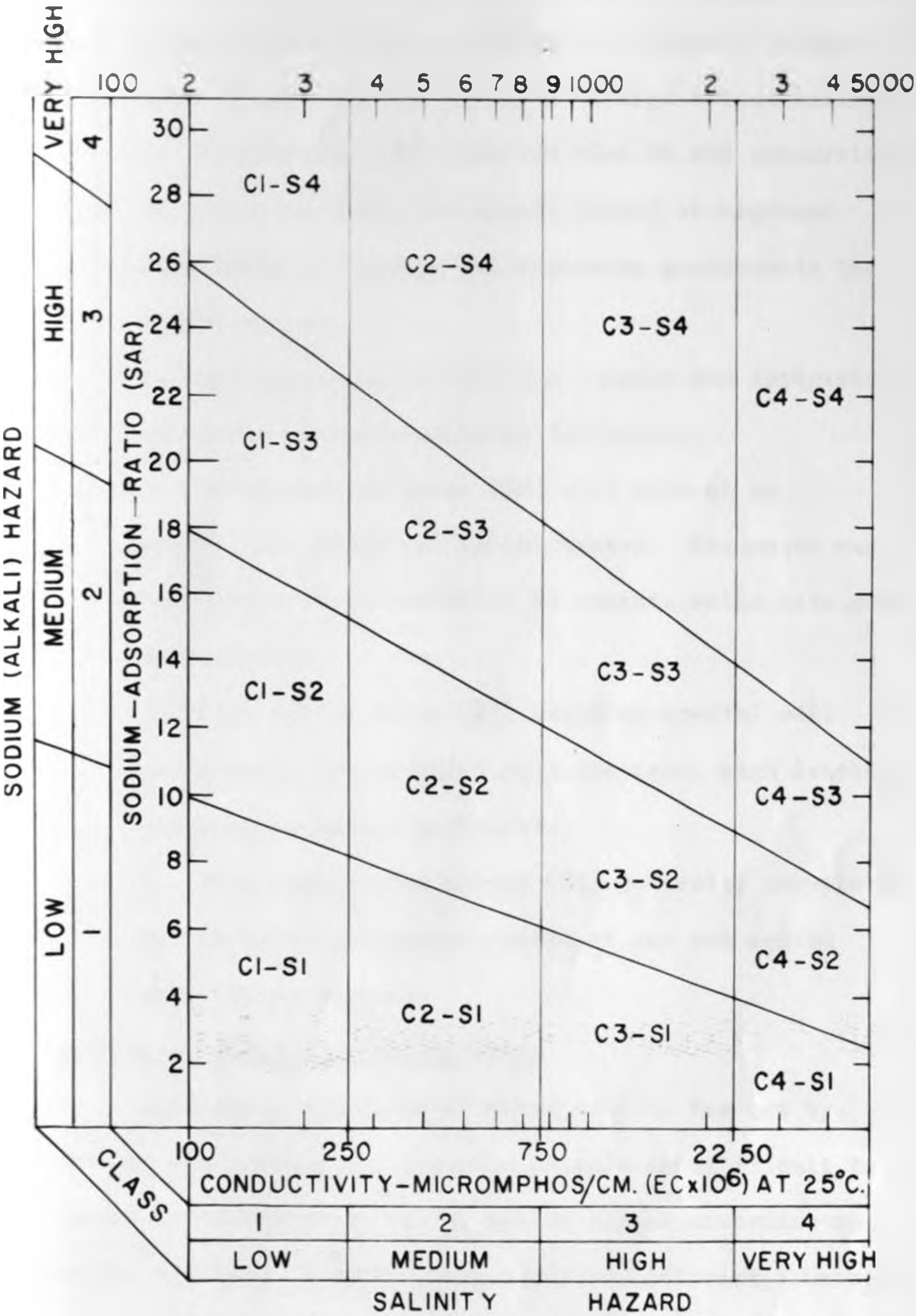


Diagram for the classification of irrigation waters.

FIG 7.1

of the Sodium Absorption Ratio (S.A.R.). Values of less than 8 are usually satisfactory, values between 10 and 15 are marginal and S.A.R. values of greater than 15 indicate the presence of high sodium hazards. It is therefore most apparent that if the proportion of sodium is high, the alkali hazard is high and conversely if Calcium and Magnesium predominate the hazard is low.

1. Low sodium water (S1) can be used for irrigation on almost all soils without difficulty.
2. Medium sodium water (S2) will present an appreciable amount of sodium hazard. The water may be used on coarse-textured or organic soils with good permeability.
3. High sodium water (S3) requires special soil management, for example, good drainage, high leaching and organic matter additions.
4. Very high sodium waters (S4) generally unsuitable for irrigation purposes except at low and medium salinity conditions.

Quality of Water for Stock Rearing

Acceptable standards of water quality for use by cattle, sheep and other domestic animals are difficult to define as tolerance to saline waters varies according to animal species. Moreover, standards in different countries are usually flexible rather than rigid, as economic and other factors such as availability of alternative sources of supply influence the levels of acceptability particularly for short term use of a given water source.

The Hydraulic Branch (1958-1961) have reported that in South Africa 5000 ppm of total dissolved solids is regarded as the upper safe limit for general stock use but cattle and sheep can survive for short periods on water with salinity of the order of 10,000 ppm. The normally accepted fluoride limit is 2.5 ppm for dairy stock and 5 ppm for beef cattle and sheep.

Hem (1959), has observed that the Department of Agriculture in Western Australia quote the upper limits for dissolved solids concentration in stock water appearing in Table VII-9. He has further indicated that some investigations have revealed that concentrations as high as 15,000 ppm are safe for limited periods but not for continuous use and some others indicate an upper limit of 5,000 ppm in water to be used by livestock.

Table VII-9

UPPER LIMITS OF DISSOLVED SOLIDS CONCENTRATION IN WATER TO BE CONSUMED BY LIVESTOCK

	PPM
Poultry	2,860
Pigs	4,290
Horses	6,435
Cattle (dairy)	7,150
Cattle (beef)	10,000
Adult sheep	12,900

Water Quality Criteria for Industrial Purposes

The quality requirement for industrial water supplies range widely and almost every industrial application has different standards. For example, food processing is a complex operation and each food processing industry has its own requirements. The limits that appear in Table VII-3 are based on drinking water limits plus special considerations for constituents which cause stains or odours. Calcium and Magnesium limits are low because many vegetables tend to harden if boiled in waters high in these ions. Water moderately high in these ions, however, is better for baking than the very soft water.

Most boiler water is conditioned before use by chemical treatment and sometimes by ion exchange or distillation. The limits of boiler fed water given in Table VII-3 indicate the extent of treatment necessary for this water. Although some raw water may be suitable for low pressure boilers, high pressure boilers require water of the greatest purity. These limits are designed to prevent both corrosion and scale formation.

Todd (1959), as shown in Table VII-10, has given some suggested water quality tolerances for industrial uses. It must, however, be emphasized once again that it is not possible to draw a rigid water quality limit for industrial waters for different industries require particular quality of water. Many industries, particularly in developed countries, have resorted to re-use of water that in former years might have been allowed to flow down the sewer or in to a surface stream. This is increasing the water quality problems. This means that waste disposal problems can be

TABLE VII-10

SUGGESTED WATER QUALITY TOLERANCES FOR INDUSTRIAL USES

(Allowable limits in ppm)

Industry or Use	Turbidity	Color	Odor and Taste	Iron as Fe	Manganese as Mn	Total Solids	Hardness as $CaCO_3$	Alkalinity as $CaCO_3$	Hydrogen Sulfide	Health	pH	Other Requirements
Air Conditioning	...	...	Low	0.5	0.5	...	...	...	1.0	...	...	No corrosiveness or slime formation
Baking	10	10	Low	0.2	0.2	...	...	...	0.2	Potable	...	
Boiler Feed												
Pressure 0-150 psi	20	80	...	...	...	3000-500	80	...	5	...	8.0	No corrosiveness or scale formation
Pressure 150-250 psi	10	40	...	...	...	2500-500	40	...	3	...	8.4	No corrosiveness or scale formation
Pressure 250-400 psi	5	5	...	...	...	1500-100	10	...	0	...	9.0	No corrosiveness or scale formation
Pressure >400 psi	1	2	...	...	...	50	2	...	0	...	9.6	No corrosiveness or scale formation
Brewing and Distilling												
Light beer, gin	10	...	Low	0.1	0.1	500	...	75	0.2	Potable	6.5-7.0	NaCl275
Dark beer, whiskey	10	....	Low	0.1	0.1	1000	...	150	0.2	Potable	7.0	NaCl275
Canning												
Legumes	10	...	Low	0.2	0.2	...	25-75	...	1.0	Potable	...	
General	10	...	Low	0.2	0.2	...	...	...	1.0	Potable	...	
Carbonated Beverages	2	10	Low	0.2	0.2	850	250	50-100	0.2	Potable	...	Organic matter infinitesimal; oxygen consumed 1.5
Confectionery	...	...	Low	0.2	0.2	100	...	...	0.2	Potable	7.0	
Cooling	50	...	...	0.5	0.5	...	50	...	5	...	...	No corrosiveness or slime formation
Food, general	10	...	Low	0.2	0.2	...	...	...	...	Potable	...	
Ice	5	5	Low	0.2	0.2	1300	...	...	...	Potable	...	SiO_2 10
Laundering	...	...	...	0.2	0.2	...	50	...	...	...	...	
Plastics, clear	2	2	...	0.02	0.02	200	...	...	...	...	...	
Paper and Pulp												
Ground wood	50	20	...	1.0	0.5	...	180	...	...	...	...	No grit or corrosiveness
Kraft pulp	25	15	...	0.2	0.1	300	100	...	...	...	...	
Soda and sulphite pulp	15	10	...	0.1	0.05	200	100	...	...	...	...	
High-grade light paper	5	5	...	0.1	0.05	200	50	...	...	...	...	No slime formation
Rayon (Viscose)												
Pulp production	5	5	...	0.05	0.03	100	8	50	...	...	...	OH 8, Al_2O_3 8, SiO_2 25, Cu 5
Manufacture	0.3	...	...	0.0	0.0	...	55	...	...	...	7.8-8.3	
Steel Manufacture	...	...	...	...	...	...	50	...	...	...	6.8-7.0	Temperature 75°F, Cl 175, suspended matter 25, minimum organic content and corrosiveness
Sugar Manufacture	...	...	...	0.1	...	...	...	...	...	...	...	Ca 20, Mg 10, SO_4 20, Cl 20, HCO_3 100
Synthetic Rubber	...	...	...	...	...	...	50	...	...	...	...	Oxygen consumed 3.0, minimum organic content and corrosiveness
Tanning	20	10-100	...	0.2	0.2	...	50-135	135	...	...	...	OH 8
Textiles												
General	5	20	...	0.25	0.25	...	...	...	...	...	...	
Dyeing	5	5-20	...	0.25	0.25	200	...	...	...	...	...	Constant composition; residual alumina <0.5

expected to increase in complexity and severity as a result of the closer approach to maximum utilization of water. For example, the waste water disposed by the Limuru Bata Shoe Company is causing odours which are offensive to the residents of the township. This is because no effective disposal method has been employed.

2. Systematic Description of the Variation of Groundwater Chemistry in Kenya

(a) Groundwaters in the sedimentary formations

The distribution and effect of sedimentary rocks on groundwater chemistry has been outlined in Chapter VI of this study.

It has earlier been shown that groundwaters in the Quaternary Sediments show a variation in the concentration of total dissolved solids. Highest concentrations are associated with water in the coastal sediments and those in the North-eastern part of the country. The lowest concentrations are associated with groundwaters occurring in the sediments within the Rift Valley.

The Coastal Quaternary Sediments have groundwater with total dissolved solids of up to and above 1,000 ppm. The Calcium and Magnesium mainly derived from the non-silicic minerals such as calcite, dolomite, limestones and gypsum have concentrations of less than 100 ppm and 50 ppm respectively. The chloride which forms part of the dominant ions show concentrations of more than 300 ppm. Bicarbonate and sulphate concentrations are not more than 200 ppm and 500 ppm respectively. The silica content is generally less than

30 ppm. Unlike the groundwaters of coastal sediments, those of Quaternary sediments in the North-Eastern Province show higher concentrations of total dissolved solids generally well over 1,000 ppm but of course ranging from a few hundreds parts per million to about 8,000 ppm. The calcium concentration in these waters is generally of the order of 200 ppm while the magnesium content is less than 100 ppm. The bicarbonate and sulphate concentrations are less than 400 ppm and 700 ppm respectively. The silica content is well above 20 ppm while chloride values of up to 5,000 ppm are found. Unlike the groundwaters in the two zones examined above, water within the Quaternary sediments in parts of the Rift Valley show considerably low amounts of total dissolved solids, but generally of the order of 500 ppm. The magnesium and calcium content in these waters is generally less than 50 ppm and 100 ppm respectively. The bicarbonate content is usually less than 400 ppm and the sulphate concentration is well below 100 ppm. Silica content is generally of the order of up to 100 ppm and the chloride concentration is well below 100 ppm.

Groundwater in the Pleistocene and Recent Coral reef shows higher concentrations of total dissolved solids which in places range to well over 2000 ppm. The calcium and magnesium concentration in these waters is generally less than 200 ppm and 100 ppm respectively. The bicarbonate content is generally of the order of up to 300 ppm, whereas the sulphate concentration is normally below 150 ppm. Silica content is generally less than 30 ppm while the chloride concentration is far above 1,000 ppm.

The Coastal Miocene and Post-Miocene sediments have groundwaters highly concentrated with salts unlike the less concentrated groundwaters of the Miccene and Post-Miocene sediments further inland. The groundwaters in these coastal sediments have a total dissolved concentration of the order of 5,000 ppm. The calcium concentration is less than 300 ppm and the magnesium content is of the order of up to 200 ppm. The sulphate and bicarbonate concentrations are of the order of less than 400 ppm and 800 ppm respectively. The chloride content is of the range of up to 2,000 ppm. The silica concentration is normally below 30 ppm.

Groundwaters in the Jurassic beds have bicarbonate concentration of up to 400 ppm and sulphate content of up to 100 ppm. In some rare occassions water with several hundred parts per million of sulphate are found. The calcium content is of the order of 200 ppm while the magnesium concentration is generally less than 100 ppm. Silica content is quite low, at times below 25 ppm. The chloride concentration is variable but amounts of over 3,000 ppm have been recorded. The total dissolved solids concentration is generally well up to and above 5,000 ppm. In places amounts of well over 15,000 ppm have been encountered.

The Duruma Sandstones Series contain groundwater with total dissolved solids of up to 10,000 ppm but higher values are not uncommon. The magnesium concentration is generally less than 200 ppm although in rare instances higher values are also found. The calcium content is of the order of up to 350 ppm. The sulphate concentration is generally below 1,000 ppm. The bicarbonate content is well up to 800 ppm. The chloride concentration which is variable is generally well below 4,000 ppm. The silica content is generally less than 20 ppm.

Groundwaters in the Sedimentary formations are not of uniform chemical composition. This may further be appreciated from the data given in Table VII-11 which clearly indicates that waters of the Duruma Sandstone series and as shown above, those of Jurassic beds contain waters highly concentrated with salts. It is clear in this table that there is a general increase in salt content from the groundwaters in the Quaternary sediments through those of the Pleistocene Coral Reef to those of Duruma Sandstone series. The modal values for given ions in groundwaters determined from Figures 6-3 to 6-29 are given in Table VII-12. The values confirm the conclusions which have already been drawn above. The facts become even much clearer from Table VII-13 which gives percentile values for given groundwater ions in respective rock units which have been read off from cumulative frequency curves given in Figures 6-30 to 6-38.

(b) Groundwaters in the Volcanic Formations

Groundwaters in the Quaternary and Tertiary basalts exhibit total dissolved solids concentration generally of less than 1,000 ppm. But apparently the Quaternary basalts situated in arid and semi-arid environment have groundwaters

TABLE VII-11

SOME MAJOR CHEMICAL CONSTITUENTS OF GROUNDWATER IN RESPECTIVE SEDIMENTARY ROCKS
IONS IN PPM

Geology	Latitude	Longtitude	TDS	F	Ca	Mg	HCO_3	SO_4
Q	N058	3601	650	2.00	4	-	416	25
	S300	4010	470	0.90	122	14	-	14
	N253	3515	520	1.50	4	-	324	-
	S006	3445	136	0.30	10	5	88	-
	S046	3626	940	5.50	45	-	-	4
	S016	3622	355	1.50	-	-	210	27
	S313	4001	20441	4.50	271	709	171	1450
	S230	3700	970	2.60	35	-	-	177
	N045	4050	11400	1.80	428	-	-	572
	N145	4004	2940	1.20	232	-	-	163
Pc	S405	3939	404	1.00	69	9	-	27
	S313	4007	-	0.40	103	30	304	64
	S356	3945	502	-	112	24	318	20
	S320	4005	265	0.50	52	8	154	10
	S336	3950	5500	-	520	568	208	482
	S403	3940	1940	-	187	168	315	198
	S357	3944	673	-	117	23	445	24
	S315	3940	1612	0.92	104	44	307	96
	S302	3957	810	0.40	-	-	324	83
	S316	4002	620	0.40	-	146	165	20
Tu + Tl	S322	3943	130	0.30	15	5	-	-
	S411	3927	110	0.20	-	-	15	34
	S349	3938	2340	0.80	245	75	376	212
	S412	3925	2462	-	132	150	320	193
	S315	3943	1307	0.50	83	79.70	355	140
	S357	3926	310	0.40	76	-	195	-
	S352	3928	3530	3.30	274	190	498	118
	S343	3927	5215	-	184	13	60	107
	S342	3929	2237	0.30	80	109	479	32
	S321	3932	6495	-	298	150	240	262

Q- Quaternary Sediments

Pc- Pleistocene and Recent Coral Reef

Tu + Tl - Upper and Lower Sandstones and grits of Duruma Sandstone Series.

TABLE VII-12 MODAL VALUES OF GIVEN IONS IN GROUNDWATER IN RESPECTIVE ROCK UNITS

Modal Values (less than indicated value in ppm)

	Geology	Ion	1st	2nd	3rd
Sedimentary Rocks	Q	Total Dissolved Solids	1,000	-	-
	Pc	" " "	1,000	-	-
	Tu + Tl	" " "	4,000	-	-
Volcanic Rocks	Qp+Pp+Mp	" " "	300	900	-
	Qb+Pb+Qb	" " "	500	1,000	-
	Ph	" " "	300	-	-
Metamorphic Rocks	X	" " "	3,000	-	-
	Xa	" " "	2,000	-	-
	Xn	" " "	2,000	-	-
Sedimentary Rocks	Q	Ca	100	-	-
	Pc	Ca	200	-	-
	Tu + Tl	Ca	300	-	-
Volcanic Rocks	Qb+Pb+Mb	Ca	10	60	100
	Ph	Ca	10	70	-
	Qp+Pp+Mp	Ca	40	90	-
Metamorphic Rocks	Xa	Ca	200	-	-
	Xn	Ca	300	600	-
	X	Ca	300	-	-
Sedimentary Rocks	Q	Mg	30	70	-
	Pc	Mg	40	80	-
	Tu +Tl	Mg	200	-	-
Volcanic Rocks	Qb+Pb+Mb	Mg	30	70	-
	Qp+Pp+Mp	Mg	20	60	-
	Ph	Mg	10	30	-
Metamorphic Rocks	Xa	Mg	100	-	-
	X	Mg	200	500	-
	Xn	Mg	100	400	-

Q --Quaternary Sediments.

Pc - Pleistocene and Recent coral reef.

Tu + Tl - Upper and Lower sandstones and grits of Durume sandstones series.

Qp+Pp+Mp - Tertiary and Quaternary phonolites.

Qb+Pb+Mb - Tertiary and Quaternary basalts.

Ph - Tertiary trachytes and tuffs.

X - Undifferentiated Basement Complex rocks.

Xa - Pelitic and semi-pelitic rocks of Basement complex.

Xn - Quartzo-feldspathic and granitoid rocks of Basement complex.

TABLE VII-13

PERCENTILE VALUES FOR GIVEN GROUNDWATER IONS IN RESPECTIVE ROCK UNITS

Geology	Ion	50%	70%	95%
Ph	Ca	15	28	102
Xn	Ca	160	220	500
Pc	Ca	50	90	350
Ph	Mg	8	18	420
Xn	Mg	100	140	390
Pc	Mg	23	35	205
Ph	Total Dissolved Solids	240	300	500
Xn	Total Dissolved Solids	650	1,350	4,000
Pc	Total Dissolved Solids	800	1,300	4,000

Ph - Tertiary trachytes and tuffs.
Xn - Quartzo-felspathic and granitoid rocks.
Pc - Pleistocene and Recent coral reef.

with a total dissolved solids concentration of more than 1,000 ppm. There is an indication, however, that Tertiary basalts situated in the same environment have groundwater of more or less similar concentrations of total dissolved solids. This is quite remarkable in basalts close to the neighbourhood of Lake Rudolf. In the groundwaters within the Quaternary basalts, the calcium concentration is generally less than 60 ppm, while in the Tertiary basalts concentrations are less than 20 ppm and 50 ppm for groundwater in the Tertiary and Quaternary basalts respectively. The bicarbonate content is generally less than 300 ppm in groundwater within the Quaternary basalts and far below 200 ppm in groundwaters in Tertiary basalts. The sulphate concentration is less than 150 ppm and 100 ppm in groundwaters within Quaternary and Tertiary basalts respectively. The chloride concentration is generally less than 800 ppm in the groundwaters of both types of basalts and the silica content is of the order of 50 ppm.

The under-saturated Tertiary and Quaternary phonolites exhibit groundwaters with a total dissolved solids concentration of up to 1,500 ppm. The calcium content is generally below 100 ppm and the magnesium concentration is normally less than 20 ppm. The bicarbonate concentration for waters in the Tertiary phonolites is generally of the order of up to 300 ppm while it is less than 100 ppm for groundwaters in the Quaternary phonolites. The chloride content is also equally variable but generally of the order of 50 ppm in groundwaters within Quaternary phonolites and less than 200 ppm in groundwaters within Tertiary phonolites. The silica content is normally less than 40 ppm in these groundwaters. There is a general indication that the Tertiary phonolites have groundwaters with a higher concentration of salts than the waters in the Quaternary phonolites.

Groundwater in the Tertiary and Quaternary trachytes has a total dissolved solids concentration of up to 600 ppm but it is true that in some cases waters with higher concentrations, even above 1,000 ppm, are found. The magnesium content in these groundwaters is less than 40 ppm, the lowest amounts usually being exhibited by the groundwater in the Quaternary trachytes. The calcium concentration is of the order of up to 100 ppm. The groundwater within the Quaternary trachytes exhibit lower concentrations of bicarbonate, generally well below 150 ppm, whereas water in the Tertiary trachytes show concentrations of up to 300 ppm. The chloride content is variable ranging to well over 200 ppm. Silica amounts range up to 100 ppm.

It is obvious, therefore, that groundwater in the volcanic formations differ from one type of rock unit to the other. This is confirmed by the data given in Table VII-14. From this table it is clear that waters with the highest concentrations of total dissolved solids are associated with the basalts. Of the phonolites and trachytes, the former have higher amounts. This observation is further confirmed by the modal values of total dissolved solids given for the basalts, phonolites and trachytes in Table VII-12.

TABLE VII-14

SOME MAJOR CHEMICAL CONSTITUENTS IN GROUNDWATER IN RESPECTIVE VOLCANIC ROCKS
Ions in PPm

Geology	Latitude	Longtitude	TDS	F	Ca	Mg	HCO_3	SO_4
Qp+Mp+Pp	S111	3651	260	0.60	-	-	72	-
	S248	3717	125	0.30	7	-	-	4
	S247	3722	285	1.80	8	-	-	6
	S324	3741	180	0.30	170	17	-	-
	S025	3734	360	8.40	4	-	-	1
	S010	3702	625	2.20	-	-	452	18
	N031	3517	272	0.80	-	-	157	-
	N047	3635	690	2.80	-	-	294	128
	S141	3651	790	2.40	56	-	-	123
	S110	3726	473	1.40	52	41	353	-
Qb+Mb+Pb	S041	3724	225	0.30	21	12	-	-
	N310	3810	1885	0.50	140	128	-	175
	S110	3726	490	1.40	-	-	-	4
	N245	3805	2265	0.90	-	-	-	294
	N416	3545	874	1.0	88	52	339	80
	N413	3641	680	1.0	51	36	340	25
	S122	3639	540	0.30	46	46	112	-
	S124	3638	354	0.50	23	15	186	-
	S038	3642	285	2.40	-	-	126	8
	S043	3709	280	0.40	-	-	166	-
Ph	S106	3639	190	1.2	5	2	-	-
	S109	3658	273	3.40	4	0.50	132	5
	S120	3647	260	0.40	8	1.00	213	7
	[illegible]	3543	286	1.20	16	8	216	5
	S103	3750	640	2.0	60	28	485	-
	S054	3633	1030	2.70	45	28	810	31
	S114	3644	260	0.60	-	-	139	-
	S010	3541	275	1.60	-	-	97	-
	S059	3708	540	0.40	56	33	104	11
	S010	3635	216	-	-	-	122	-

Qp+Mp+Pp - Tertiary and Quaternary phonolites.
Qb+Mb+Pb - Tertiary and Quaternary basalts.
Ph - Tertiary trachytes and tuffs.

From this table it may be accepted that the highest concentration (in terms of modal values) of calcium are associated with groundwaters in the phonolites while the highest magnesium values are associated with the groundwater in the basalts. The percentile values for calcium, magnesium and total dissolved solids for groundwaters in the trachytes are shown in Table VII-13.

(c) Groundwater in the Metamorphic Formation

The pelitic and semi-pelitic metasediments shown in Figure 6-2 contain groundwaters with a concentration of up to 5,000 ppm of total dissolved solids. As shown in Table VII-12, this water has a modal value of less than 2,000 ppm of total dissolved solids. Modal values for calcium and magnesium in this water are also given in this table. The magnesium concentration is generally less than 100 while the calcium content is of the order of up to 200 ppm. The sulphate content ranges to about 300 ppm, while the bicarbonate concentration is in the order of 500 ppm. Chloride concentrations of up to and above 1,000 ppm have been recorded in these waters. The silica content is generally less than 90 ppm.

Groundwaters within the calcareous metasediments show considerable content of total dissolved solids ranging to about 4,000 ppm. The magnesium and calcium concentration is generally up to and less than 200 ppm and 300 ppm respectively. The bicarbonate concentration is of the order of 500 ppm while the sulphate content is generally below 200 ppm. The chloride content is variable but generally less than 300 ppm although occassionally higher concentrations are encountered. The silica content in these waters is far below 60 ppm.

The quartzo-feldspathic rocks contain water with total dissolved solids concentration of up to 3,000 ppm. Modal values (of total dissolved solids) for calcium and magnesium are given in Table VII-12 while percentile values for the same ions are given in Table VII-13. The bicarbonate concentration is less than 1,500 ppm but higher concentrations have been encountered. The silica content is normally less than 80 ppm. It is interesting to note that the granitic rocks especially those located in high rainfall and low temperature areas contain water with very low concentrations of total dissolved solids, usually below 500 ppm.

The Migmatites exhibit groundwaters with generally less than 2,000 ppm of total dissolved solids. The magnesium and calcium concentration in these waters if generally less than 50 ppm and 100 ppm respectively. The bicarbonate concentration shows values of up to 200 ppm. The chloride content is generally less than 100 ppm but some observations have shown higher concentrations. The silica content is generally of the order of up to 80 ppm.

The undifferentiated basement rocks have groundwater containing up to 4,000 ppm of total dissolved solids. Modal values of total dissolved solids, calcium and magnesium in this water are given in Table VII-12.

Rocks of the Nyanzian, Kavirondian and Bukoban systems in western Kenya contain water which is comparable to that in the volcanic rocks situated within the well watered environment. The total dissolved solids concentration is generally below 500 ppm in this water and other principal ions examined above show considerably low concentrations.

As shown in Table VII-15, groundwater in the Pelitic and semi-pelitic metasediments and calcareous rocks have the highest amounts of total dissolved solids. The table also shows that the water in the metamorphic rocks is variable with regard to the concentration of total dissolved solids and other major chemical constituents.

3. Suggested Groundwater Zones and the Suitability of Water for Various Uses

Delimitation of the country into groundwater zones or units is a complex task. This is complicated by the variability of the factors that influence the groundwater chemistry. This is further complicated by the fact that the water chemistry varies not only in space and time but also with depth. For example, groundwater chemistry in each of the examined rock types is not uniform and that this varies from one rock unit to the other and may be modified by other factors acting in any given environment. This then means that a given rock unit may exhibit groundwater of varying composition depending on the other environmental factors that influence the chemistry of such water. Geologic effects on groundwater chemistry can also modify the effects of the other environmental factors such that the chemistry of given

TABLE VII-15

SOME MAJOR CHEMICAL CONSTITUENTS IN GROUNDWATER IN RESPECTIVE METAMORPHIC ROCKS

IONS IN PPM

Geology	Latitude	Longitude	TDS	F	Ca	Mg	HCO_3	SO_4
Xc	S128	3750	380	1.40	32	33	254	-
	S323	3834	3820	1.20	334	260	-	-
	S037	3811	910	-	141.6	32	528	-
	S113	3744	1140	2.10	-	125	280	128
	S120	3810	999	-	141	32	528	-
	S110	3805	765	1.20	67	34	-	84
Xg	S321	3849	1090	0.60	219	21	-	188
	S327	3843	3820	1.20	334	260	-	-
	N030	3508	180	0.54	21.50	11	110	10.70
	N043	3822	840	2.20	20	61	566	51
	S157	3715	950	0.60	100	44	-	200
	S153	3652	990	2.70	125	55	433	87
	S154	3710	570	1.80	80	38	360	57
	S148	3737	1295	1.40	149	-	-	477
	S149	3709	816	0.80	53	40	440	-
	S035	3749	2505	1.20	98	135	-	70
	S145	3707	890	28.50	62	52	445	160
	S020	3847	3350	0.80	40	26	1110	319
	S002	3756	170	1.00	6	-	-	4
	S039	3824	4780	1.80	556	319	367	329
Xm	S128	3703	605	1.60	62	14	-	8
	S148	3825	2685	1.30	268		26	277
	S148	3740	1170	1.80	166	62	336	50
	S107	3740	879	2.40	94	36	437	48
	S121	3738	321	0.80	-	-	29	-
	S247	3804	2015	1.20	297	103	308	264
	S158	3656	1035	0.90	137	48	345	98
	S024	3814	1990	6.00	68	144	483	342
	S206	3647	1208	0.00	115	89	464	26
	S200	3645	2890	5.20	91	91	394	728

Xc - Calcareous Parent

Xg - Migmatites

Xn - Quartzo-feldspathic granitoid rocks of the Basement complex

Xm - Pelitic and semipelitic rocks of the Basement complex.

water reflects essentially the geologic nature of the aquifer. This may also raise the problem of composite geology. Taking into account all these factors and bearing in mind the need for water development areas in the country, Kenya has been divided into four broad zones which are shown in Figure 7-2. These divisions have been made mainly on the basis of maximum concentrations of total dissolved solids in conjunction with other environmental considerations. These zones will only serve as a base for detailed water development work in future. As more information becomes available, more rigid boundaries will be demarcated. Nevertheless, the present boundaries will serve as a useful basis for water resource planning and development. Local variations in the physical controls of groundwater chemistry may give anomalous concentration of any given ion in any one of the suggested zones and this fact must be accommodated in this analysis.

??? where?? wapi?
In Vol.
which [illegible]

As shown in Figure 7-2 the suggested groundwater zones are as follows:-

__Zone I__: This is a zone consisting of very low salinity water, generally with a total dissolved solids concentration of up to 1,000 ppm.

__Zone II__: A zone of relatively moderate salinity, with a total dissolved solids concentration of up to 5,000 ppm.

__Zone III__: A zone of relatively very high salinity, generally with a total dissolved solids concentration of up to 8,000 ppm.

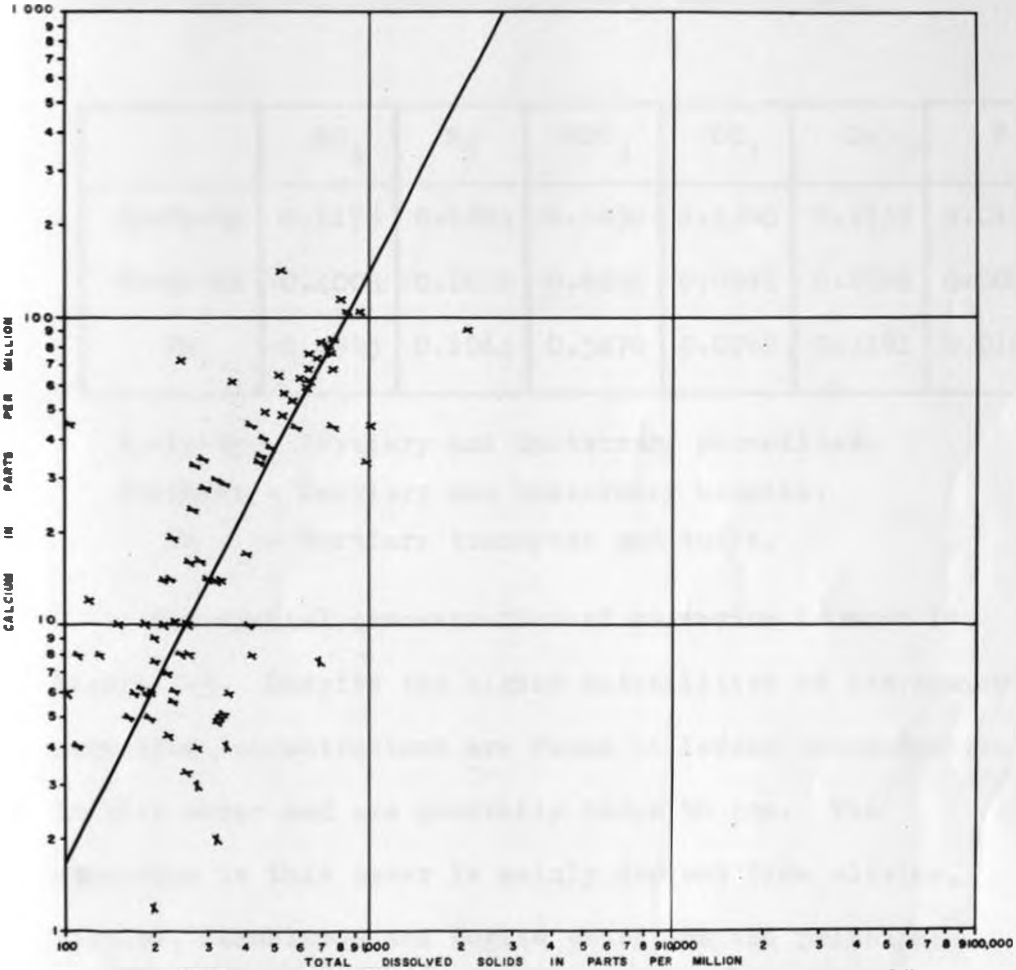
__Zone IV__: A zone of extremely high salinity, with total dissolved solids concentration of up to and above 8,000 ppm.

Zone I

As shown in Figure 7-2 this zone covers parts of Nyanza, Western, Central and Rift Valley Provinces as well as the Nairobi Extra - Provincial District. It is a zone mainly situated within the volcanic formations but also covers groundwaters within the Basement complex rocks as well as the Nyanzian, Kavirondian and Bukoban rocks of western and south-western Kenya. This is a zone within the high rainfall and well watered areas of Kenya. The temperatures in parts of this zone are relatively low and the evaporation rates are correspondingly low.

The concentration of total dissolved solids in the groundwater within this zone as shown in Figure 7-2, is generally less than 1,000 ppm, although some analyses reveal higher concentrations in some places. This variation is generally with depth and can be attributed to the geologic and hydrologic variables acting upon the groundwater chemistry.

Calcium is the most abundant and extremely mobile element in the earth's crust. It is mainly derived from the silicic minerals such as amphibole, pyroxenes and feldspars which form the volcanic rocks. Despite its abundance in the earth's crust, its concentration in the water of this zone is far below 100 ppm. The spatial concentration of calcium in Kenya's groundwater is shown in Figure 7-3. There appears to be a general positive relationship between total dissolved solids and calcium in the Tertiary trachytes and tuffs and this is illustrated in Figure 7-4. The correlation coefficient for this relationship, as shown in Table VII-16, is 0.3481.



Relationship between Total Dissolved Solids and Calcium in Groundwater within the Tertiary Trachytes and Tuffs

FIG 7 4

Other correlation coefficients for respective ions in given rock units for groundwater in the volcanic rocks are given in this table.

TABLE VII-16

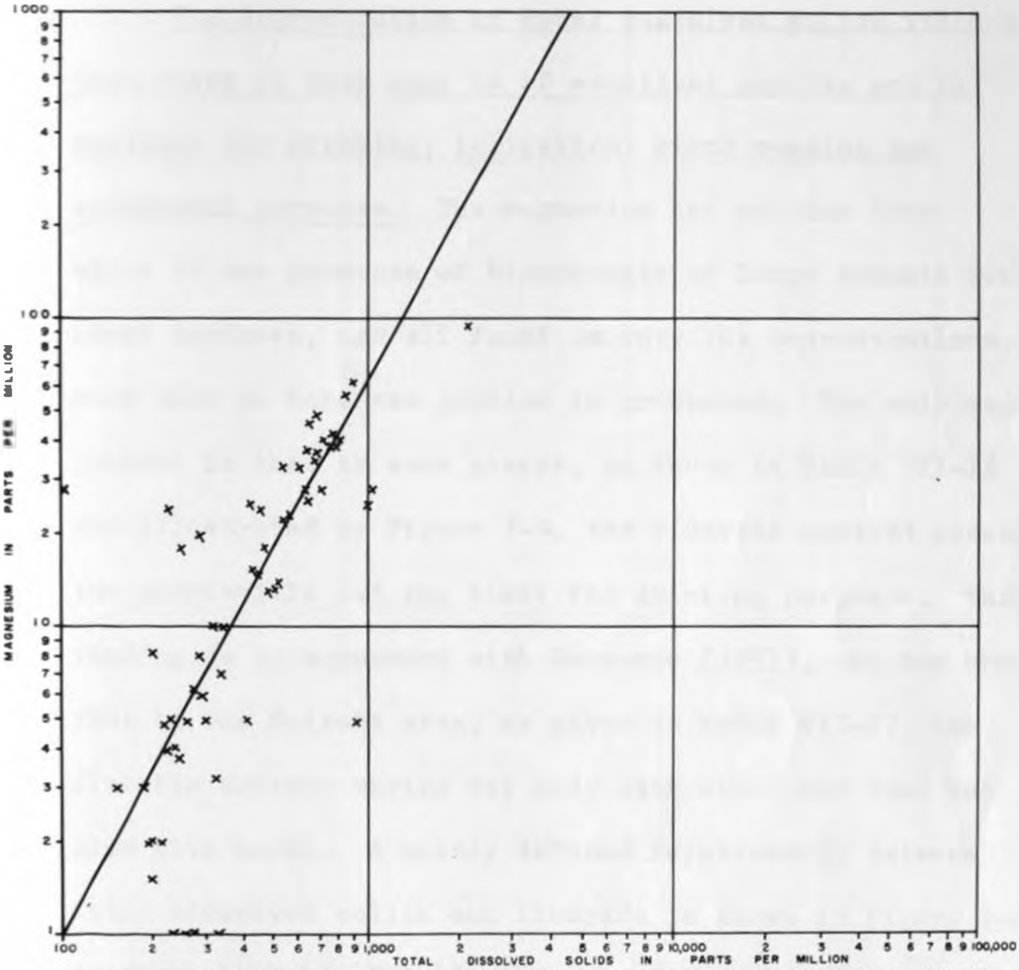
CORRELATION COEFFICIENTS SHOWING THE RELATIONSHIP BETWEEN TOTAL DISSOLVED SOLIDS AND GIVEN IONS IN GROUNDWATER FOR RESPECTIVE VOLCANIC ROCK TYPES.

	SO_4	Mg	HCO_3	CO_3	Ca	F
Mp+Pp+Qp	0.1179	0.1603	0.3450	0.1300	0.2739	0.0125
Pb+Qb+Mb	0.4003	0.1076	0.6031	0.0595	0.2792	0.0029
Ph	0.4925	0.1064	0.5470	0.0282	0.3481	0.0106

Mp+Pp+Qp - Tertiary and Quaternary phonolites.
Pb+Qb+Mb - Tertiary and Quaternary basalts.
Ph - Tertiary trachytes and tuffs.

The spatial concentration of magnesium is shown in Figure 7-5. Despite the higher solubilities of its compounds magnesium concentrations are found in lesser concentrations in this water and are generally below 50 ppm. The magnesium in this water is mainly derived from olivine, biotite, hornblende and augite which are the principal minerals forming the volcanic rocks. Figure 7-6 portrays the general positive relationship between total dissolved solids and magnesium in the Tertiary tuffs and trachytes and as given in table VII-16 the correlation coefficient for this relationship is 0.1064.

The concentration of bicarbonate in the groundwater of



Relationship between Total Dissolved Solids and Magnesium in Groundwater within the Tertiary Trachytes and Tuffs

FIG 76

this zone, as shown in Figure 7-7 is generally less than 400 ppm. This is one of the dominant anion in this water.

The sulphate concentrations which have been said to be responsible for low productivity in the East African lakes are generally as shown in Figure 7-8 well below 100 ppm.

The concentration of total dissolved solids indicate that water in this zone is of excellent quality and is suitable for drinking, irrigation, stock rearing and industrial purposes. The magnesium and calcium ions which in the presence of bicarbonate in large amounts could cause hardness, are all found in very low concentrations, such that no hardness problem is presented. The only major problem is that in some places, as shown in Table VII-14 and illustrated by Figure 7-9, the fluoride content exceeds the permissible 1.5 ppm limit for drinking purposes. This finding is in agreement with Gevaerts (1957), who has shown that in the Nairobi area, as given in Table VII-17, the fluoride content varies not only with space and time but also with depth. A poorly defined relationship between total dissolved solids and fluoride is shown in Figure 7-10. As shown in Table VII-16, the correlation coefficient is only 0.016.[7] In assessing the safety of a water with respect to the fluoride concentration, the total daily fluoride intake by the individual must be considered. Apart from variation in climatic conditions, it is well known that in certain countries fluoride-containing food form an important part of the daily diet. These factors must be born in mind

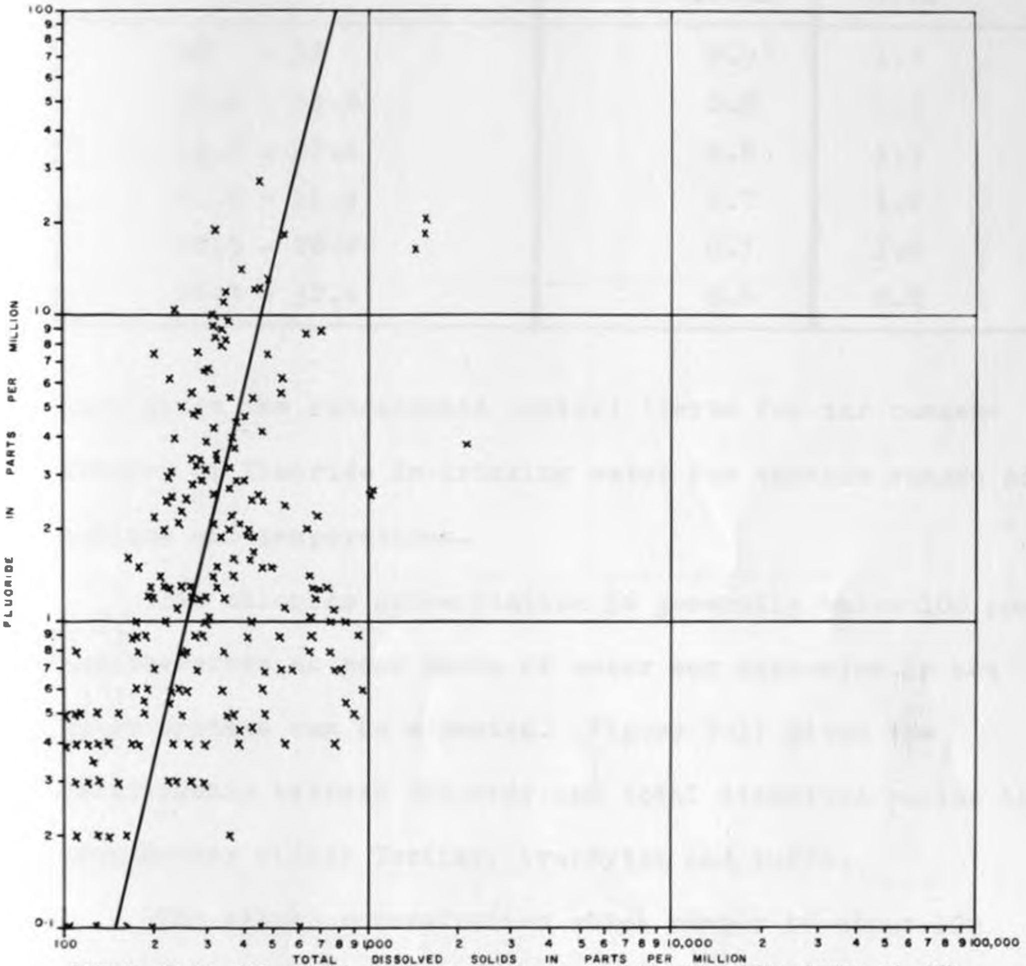
0.016

TABLE VII-17

FLUORIDE CONCENTRATION IN PARTS OF NAIROBI

Borehole Number	Depth in Feet	Fluoride in ppm	Date
203	420	1.2	1950
390	460	1.9	1954
404	500	3.6	1952
730	400	1.4	1950
792	450	9.1	1952
955	470	2.5	1952
1014	500	9.8	1952
1034	451	1.3	1950
1366	700	2.6	1952
1548	705	12.3	1952
1987	710	12.4	1953

in deciding the concentration of fluoride to be permitted in drinking water. Fluorides are also regarded as essential constituents of drinking water, particularly with regard to the prevention of dental problems in children . If the concentration in drinking water of a community is less than 0.5 ppm the incidence of dental problems is likely, so communal supplies of water are fluoridated to bring the fluoride concentration within the required level. The dental fluorosis, quite common in parts of Central Province of Kenya, is thought to be the result of high concentration of fluoride in the water supply. Water in some parts of this zone then show fluoride concentrations above the permissible level for drinking purposes, but quite acceptable for stock rearing. As shown in Table VII-18 the W.H.O.(1971)



Relationship between Total Dissolved Solids and Fluoride in Groundwater within Tertiary Trachytes and Tuffs

FIG 7 10

TABLE VII-18

RECOMMENDED CONTROL LIMITS FOR FLUORIDES IN DRINKING WATER

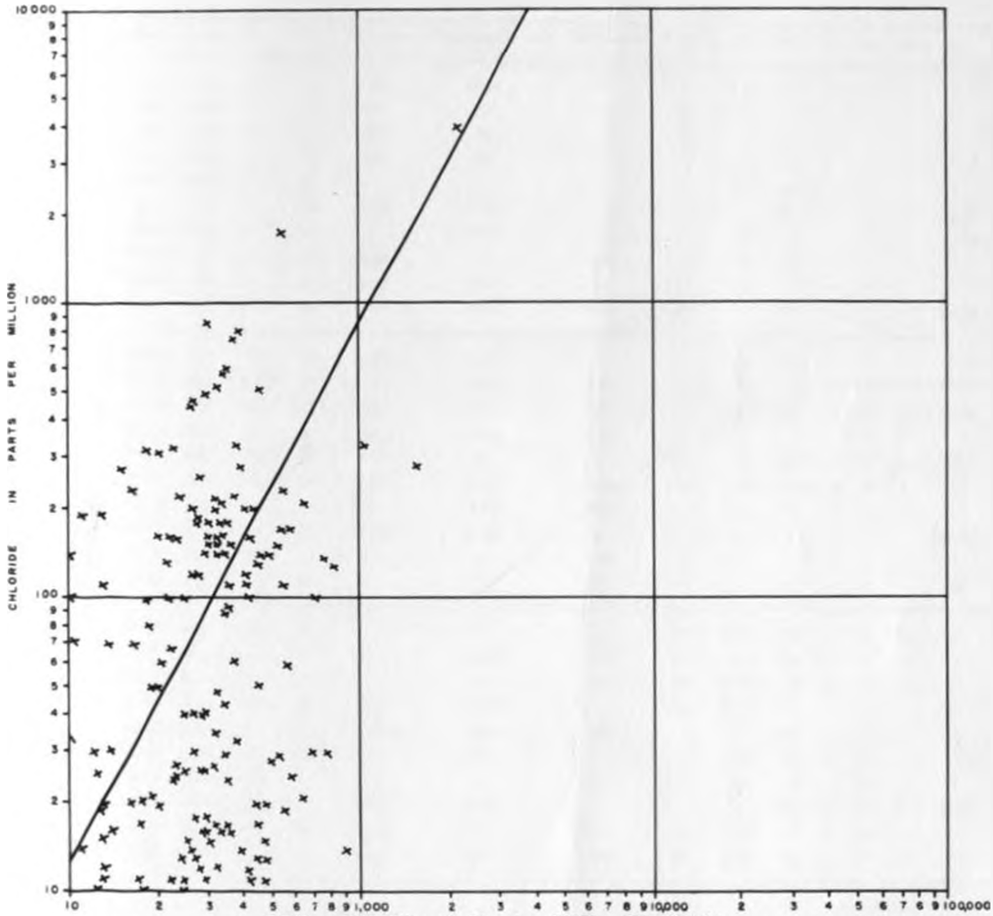
Annual Average of Maximum Daily Temperature in °C	Reccmmended Control Limits for Fluorides (as F) in Mg/l	
	LOWER	UPPER
10 - 12	0.9	1.7
12.1 - 14.6	0.8	1.5
14.7 - 17.6	0.8	1.3
17.7 - 21.4	0.7	1.2
21.5 - 26.2	0.7	1.0
26.3 - 32.6	0.6	0.8

have given the recommended control limits for the concentration of fluoride in drinking water for various ranges of maximum air temperatures.

The chloride concentration is generally below 100 ppm and therefore no poor taste of water nor corrosion in hot water systems can be expected. Figure 7-11 gives the relationship between chloride and total dissolved solids in groundwater within Tertiary trachytes and tuffs.

The silica concentration which ranges to about 100 ppm may be undesirable for industrial purposes. For example, it may form a hard coating on the steam-turbine blades of high pressure boilers. In such cases the removal of silica through distillation or other chemical processes from such boiler feedwaters is necessary.

As shown in Table VII-19 nitrate which represents the highly oxidized phase in the nitrogen cycle, is only detected



Relationship between Total Dissolved Solids and Chloride in Groundwater within the Tertiary Trachytes and Tuffs

FIG 7 11

TABLE VII-19

SOME OF THE MINOR CONSTITUENTS IN GROUNDWATER IN RESPECTIVE VOLCANIC ROCKS

IONS IN PPM

Geology	Lat.	Long.	NO_2	NO_3	F+S.Amm.	Albuminoid Amm.	Hardness	Silica	Fe	Cl	Cu	Pb	Na+K	O_2	CO_2
Qp+Np+Pp	S011	3740	-	-	0.60	0.08	-	50	1.9	6	-	-	-	-	-
	S012	3528	-	-	Tr	Tr	-	8	4.8	8	-	-	-	-	-
	S020	3727	-	-	Tr	Tr	60	50	-	17	-	-	-	-	Tr
	S020	3739	-	-	Tr	Tr	-	6	1.7	17	-	-	-	-	-
	S024	3518	-	-	-	-	-	50	2.8	14	-	-	-	-	Tr
	S025	3700	-	Tr	0.18	0.12	-	-	-	413	-	-	-	1.12	-
	S025	3735	-	-	-	0.06	-	30	0.70	12	-	-	-	1.20	-
	S032	3727	-	-	0.80	Tr	190	50	0.70	54	-	-	-	-	-
	S040	3510	-	-	0.18	0.28	-	20	2.0	12	-	-	-	-	-
	S242	3748	-	-	Tr	0.03	440	90	-	108	-	-	-	0.54	1.2
Nb+Qb+Pb	N032	3831	Tr	Tr	0.16	0.15	-	18	1.2	63	-	-	-	0.84	-
	N209	3811	1.10	-	0.04	0.05	240	35	-	25	-	-	-	0.20	-
	N309	3809	2.0	0.02	0.15	0.01	885	40	-	840	-	-	-	0.40	-
	N413	3641	-	-	Tr	0.40	276	65	Tr	73	-	-	-	-	-
	N416	3545	Tr	Tr	-	-	-	36	Tr	150	-	-	-	-	-
	N420	3655	Tr	Tr	0.02	0.19	392	14	0.02	234	-	-	-	5	-
	S025	3657	-	-	Tr	0.02	236	8	0.7	109	-	-	-	-	Tr
	S122	3639	-	Tr	0.20	0.16	-	-	-	53	-	-	-	0.96	-
	S201	3722	Tr	-	-	-	30	40	1.2	37	-	-	-	-	-
	S205	3649	Tr	Tr	-	Tr	597	27	Tr	320	-	-	-	Tr	-
Ph	S110	3650	Tr	-	-	-	-	74	0.70	16	-	-	-	-	Tr
	S111	3637	-	-	Tr	1.10	-	40	-	20	-	-	-	-	Tr
	S115	3444	-	-	-	-	-	36	4.8	8	-	-	-	-	-
	S115	3640	Tr	Tr	0.16	0.04	-	50	1.2	10	-	-	-	-	-
	S117	3649	-	-	0.40	0.06	35	-	-	10	-	-	-	-	-
	S109	3658	-	Tr	Tr	Tr	-	9	0.14	16	-	-	-	Tr	-
	S106	3639	Tr	-	-	-	-	26	Tr	9	-	-	-	-	Tr
	S103	3705	Tr	Tr	Tr	0.02	-	-	-	280	-	-	-	0.02	-
	S102	3638	Tr	Tr	Tr	Tr	-	26	0.70	8	-	-	-	-	Tr
	S056	3634	-	-	Tr	Tr	228	86	2.0	33	-	-	-	Tr	Tr

Qp+Np+Pp - Tertiary and Quaternary phonolites

Nb+Qb+Pb - Tertiary and Quaternary basalts

Ph - Tertiary trachytes and tuffs

in trace amounts in the water of this zone. High concentrations in drinking water generally above 45 ppm cause a disease called infant Methemoglobinemia.

The nitrate, nitrite and other ammonia compounds shown in Table VII-19 may indicate organic or other pollution such as may result from the application of fertilizers. However, these concentrations are so low that no pollution of this water is suggested. For example, a concentration of 0.30 ppm of free and saline ammonia would normally be regarded as indicating manurial pollution. This is particularly so when the concentration exceeds that of albuminoid ammonia. The amount of oxygen absorbed in the water within this zone, does not, however, confirm the presence of much organic material.

The discussion above indicates that, with exception of some excess fluoride and silica concentration, the water in this zone is generally soft and of extremely low salinity. They are thus of excellent quality for all uses.

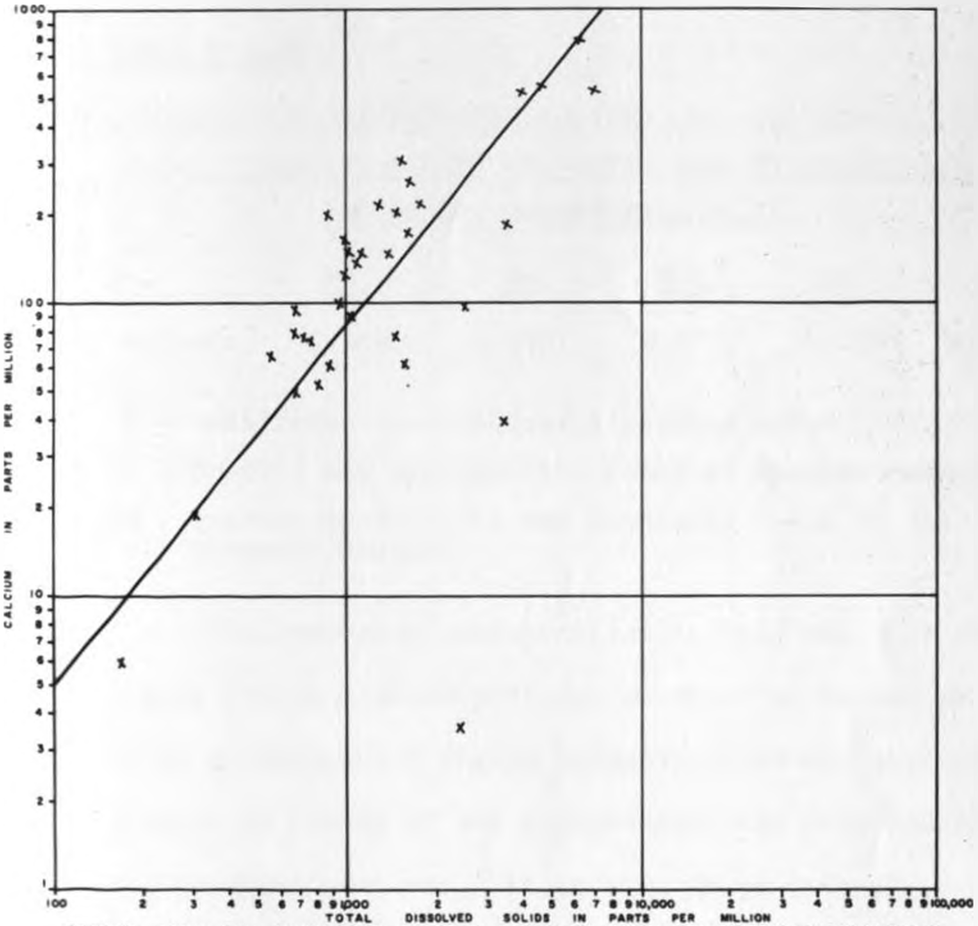
Zone II

The suggested area covering zone II is shown in Figure 7-2. It is mainly consisting of the eastern half of Kenya and parts of the southern portions of the Rift Valley. This is a zone of relatively low rainfall, high temperatures (see chapter VI) and considerably high evaporation rates. It is an area far removed from areas of high water recharge. As shown in Figure 6-2 groundwater in this zone occurs in the metamorphic, volcanic and sedimentary rocks.

TDS

The concentration of total dissolved solids in this zone, as shown in Figure 7-2 is generally up to 5,000 ppm. In relative terms, then, this is a zone of moderate salinity. These concentrations are far in excess for drinking water and most other uses. As stated earlier on in this chapter, twice the amount of recommended amounts of total dissolved solids concentration in drinking water has apparently not done any injurious harm to human beings. It is, therefore, necessary to note that this water is not exclusively unsuitable for most uses because much will depend on the relative concentrations of other ions in the water.

The calcium concentration as shown in Figure 7-3 is generally less than 400 ppm but occasionally higher amounts are found. In the metamorphic formations the calcium is drawn from the metamorphic rocks consisting of such minerals as apatite, wollastonite, fluorite and various members of the feldspar, amphibole and pyroxene groups. The same is true for some of the volcanic rocks whereas for the sedimentary rocks it is mainly derived from the non-silicic minerals such as limestone, dolomite and other calcium-bearing minerals. The relationship between calcium and total dissolved solids in the quartzo-fledspathic and granitoid rocks of the Basement complex is shown in Figure 7-12, and the correlation coefficients for total dissolved solids and other ions in combined rocks of the Basement complex are given in Table VII-20. Calcium within this range of concentration has ~~no known~~ effect on the health of human beings. A.P.H.A., A.W.W.A. and W.P.C.F. (1971), have shown that small



Relationship between Total Dissolved Solids and Calcium in Groundwater within the Quartzo Felspathic and Granitoid Rocks of the Basement Complex

FIG. 7.12

concentrations of calcium carbonate combat corrossion of metallic pipes by laying down a protective coating. They further show that appreciable calcium salts on the other hand break down on heating to form harmful scales in boilers, pipes and cooking utensils. Chemical softening of this water is therefore necessary.

TABLE VII-20

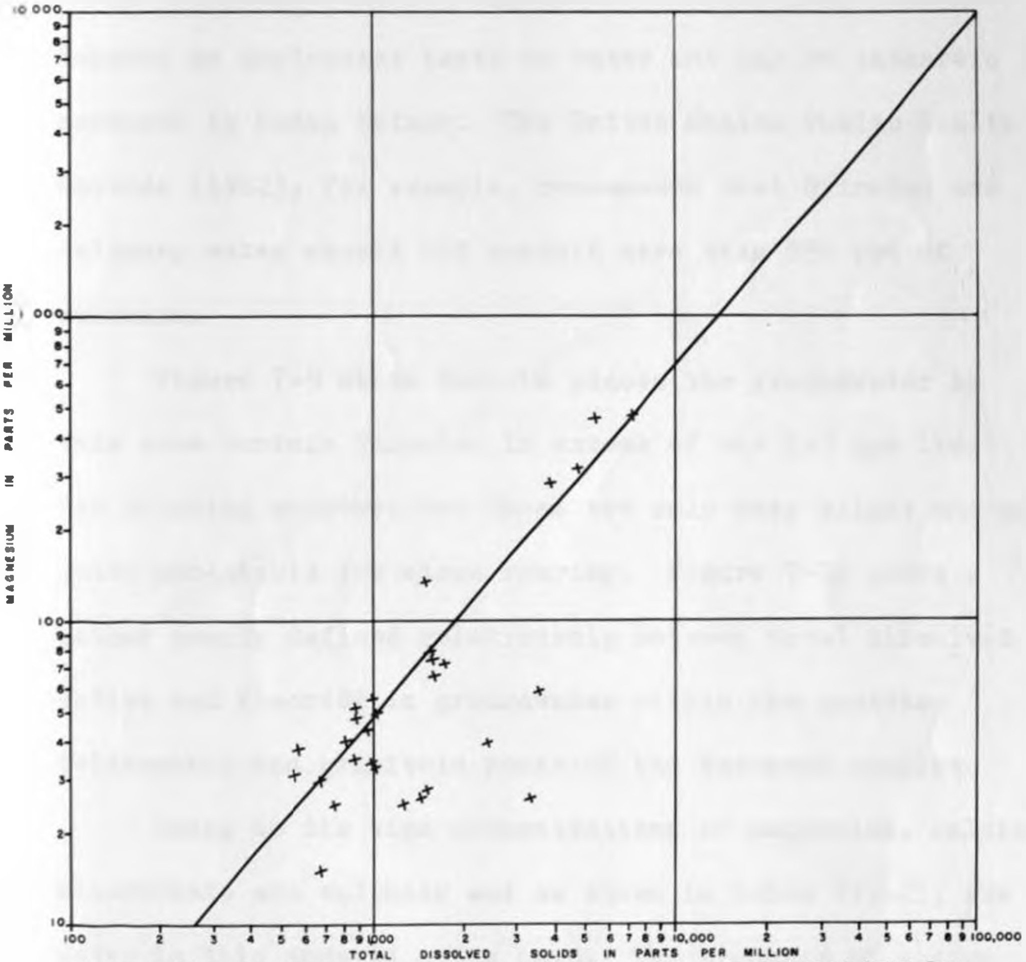
CORRELATION COEFFICIENTS SHOWING THE RELATIONSHIP BETWEEN TOTAL DISSOLVED SOLIDS AND GIVEN IONS IN GROUNDWATER FOR RESPECTIVE METAMORPHIC ROCKS

	SO_4	Mg	HCO_3	CO_3	Ca	F
X+Xa+Xn	0.3691	0.2781	0.0725	0.2786	0.6154	0.0017

X - Undifferentiated Basement complex rocks
Xa - Pelitic and semi-pelitic rocks of Basement complex
Xn - Quartzo-feldspathic and granitoid rocks of the Basement complex.

The magnesium concentration in this water as shown in Figure 7-5 is generally of the order of up to 200 ppm. No doubt occassionally higher concentrations are also found and this is in excess of the recommended less than 150 ppm limit for drinking purposes. It is also known that magnesium salts break down on heating to form deleterious scales in boilers and concentrations in excess of 125 ppm can also exert carthartic and diuretic action. Figure 7-13 shows the positive relationship between total dissolved solids in groundwater within the quartzo-feldspathic and granitoid rocks of the Basement complex.

The bicarbonate concentration as indicated in Figure 7-7 is generally less than 800 ppm but higher concentrations



Relationship between Total Dissolved Solids and Magnesium in Groundwater within the Quartzo-Felspathic and Granitoid Rocks of the Basement Complex

FIG 7 13

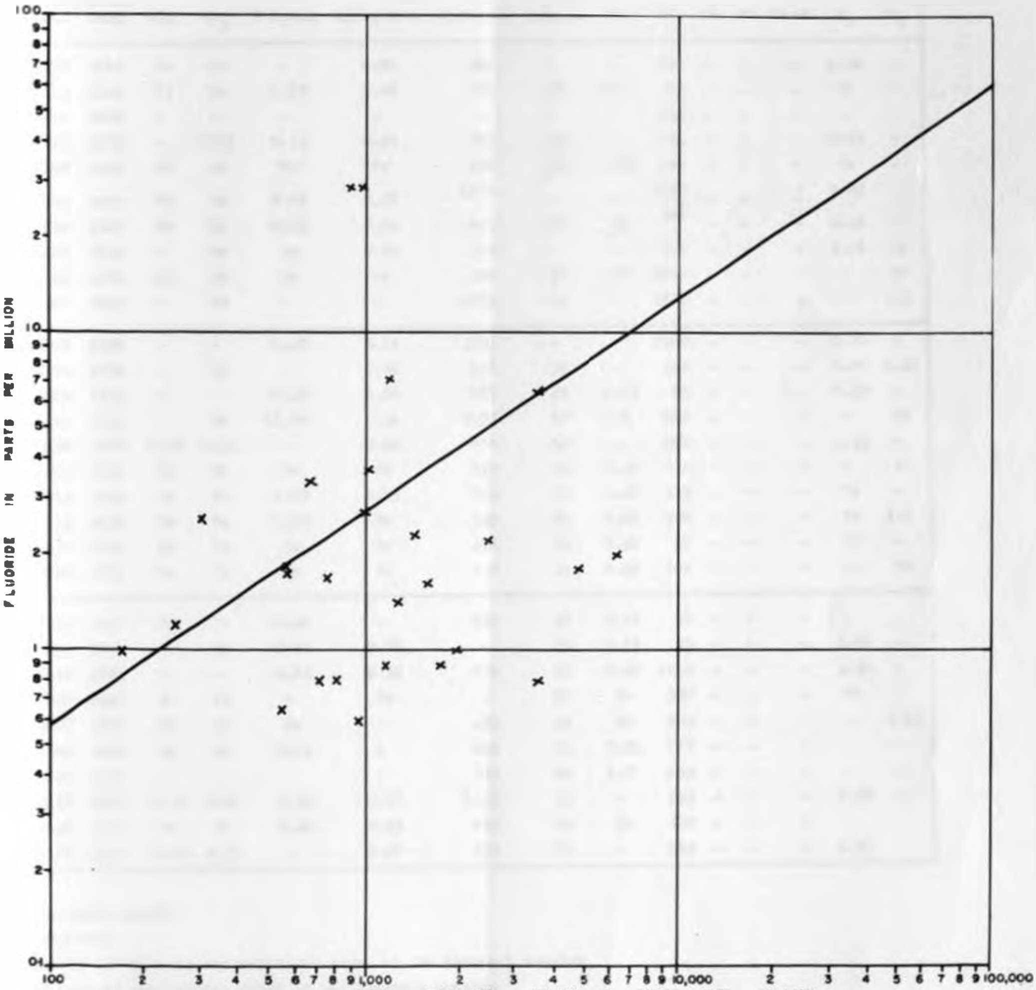
are also rarely encountered. This is rather unsuitable for most uses.

The sulphate concentration which is shown in Figure 7-8 is variable but generally less than 500 ppm, with higher concentrations which are not very uncommon. The excess sulphate, particularly when associated with these large concentrations of magnesium and other alkali metals, imparts an unpleasant taste to water and may be cathartic if consumed by human beings. The United States Public Health Service (1962), for example, recommends that drinking and culinary water should not contain more than 250 ppm of sulphate.

Figure 7-9 shows that in places the groundwater in this zone contain fluoride in excess of the 1.5 ppm limit for drinking purposes but these are only very slight and are quite acceptable for stock rearing. Figure 7-14 gives a rather poorly defined relationship between total dissolved solids and fluoride in groundwater within the quartzo-feldspathic and granitoid rocks of the Basement complex.

Owing to the high concentrations of magnesium, calcium, bicarbonate and sulphate and as shown in Table VII-21, the water in this zone is quite hard. The presence of sodium and potassium ions could render these waters alkaline. This very hard water may cause encrustation in pipes, household fixtures and cooking utensils. The silica content is generally below 100 ppm. This then means that treatment of such water is necessary before applying it to any industrial uses.

The concentration of chloride as given in Table VII-21



Relationship between Total Dissolved Solids and Fluoride in Groundwater within the Quartzo-Felspathic and Granitoid Rocks of the Basement Complex

FIG. 7 14

TABLE VII-21

SOME OF THE MINOR CHEMICAL CONSTITUENTS IN GROUNDWATER IN RESPECTIVE METAMORPHIC ROCKS

IONS IN PPM

Geology	Coordinates Lat.	Long.	NO_2	NO_3	F+S.Amm	Album.Amm.	Hardness	Silica	Fe	Cl	Cu	Pb	Na+K	O_2	CO_2
Xc	S120	3810	Tr	Tr	-	0.06	485	-	-	193	-	-	-	0.54	-
	S113	3744	Tr	Tr	0.82	0.06	605	56	1.0	303	-	-	-	Tr	-
	S110	3806	-	-	-	-	-	-	-	178	-	-	-	-	-
	S110	3805	-	0.01	0.33	0.10	310	35	-	84	-	-	-	0.85	-
	S128	3750	Tr	Tr	Tr	Tr	351	74	0.20	62	-	-	-	Tr	-
Xg	S344	3903	Tr	Tr	0.06	0.08	4179	-	-	5020	-	-	-	0.02	-
	S150	3812	Tr	Tr	0.05	0.05	807	60	Tr	400	-	-	-	0.30	-
	S122	3810	-	Tr	Tr	0.10	506	-	-	211	-	-	-	1.04	Tr
	S344	3903	Tr	Tr	Tr	Tr	396	50	Tr	6060	-	-	-	-	Tr
	S327	3843	-	Tr	-	-	1875	70	-	1830	-	-	-	-	2.5
Xn	S222	3758	-	-	0.07	0.14	3238	-	-	2980	-	-	-	0.28	-
	S222	3754	-	Tr	-	0.06	558	90	-	344	-	-	-	0.95	1.40
	S200	3645	-	-	0.22	0.06	189	42	0.15	85	-	-	-	1.09	-
	S157	3715	-	Tr	11.20	1.34	1199	60	1.8	121	-	-	-	-	Tr
	S156	3716	0.30	0.11	-	0.04	850	50	-	490	-	-	-	1.35	-
	S155	3710	Tr	Tr	Tr	Tr	532	34	0.40	241	-	-	-	-	-
	S153	3700	Tr	Tr	0.02	0.03	749	23	0.18	379	-	-	-	Tr	-
	S153	3652	Tr	Tr	0.04	Tr	539	24	0.68	228	-	-	-	Tr	1.0
	S150	3715	Tr	Tr	Tr	Tr	356	74	0.60	52	-	-	-	Tr	-
	S149	3709	Tr	Tr	Tr	Tr	330	34	0.40	241	-	-	-	-	Tr
Xa	S232	3647	Tr	Tr	0.40	-	257	38	0.10	27	-	-	-	-	-
	S230	3700	-	Tr	0.41	0.18	-	23	0.15	25	-	-	-	3.60	-
	S222	3812	-	-	0.16	0.36	270	16	0.40	1210	-	-	-	3.30	-
	S206	3647	Tr	Tr	-	Tr	-	27	Tr	320	-	-	-	Tr	-
	S207	3800	Tr	Tr	Tr	-	383	36	Tr	165	-	-	-	-	0.10
	S200	3800	Tr	Tr	0.04	-	463	75	0.05	217	-	-	-	-	-
	S200	3645	-	-	-	-	363	60	1.2	139	-	-	-	-	-
	S148	3825	0.32	0.60	0.38	0.17	1395	45	-	934	-	-	-	2.50	-
	S148	3740	Tr	Tr	0.40	0.05	673	76	Tr	380	-	-	-	-	-
	S128	3703	0.10	0.13	-	0.07	215	70	-	182	-	-	-	0.57	-

Xc - Calcareous parent

Xg - Migmatites

Xn - Quartzo-feldspathic and granitoid rocks of the Basement complex

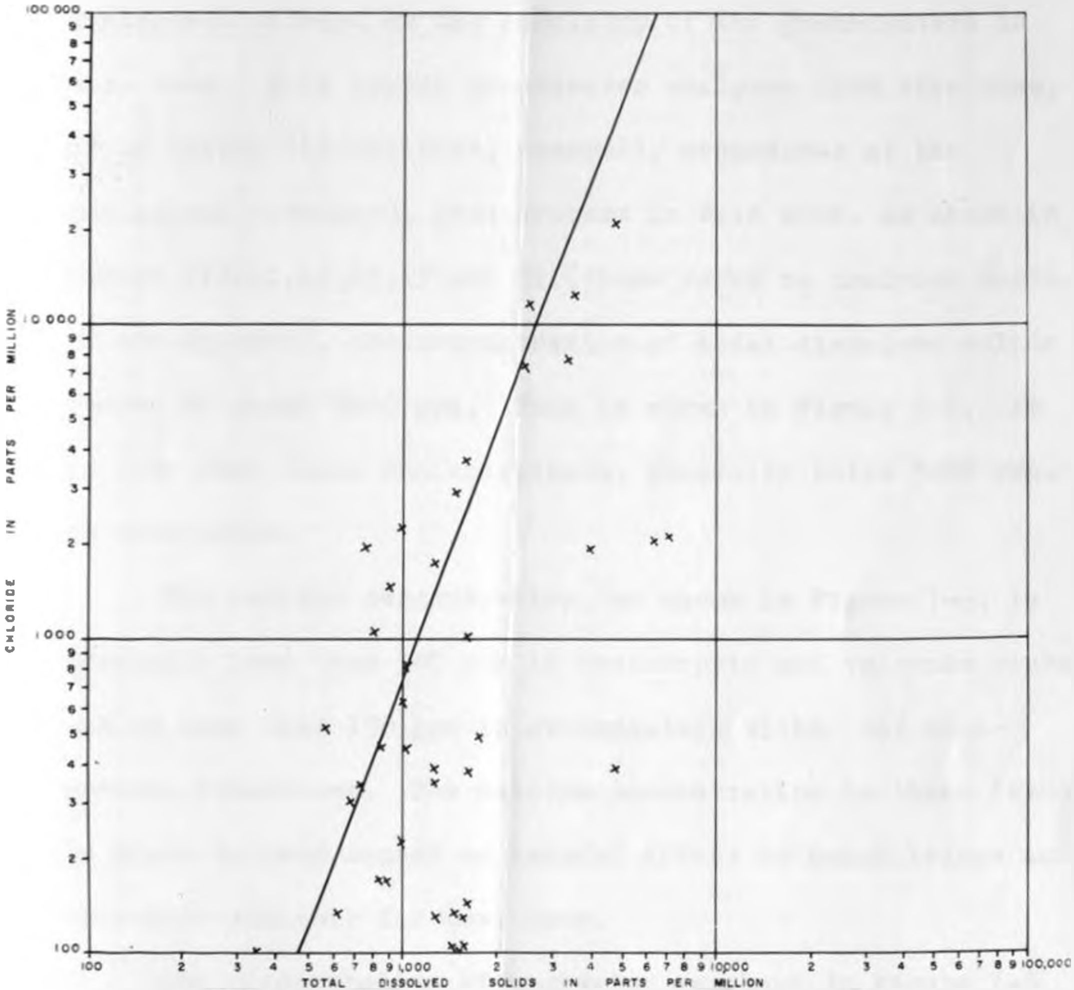
Xa - Pelitic and semipelitic rocks of the Basement complex shows that the chloride content is generally less than 300 ppm but higher concentrations are also recorded. Figure 7-15 shows the relationship between total dissolved solids and chloride for groundwater in the quartzo-feldspathic rocks of the Basement complex. The concentration of chloride, although unsuitable for most uses, is not wholly unacceptable for domestic and other purposes.

The concentration of the ammonia compounds shown in Table VII-21 are extremely low and could mean that the level of pollution is negligible. This is further confirmed by the very low values for the oxygen absorbed. As indicated earlier, pollution can adequately be determined by the biological examination of the water.

It is evident that groundwater in this zone has high concentration of total dissolved solids but which could be permissible for stock rearing and growing of some salt tolerant crops. The water could also be used for general household purposes but it is recommended that the detected hardness first be reduced by chemical treatment of the water. This could then mean that after the silica content has also been reduced the water could be ~~suitanle~~ suitable for other industrial purposes. At times it may be necessary to defluoridate the water so that the fluoride content is within the tolerable limits.

Zone III

This zone, as shown in Figure 7-2, covers parts of the arid and semi-arid areas of Kenya lying mainly in the North-eastern and Northwestern parts of the country. As indicated



Relationships between Total Dissolved Solids and Chloride in Groundwater within the Quartzo-Feldspathic and Granitoid Rocks of the Basement Complex

FIG 7.15

in chapter VI, temperatures and rates of evaporation are extremely high in these areas. The rainfall is considerably low. These areas, as shown in Figure 6-2, are covered by sedimentary, volcanic and metamorphic rocks.

It is clear from the groundwater analysis in this zone that other environmental factors have greatly influenced the geological effects on the chemistry of the groundwaters in this zone. With sparse groundwater analyses from this zone, it is fairly obvious that, generally regardless of the geological formation, groundwaters in this zone, as shown in Tables VII-11,14,15,19 and 22 (these refer to analyses north of the Equator), the concentration of total dissolved solids ranges to about 8000 ppm. This is shown in Figure 7-2. It is true that lower concentrations, generally below 5000 ppm, do also occur.

The calcium concentration, as shown in Figure 7-3, is generally less than 100 ppm in metamorphic and volcanic rocks and is less than 150 ppm in groundwaters within the sedimentary formations. The calcium concentration in these levels is known to have caused no harmful effect to human beings and therefore suitable for most uses.

The concentration of magnesium as shown in Figure 7-5 indicates that for groundwaters in the metamorphic and volcanic rocks the concentration is generally less than 50 ppm. In the sedimentary rocks, however, groundwaters show concentrations of magnesium of generally up to 100 ppm. This means that these concentrations are suitable for most uses.

TABLE VII-27

SOME OF THE MINOR CHEMICAL CONSTITUENTS IN GROUNDWATER IN RESPECTIVE SEDIMENTARY ROCKS

IONS IN PPM

Geology	COORDINATES Lat.	Long.	NO_3	NO_2	F+S.Amm.	Album.Amm.	Hardness	Silica	Fe	Cl	Cu	Pb	Na+K	O_2	CO_2
Q	N145	4002	Tr	Tr	-	-	-	-	-	7360	-	-	-	-	-
	N147	4004	0.55	2.75	8.10	0.48	500	10	-	644	-	-	-	5.0	-
	N200	3945	0.10	5.00	-	-	276	110	0.10	18	-	-	-	0.10	-
	N307	3536	-	Tr	-	2.00	570	-	-	1060	-	-	-	-	-
	S003	3451	Tr	-	Tr	Tr	145	80	Tr	40	-	-	-	-	-
	S004	3458	-	Tr	0.04	-	179	60	Tr	40	-	-	-	Tr	-
	S006	3445	-	Tr	1.44	0.28	-	24	2.8	650	-	-	-	4.00	Tr
	S009	3512	Tr	Tr	Tr	Tr	335	20	0.40	3	-	-	-	-	Tr
	S009	4034	-	-	0.12	0.02	80	25	0.30	164	-	-	-	0.02	-
	N101	3939	0.50	-	-	-	-	23	-	30	-	Tr	197	-	13
	S020	3600	-	Tr	0.24	0.4	-	54	0.20	220	-	-	-	2.00	Tr
Pc	S443	3939	-	-	-	-	-	-	-	4300	-	-	-	-	2.0
	S429	3929	Tr	Tr	0.03	0.02	282	25	1.5	19	-	-	-	-	-
	S403	3940	Tr	Tr	0.32	0.14	-	-	-	908	-	-	-	1.26	-
	S348	3948	Tr	Tr	Tr	0.06	358	20	0.3	1170	-	-	-	-	-
	S349	3948	Tr	Tr	Tr	0.06	376	40	0.40	3200	-	-	-	-	-
	S315	3940	-	-	Tr	0.02	-	9	0.70	600	-	-	-	0.40	-
	S126	4002	Tr	-	-	0.04	-	19	0.20	118	-	-	-	0.20	Tr
	S126	4003	-	Tr	0.6	0.04	-	26	Tr	1680	-	-	-	0.50	-
	S126	4005	Tr	Tr	0.05	Tr	-	10	0.60	460	-	-	-	-	-
	S116	4002	-	-	0.04	0.02	-	5	0.60	1640	-	-	-	-	-
Tu+Tl	S413	3925	-	-	0.02	0.07	-	48	1.8	390	-	-	-	0.30	-
	S412	3925	-	-	0.09	0.06	-	30	1.6	900	-	-	-	0.20	-
	S411	3927	-	-	0.54	0.07	-	16	0.18	2925	-	-	-	0.05	Tr
	S410	3926	-	-	0.08	0.08	-	18.5	0.75	1380	-	-	-	0.04	-
	S410	3910	-	-	0.60	0.40	318	46	3.50	1020	-	-	-	-	-
	S409	3919	Tr	Tr	0.02	0.04	648	13	0.17	1040	-	-	-	0.42	-
	S406	3914	-	-	0.70	0.05	703	10	0.12	900	-	-	-	0.30	-
	S413	3924	-	-	0.08	0.05	349	40	6.4	520	-	-	-	0.30	-
	S412	3925	-	-	0.08	0.02	783	-	-	980	-	-	-	0.21	Tr
	S411	3928	Tr	Tr	0.19	0.02	446	9	0.30	560	-	-	-	0.20	-

Q – Quaternary Sediments

Pc – Pleistocene and Recent Coral reef

Tu+Tl – Upper and Lower sandstones and grits of Duruma Sandstone Series.

As shown in Figure 7-7 the bicarbonate concentration in these waters is generally of the order of 200 ppm but higher concentrations getting up to 400 ppm are also encountered. The concentrations may be acceptable for most uses.

The sulphate concentration is shown in Figure 7-8 and is generally of the order of less than 200 ppm and could be permissible for most uses.

The concentration of fluoride, illustrated in Figure 7-9 indicates that the fluoride content is generally within the acceptable limits for human being and domestic animals.

High concentrations of chloride particularly in groundwaters in the sedimentary formations are quite common. It is possible that with sodium concentrations (undetermined in this analysis) these waters could be extremely saline in nature, especially when the calcium and magnesium concentrations are low. Chloride concentrations of up to and above 5000 ppm have been recorded in some of these waters. The suitability of these waters for most agricultural purposes, as shown in Figure 7-1, will depend on the ratio of sodium to other ions in these waters. High chloride concentrations depending on ratio of magnesium and calcium, could give very unpleasant taste in these waters and render them unsuitable for industrial purposes. This is particularly so when the silica content is quite low.

As shown in Table VII-19 and VII-22, some ammonia constituents have been detected in this water and could be indicative of some negligible amounts of pollution.

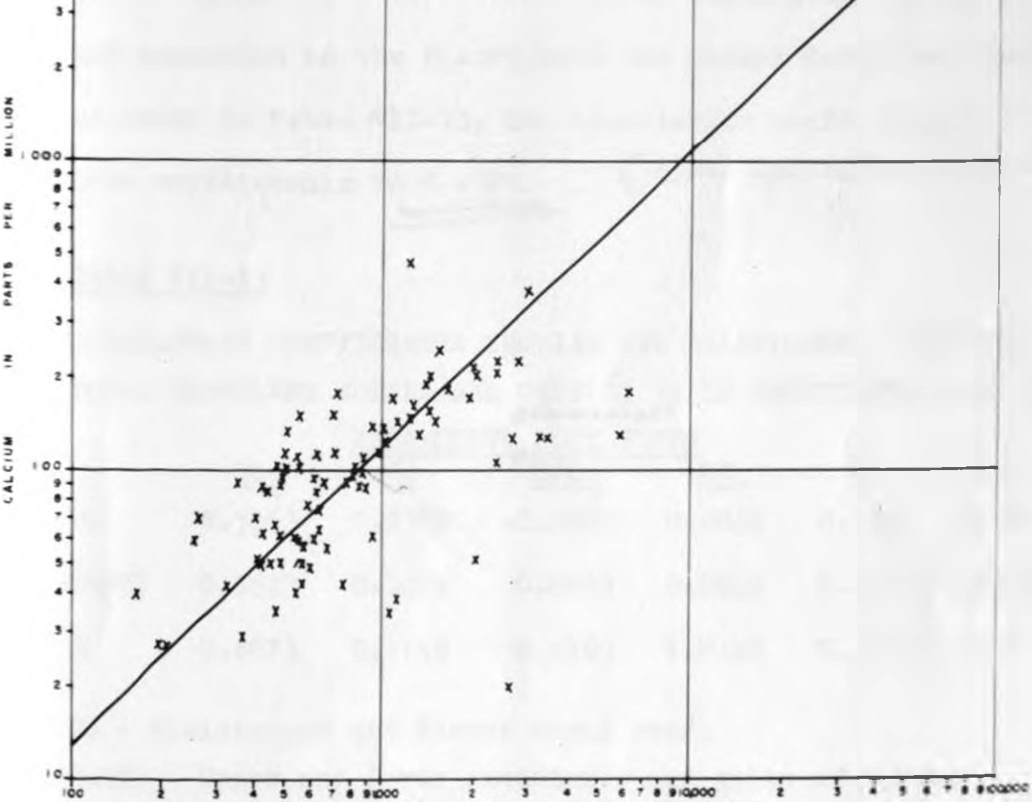
It is quite evident that water in this zone is quite suitable for stock rearing and could be quite suitable for other purposes except for the high chloride content which in the presence of sodium make this water extremely saline. This chloride content, since it forms some encrustations in metallic pipes, could have some deleterious effects on human beings who consume water from these pipes. Chemical reduction of the salt in this water by chemical processes is desirable if it has to be used for other purposes. For irrigation purposes, factors other than the water itself have to be taken into account. These may include climatic factors, soils, topography and nature of crops to be grown.

Zone IV (COAST)

This zone, as shown in Figure 7-2, extends parallel to the adjoining Indian Ocean. It is a zone mainly covered by marine sedimentary formations and in places receives a fair amount of rainfall. The temperatures are high and the rates of evaporation are also relatively high.

The total dissolved solids concentration is much higher than that in the zones already described. Amounts of up to and above 8,000 ppm of total dissolved solids have been recorded in this zone. Such a concentration of salts in groundwater is suitable for stock rearing rather than for drinking purposes. As has been pointed out before, high concentrations of total dissolved solids have had no injurious effects on the health of human beings.

As shown in Figure 7-3, the calcium concentration is up to 800 ppm. Figure 7-16 gives the relationship between



Relationship between Total Dissolved Solids and Calcium in Groundwater within Pleistocene and Recent Coral Reef

FIG 7.16

otal dissolved solids and calcium for groundwaters in he Pleistocene and Recent Coral reef. The correlation oefficient for this relationship as shown in Table VII-23 s 0.6734. These calcium concentrations are not permissible 'or most uses, although they have no harm on human health.

The magnesium concentration, as shown in Figure 7-5 exceeds the permissible limits for most uses in that the concentrations are up to and above 200 ppm. Figure 7-17 gives a positive correlation between total dissolved solids and magnesium in the Pleistocene and Recent Coral Reef and as shown in Table VII-23, the correlation coefficient for this relationship is 0.2389. (too low and insignificant)

TABLE VII-23

CORRELATION COEFFICIENTS SHOWING THE RELATIONSHIP BETWEEN TOTAL DISSOLVED SOLIDS AND GIVEN IONS IN GROUNDWATER FOR RESPECTIVE SEDIMENTARY ROCK TYPES

	SO_4	Mg	HCO_3	CO_3	Ca	F
Pc	0.5563	0.2389	-0.0010	0.0030	0.6734	0.0072
Tu+Tl	0.0647	0.1094	0.0097	0.0035	0.4119	0.0018
Q	0.6073	0.3749	0.6103	1.8348	0.4253	0.0659

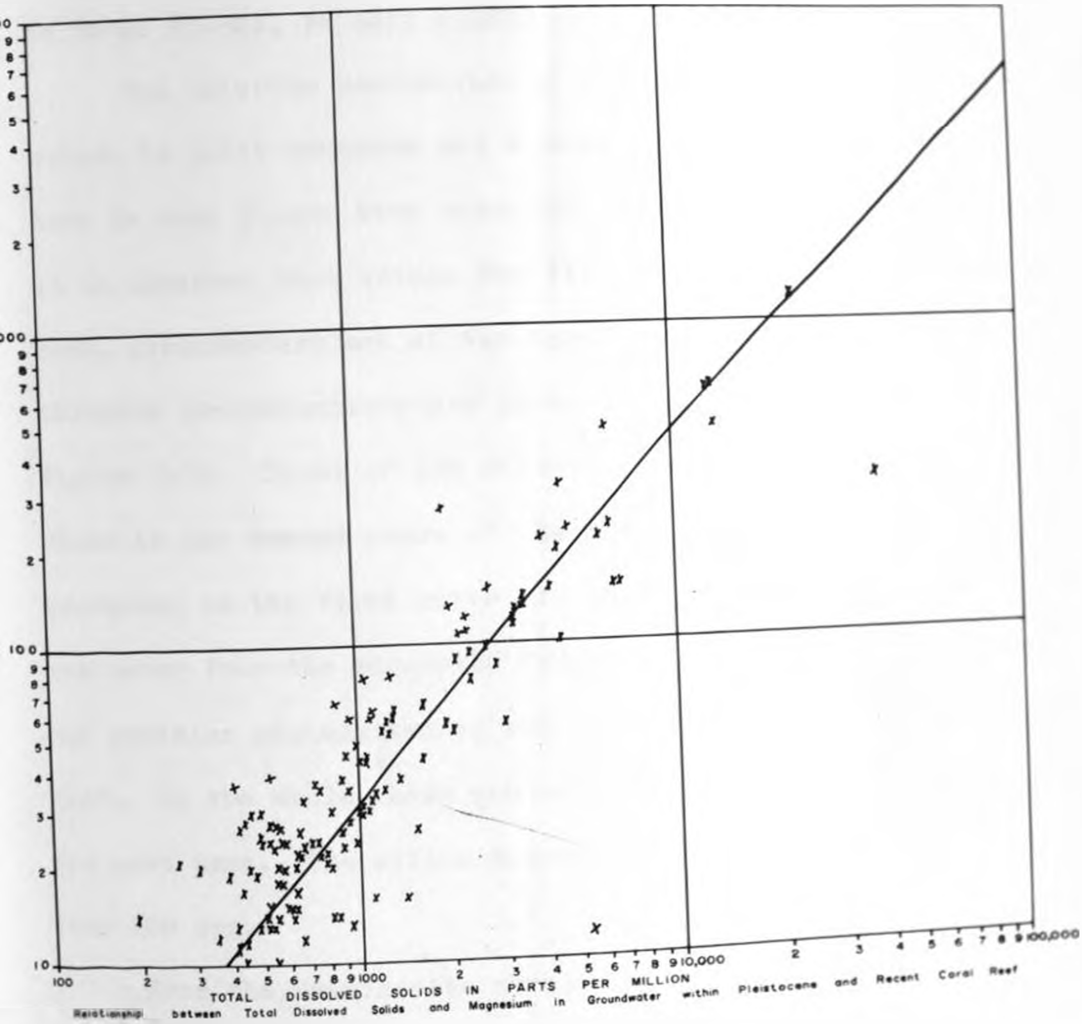
Pc - Pleistocene and Recent coral reef.

Tu+Tl - Upper and Lower sandstones and grits of Duruma sandstone series.

Q - Quaternary sediments.

The bicarbonate concentration in these waters is generally below 1,000 ppm and as shown in Figure 7-7, this is above the acceptable concentrations for most uses.

The sulphate content in the groundwaters of this zone is shown in Figure 7-8 and indicates that concentrations are less than 2000 ppm. This is not suitable for most uses.



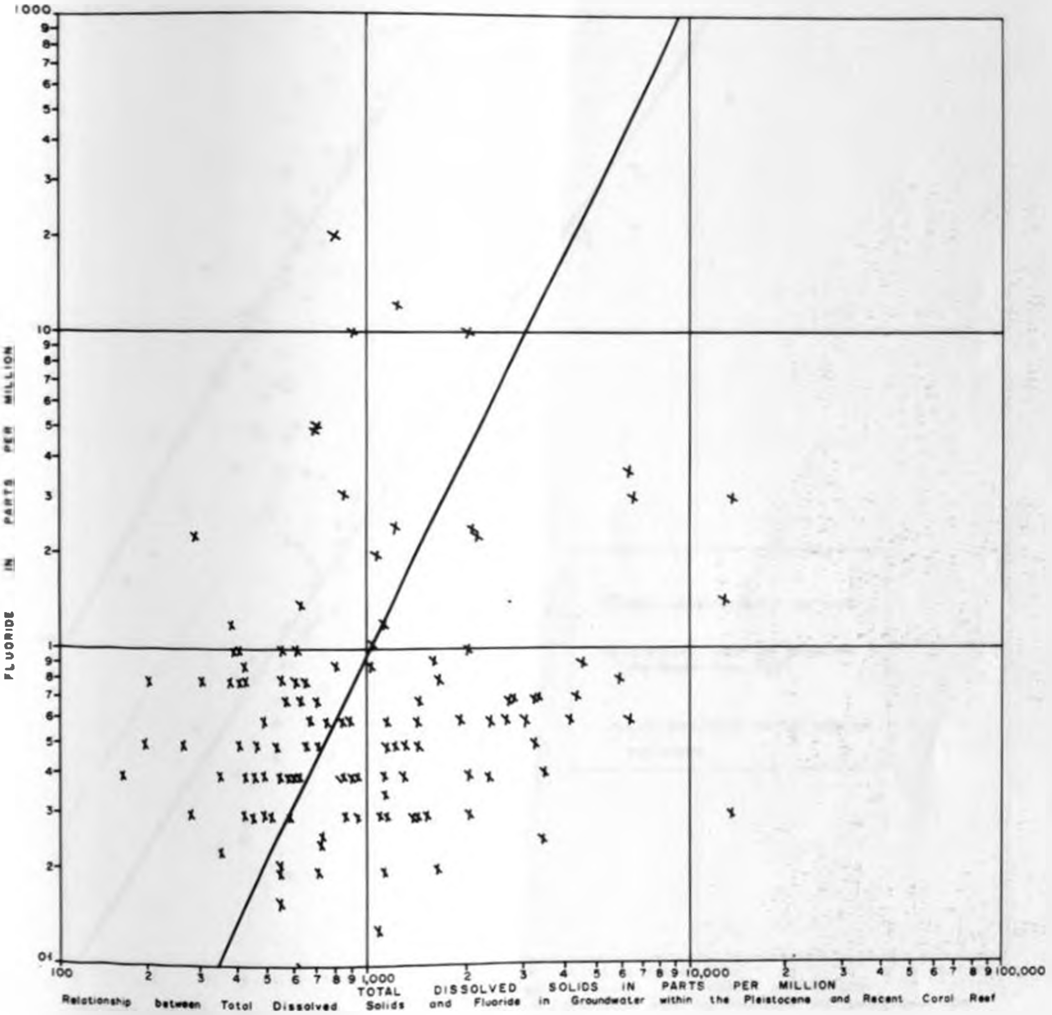
Relationship between Total Dissolved Solids and Magnesium in Groundwater within Pleistocene and Recent Coral Reef

FIG 7 17

The fluoride content as illustrated in Figure 7-7 is generally less than 10 ppm and most of the water is well within the acceptable 1.5 ppm limit. A very poor relationship is shown in Figure 7-18 between fluoride and total dissolved solids in the Pleistocene and Recent coral reef. The correlation coefficient for this relationship, as shown in Table VII-23, is only 0.0072.

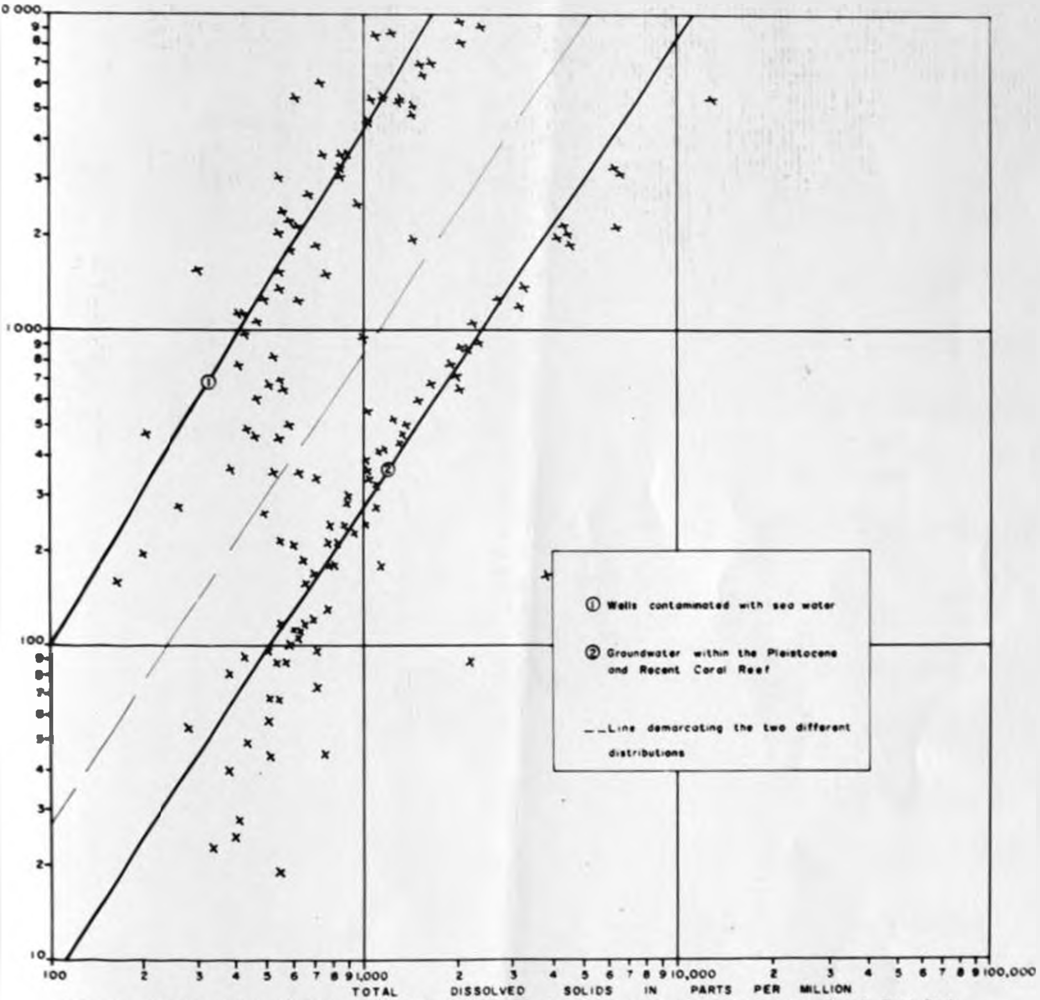
The chloride concentration in some of these groundwaters is quite enormous and values of over 10,000 ppm have in some places been recorded. As shown in Figure 7-19, it is apparent that within the Pleistocene and Recent coral reef, groundwaters are of two types. Those containing high chloride concentrations are given in the first curve of Figure 7-19. Those of low chloride concentration are shown in the second curve of the same figure. Those appearing in the first curve are wells contaminated with sea water from the adjoining Indian Ocean while the second one contains groundwater in the Pleistocene and Recent coral reef. On the whole these concentrations are not desirable for most uses. The silica concentration is generally less than 100 ppm.

From the examination of the discussion above, and from data in Tables VII-11 and 22, it is quite evident that there are minor traces of ammonia compounds and oxygen. These values are indicative of pollution but conclusive evidence is desirable and should be based on bacteriological examination of the water. Water derived from the Duruma Sandstone Series and Jurassic beds is quite hard and saline.



Relationship between Total Dissolved Solids and Fluoride in Groundwater within the Pleistocene and Recent Coral Reef

FIG 7 18



Relationship between Total Dissolved Solids and Chloride in Groundwater within the Pleistocene and Recent Coral Reef

FIG 7 19

This is a result of the high concentrations of calcium, magnesium, bicarbonate, chloride (in the presence of sodium) and sulphate. This water is therefore undesirable for most household purposes except after chemical treatment. It may be suitable for stock rearing and growing of crops with a high degree of salt tolerance. It is also unsuitable for industrial uses except after chemical treatment. However, this water is not wholly unsuitable for all uses.

SUMMARY

The preceeding discussion is not only important from the theoretical point of view but it could also be useful in the planning and development of the groundwater resources of Kenya. The following points emanate from the discussion:-

(1) Groundwater resources in Zone I are of excellent quality and are suitable for most uses. These include stock rearing, irrigation, industry and general household. In some cases, however, the water should be defluoridated to reduce the concentration of the fluorides to the accepted 1.5 ppm level for drinking purposes. It is also necessary to reduce the silica content for most industrial uses. The principal ions in these waters are bicarbonate, carbonate and silica. It is also possible that sodium is present in these waters. These waters have relatively low amounts of total dissolved solids and are quite soft.

(2) Groundwaters in Zone II contain relatively high concentrations of magnesium, calcium and bicarbonate and hence the appreciable amount of hardness. Reduction of hardness in these waters is desirable. In places the water

contains high fluoride concentrations which should be reduced together with silica if the water is meant for drinking and industrial purposes. Bicarbonate, magnesium, calcium, carbonate and to some extent silica are among the dominant ions in these waters.

The total dissolved solids, although high and getting to 5,000 ppm, could be acceptable for stock rearing, irrigation and other uses.

(3) Groundwaters in what has been referred to as Zone III have high concentrations of total dissolved solids mainly because of chloride and possibly sodium ions. These waters could be used for stock rearing and in some special circumstances growing of salt-tolerant crops. This salt concentration will be determined by the amount of sodium in relation to the amount of other ions like calcium and magnesium. The water is otherwise moderate to extremely low in hardness and in some cases may require treatment before use. This water, although unsuitable for most uses, could be used for general household purposes without exerting any adverse effect on human health. The fluoride and silica concentrations are well within the limits for drinking and industrial purposes.

(4) Groundwater resources within Zone IV are known to be highly charged with chloride and sodium as a result of the saline marine sediments in which they occur and also as a result of salts derived from the adjoining Indian Ocean. The water is quite hard for most uses because of the high concentration of magnesium, calcium and bicarbonate. The fluoride

content is generally within the acceptable limits although in some places higher concentrations are encountered and need chemical treatment before use. These concentrations are nevertheless quite acceptable for stock rearing. Although this water is not suitable for most uses, it may, however be used mainly for stock rearing and with no alternative source of water, these highly saline waters could be used for other domestic purposes and under very special conditions the growing of highly salt-tolerant crops.

(5) The suggested groundwater zones are by no means exhaustive and are meant to be a base for water resource development and further detailed research.

✓ 4. Areas for Further Research: *

(1) For efficient planning and development of water resources in the country, detailed investigations of the groundwater quality in each of the suggested zones is desirable. This study will be particularly relevant in solving the water problems in the dry North-eastern, North-western and Ukambani parts of the country. At present the information from existing boreholes is not adequate in some of these areas. Intensified data collection from these areas will have to be carried out in order to facilitate detailed mapping of the groundwaters. Detailed geohydrological maps will be necessary for effective planning of water resources for the general livelihood of the existing population, their animals, industries and general agricultural purposes.

(2) In order to ascertain the degree of pollution and acceptability of water for drinking purposes, it is necessary to carry out bacteriological and virological examination of the water in given groundwater zones. This kind of investigation is also desirable for surface water resources of the country.

(3) In order to develop the groundwater resources fully, it is necessary to carry out a detailed survey of the potential availability of the groundwater in each of the suggested zones. The borehole data already available should be analyzed so as to give a clear picture of the groundwater availability in the whole country. Field investigations should be organized so as to supplement the already available information. Such groundwater surveys are useful for future planning of irrigation, other agricultural development, industrial development and human settlement.

(4) At present surface water chemistry data exist. It is necessary to carry out extensive analysis of the quality of this water. This study could be extended to cover the potentiality of surface waters in terms of providing hydroelectric power, irrigation and the occurrence and prediction of floods.

(5) Estimation of the rate of chemical degradation of landscapes in various geologic and climatic regions is quite desirable. Such a study could be able to determine the geochemical and water budget for Kenya. This would also enable the rationalization of water chemistry in terms of weathering reactions in the context of the existing laws of

mineral and chemical equilibria. Such a study would be of great use in the conservation of natural resources and planning of agricultural practices. This will also indicate the degree of man's interference with the surface and groundwater quality.

(6) An investigation into the problems of the variation of groundwater chemistry in the flow process with depth and time is necessary. This would be of value particularly when drilling for water. This is desirable in each one of the suggested zones.

(7) The chemical analysis of precipitation is quite important for it will show to what extent rainfall influences the groundwater chemistry. Such information could be useful also for the rural population that is greatly tending to taping of rainwater for domestic and household purposes.

(8) Water classification in terms of major ions occurring in waters of any one given zone will be quite useful. This will then mean that the undetermined elements of the present analysis such as sodium, potassium and other toxic substances will be determined with a view to finally solving the problems related to hydrogeochemical reactions and equilibrium geochemistry.

REFERENCES

ABLESON, H.E. (1959). Researches in Geochemistry Volume I. Chapter by H.E. Hawkes on Geochemical Prospecting pp. 62-77.

AHRENS, L.H. (1965). Distribution of Elements In Our Planet. McGraw Hill 110 pp.

AHRENS, L.H. (1963). Element Distribution in Igneous rocks, Negative Skewness of SiO_2 and K: Geochimica et Cosmochimica Acta, 1963.

AHRENS, L.H. (1957). Lognormal-type Distribution (iii): Geochimica et Cosmochimica Acta, Volume II, pp. 205-212.

AHRENS, L.H. (1957). The Lognormal Distribution of Elements (ii): Geochimica et Cosmochimica Acta Volume 6 pp. 121-131.

AHRENS, L.H. (1954). The Lognormal Distribution of Elements (a fundamental Law of Geochemistry and its subsidiary): Geochimica et Cosmochimica Acta Volume 5 pp. 49-73.

ALLEN, P. (1945). Lognormal Distributions: Nature, Volume 156, pp. 746-749.

ANDERSON, D.H., and HAWKES, H.E. (1959). Relative Mobility of the Common Elements In Weathering of some Schist and Granite Areas: Geochimica et Cosmochimica Acta, Volume 14 pp. 204-210.

A.P.H.A., A.W.W.A., and W.P.C.F. (1971). Standard Methods for the Examination of Water and Waste-water, 13th Edition, 874 pages.

AUBREY, K.V. (1954). Frequency Distribution of the Concentration of Elements in Rocks: Nature, Volume 174 No. 4420 pp. 141-142.

BACK, W. (1960). Origin of Hydrochemical Facies of Ground-water in the Atlantic Coastal Plain: 21st International Geological Congress, Copenhagen, 1960, Proceedings, Part I, pp. 87-95.

BAKER, B.H. (1968). An Outline of the Geology of Kenya (*Unpublished Paper*), *University of Nairobi*.

BAKER, B.H. (1970). Tectonics of Kenya Rift Valley: (*Unpublished Ph.D. Thesis of the University of East Africa*).

BAKER, B.H., and WILLIAMS, L.A.J. (1969). Outline of the Geology of the Rift Valley in Southern Kenya (*Unpublished Paper*), *University of Nairobi*.

BARNES, H.L. (1967). Geochemistry of Hydrothermal Deposits; Holt, Rinehart and Winston Inc., 670 pp.

BEAUCHAMP, R.S.A. (1953). Sulphates in African Inland Waters: *Nature, Volume 171, pp. 769-771*.

BECKLEY, V.A. (1953). Anti Erosion and Soil Conservation Measures: *Proceedings of the 2nd Conference of East African Agricultural Chemists, pp. 60-61*.

BIEN, G.S., CONTOIS, D.E. and THOMAS, W.H. (1968). The Removal of Soluble Silica from fresh water entering the Sea: *Geochimica et Cosmochimica Acta, 1958, Volume 14 pp. 35-54*.

BISHOP, W.W., and TRENDAL, A.F. (1967). Erosion Surfaces, Tectonics and Volcanic Activity in Uganda: *Quarterly Journal of the Geological Society* of London, Volume 123 pp. 385-411.

BROCK, D.T. (1971). Bimodal Distribution of pH Values of Thermal Springs of the World: *Geological Society of America Bulletin, Volume 82, pp. 1393-1394*.

BUCHAN, S. (1963). Geology in Relation to Groundwater: *Institution of Water Engineers, Volume 17 No. 3, May 1963, pp. 153-163*.

BUSH, A.G. (1920). A project for the Drainage and Town Planning of Mombasa Island, Nairobi Government Printer 22 pages.

CALKINS, D., and DUNNE, T. (1970). A Salt Tracing Method of Measuring Channel Velocities in Small mountain streams: Sleeper River Research, Watershed, Danville Vermont and McGill University, Montreal; Journal of Hydrology II pp. 379-392.

C.E.N.T.O. (1969). Cento Seminar on Evaluation of Water Resources with Scarce Data, Tehran, Iran 502 pp., 1969.

CLARKE, F.W. (1924). The Data of Geochemistry 5th Edition: United States Geological Survey Bulletin, 770, 841 pp.

COLE, S.M. (1950). An outline of the Geology of Kenya, Pitman, 58 pp.

COUSINS, C.A. (1956). The Value Distribution of Economic Minerals with Special Reference to the Witwaterstrand Gold Reefs: Transactions of the Geological Society of South Africa, Volume LIX, pp. 97-121.

DAVIS, S.N. (1964). Silica in Streams and Groundwater: American Journal of Science, Volume 262, pp. 870-891.

DAVIS, S.N., and De WEIST (1966). Hydrogeology.

DIXEY, F. (1946). Rural Water Supplies in Africa: South African Geographical Journal, Volume XXVIII.

DIXEY, F. (1956). Erosion Surfaces in Africa. Some Considerations of Age and Origin: Transactions of the Geological Society of South Africa, Volume 58, pp. 265-280.

DIXEY, F. (1938). Some Observations of the Physiographic Development of Central and Southern Africa: Transactions of the Geological Society of South Africa, Volume 41, pp. 113-171.

DIXON, H.H. (—). The Estimation of the Catchment Yields of Rivers in the Kinangop Area of Kenya, 10 pages.

DONALD, E.W., JOHN, D.H., and WARING, G.A. (1963). Chemical Composition of Subsurface Waters: United States Geological Survey Professional Paper, 440F.

DOSAJ, N.P. and WALSH, J. (1970). Bibliography of the Geology of Kenya, 1859-1968: Bulletin 10, Geological Survey of Kenya.

DOW (Chairman), (1953-1955). East African Royal Commission Report, London, 481 pp.

DUNNE, T. (1970). Runoff Production in a Humid Area: United States Department of Agriculture, Ars. 41-160.

DUNNE, T., and BLACK, R.D. (1970). Partial Area Contributions to Storm Runoff in small New England Watershed

DURUM, W.H., HEIDIEL, S.G., and TISON, L.J. (1961). Worldwide Runoff of Dissolved Solids: United States Geological Survey Professional Paper, 424C pp. 326-329.

E.A.M.D. (—). The Weather of East Africa: East African Meteorological Department Pamphlet, Series No. 7, Part I, 10 pp.

E.A.M.D. (1964). Climatological Statistics for East Africa and Seychelles, Part I, Kenya and Seychelles.

E.A.M.D., (1962). Climatic Seasons of East Africa: East African Meteorological Department Pamphlet, Series No. 8, 3 pp.

E.A.M.D. (1966). Monthly and Annual Rainfall in Kenya During the 30 years, 1931-1960.

E.A.M.D. (1967). Meteorological Data Recorded at Agricultural, Hydrological and Other Research Stations in Kenya during the years 1963, 1964 and 1965.

E.A.M.D. (1969). Meteorological Data Recorded at Agricultural, Hydrological and Other Research Stations in Kenya during the years 1966-1967.

E.A.M.D. (1970). Meteorological Data Recorded at Agricultural, Hydrological and Other Research Stations in Kenya in 1968.

E.A.M.D. (1970). The Weather of East Africa during 1969.

E.A.M.D. (1970). Temperature Data for Stations in East Africa, Part I, Kenya.

E.A.M.D. (1947). Mean and Extreme Values of certain Meteorological Elements for Selected Stations in East Africa: British East African Meteorological Service.

GARRELS, R.M., and CHRIST, C.C. (1965). Solutions, Minerals and Equilibria; Harper and Row, N.Y. and John Weatherhill, Inc., Tokyo, 450 pp.

GEOLOGICAL SURVEY OF KENYA (—). Regional Geological Reports, Nos. 1-83. Government Printer, Nairobi.

GEVAERTS, E.A.L. (1964). Hydrogeology of the Nairobi Area: Water Development Department, Technical Report No. 1, 33 pages.

GEVAERTS, E.A.L. (1957). Report on the Geology and Groundwater Conditions in Nairobi and Surrounding Areas: Public Works Department, Hydraulic Branch, Technical Paper No. 3, 136 pages.

GILLMAN, C. (1943). A Reconnaissance Survey of the Hydrology of Tanganyika Territory in Its Geographical Settings: Water Consultants Report No. 6, 1940.

GORHAM, E. (1961). Factors influencing supply of Major Ions to Inland Water with special Reference to the atmosphere: Geological Society of America Bulletin, Volume 72, pp. 795-840.

GORHAM, E. (1955). On Some Factors Affecting the Chemical Composition of Swedish Fresh Waters: Geochimica et Cosmochimica Acta, Volume 7, pp. 129-150.

GORHAM, E. (1955). On the Acidity and Salinity of Rain: Geochimica et Cosmochimica Acta, Volume 7, pp. 231-257.

GORREL, H.A. (1958). Classification of Formation Waters based on Sodium Chloride Content: Bulletin of the American Association of Petroleum Geologists Volume 42, No. 10, pp. 2513-2522.

GRIFFITHS, J.F. (1958). Climatic Zones of East Africa: East African Agricultural Journal, Volume 23, pp. 178-185.

GRIFFITHS, J.F. (1958). An Initial Investigation of the Annual Rainfall in East Africa: E.A.M.D. Memoirs, Volume III No. 5.

GRUNDY, F. (1963). Rainfall and River Discharge in Kenya during the Floods of 1961-1962, 33 pages.

HARMON, C. (1957). Proceedings of the Conference on New Research Methods in Hydrology: Scripps Institution of Oceanography, La Jolla, California.

HELGESON, H.C. (1964). Complexing and Hydrothermal Ore Deposition, 128 pp. Pergamon Press.

HEM, J.D. (1969). Study and Interpretation of the Chemical Characteristics of Natural Water: Geological Survey Water Supply Paper No. 1473, 269 pages.

HENDRICKSON, G.E., and KRIEGER, R.A. (1960). Relationship of Chemical Quality of Water to Stream Discharge in Kentucky: <u>21st International Geological Congress Copenhagen Proceedings, Part I, pp. 66-75</u>.

HOEL, P.G. (1969). Introduction to Mathematical Statistics, 331 pp., John Wiley and Sons, Inc.

HOLMES, A. (1970). Principles of Physical Geology, 1288 pp. E.L.B. Society.

HYDRAULIC BRANCH (1958-1961). An Investigation into the Water Resources of the Ewaso-Ngiro Basin: <u>Abridged Report No. 5, Hydraulic Branch, 50 pp</u>.

JAMES, T.C. (1967). Thermal Springs in Tanzania: <u>Institute of Mining and Metallurgy Transactions Volume 76, Bulletin 723, pp. B1-B18</u>.

JENKINSON, A.F. (—). Statistics of Extremes (<u>Unpublished paper</u>) <u>University of Nairobi</u>.

JONES, G.H.G. (1935). Description of 33 Soil Series Occuring in Kenya: <u>Proceedings of 2nd Conference of East African Agricultural Chemists, pp. 58</u>.

KANTHACK, F.E. (1945). Report on Augmentation of Water Supply for the Nairobi Municipal Area, Government Printer, Nairobi.

KING, B.C. (1957). The Geomorphology of Africa, Erosion Surfaces and their Mode of Origin: <u>Science Progress No. 180, pp. 672-681</u>.

KOCH, G.S., and LINK, R.F. (1970). Statistical Analysis of Geological Data, John Wiley, 375 pages.

LANEY, R.L. (1972). Chemical Quality of Water in the Tucson Basin Arizona: <u>United States Geological Survey Water-Supply paper 1939-D, pp. D1-D46</u>.

LANGBEIN, W.B. (1949). Annual Runoff in the United States. United States Geological Survey Circular.

LANGBEIN, W.B., and DAWDY, D.R. (1964). Occurrence of Dissolved Solids in Surface Waters of the United States: United States Geological Survey Professional Paper, 501D, pp. D115-D117.

LEPELTIER, C. (1964). A Simplified Statistical Treatment of Geochemical Data by Graphical Representation: Economic Geology Volume 64, pp. 538-550.

LIVINGSTONE, D.A. (1963). Chemical Composition of Rivers and Lakes: United States Geological Survey Professional Paper 440-G.

LOHHR, E.W., and LOVE, J.K. (1952). The Industrial Utility of Public Water Supplies in the United States: Geological Survey Water Supply Paper, 1300, Part I and II.

LUMB, F.E. (1971). Probable Maximum Precipitation (PMP) in East Africa for Durations up to 24 hours: E.A.M.D. Technical Memorandum No. 16.

MASON, B. (1966). Principles of Geochemistry 3rd Edition, John Wiley, 329 pp.

McCALL, G.J.H. (1957). Geology and Groundwater Conditions in the Nakuru Area: Technical Report No. 3, Ministry of Works, Hydraulic Branch.

McCONNEL, R.B. (1955). Erosion Surfaces of Uganda: Colonial Geology and Mineral Resources Survey Volume 5, No. 4, pp. 425-428.

MILLER, R.I., and KAHN, J.S. (1962). Statistical Analysis in Geological Sciences, 483 pp. John Wiley.

MILLER, P.J. (1961). Solutes in Small Streams Draining Single Rock Types, Sangre de Cristo Range, New Mexico: Geological Survey Water Supply Paper 1535-F, pp. 1-20.

MILNE, G. (1935). Some Suggested Units of Classification and Mapping Particularly for East African Soils: Proceedings of the 2nd Conference of East African Agricultural Chemists pp. 48-49.

MILNE, G. (1935). The extent to which Volcanic Rocks give Rise to Distinctive Soils, Examined from East African Occurrences: Proceedings of the 2nd Conference of East African Agriculture Chemists pp. 49-50.

MILNE, G. (1935). Del Villar's Defination of Alluvial Soils: Proceedings of the 2nd Conference of East African Agricultural Chemists pp. 50.

MILNE, G. (1935). Provisional Soil Map of East Africa: Transactions of the 3rd International Congress on Soil Science, 266 pp.

MINES AND GEOLOGICAL DEPARTMENT (—). Annual Reports.

MUNGER, E.S. (1950). Water Problems of Kitui District: Geographical Review, Volume XL, 1950, pp. 575-582.

NYANDAT, N.N. (1971). Characterisation of Soil at Fertilizer Demonstration and Experiment Sites: National Agricultural Laboratories, Nairobi.

OBASI, G.O.P. (—). Water Balance in Nigeria: University of Nairobi.

ODINGO, R.S. (1971). Kenya Highlands, Land Use and Agricultural Development: E.A.P.H. Nairobi, 229 pages.

OJANY, F.F. (1969). The Inselbergs of Eastern of Kenya with Special Reference to Ukambani Area: Annals of Geomophology: Zeitschrift fur Geomophologie Neue Folge Band 13, 1969, Heft 2, Seite 196-206.

OJANY, F.F. (1968). The Geography of East Africa: Published in Zamani: A Survey of East African History edited by B.A. Ogot and J.A. Kieran.

OKOTH, W. (1966). River Hagaan, Hydrological Studies of Uppsala University, Department of Physical Geography, (Unpublished paper).

OLLIER, C.D. (1963). Insolation Weathering: Examples from Central Australia: American Journal of Science Volume 261, pp. 376-381.

OLLIER, C.D. (1969). Weathering 304 pp., Oliver and Boyd.

OMINDE, S.H. (1968). Land and Population Movement in Kenya, 202 pages, Heinemann.

OMINDE, S.H. (Editor) (1971). Studies in East African Geography of Development, Heinemann, 273 pp.

OMINDE, S.H., and OJANY, F.F. (1969). Will Irrigation Work on Kenya's Kano Plains? African Scientist Volume 1, pp. 19-20, E.A.P.H. Nairobi, 48 pp.

PARKER, R.L. (1967). Composition of Earth Crust: United States Geological Survey Professional Paper, 440-D.

PARSONS, E. (1945). Principles Governing Water Finding: East African Association of Engineers.

PARTINGTON, J.R. (1960). A College Course of Inorganic Chemistry, Mac Millan, London.

PENN, F.A. (1971). The Composition of Waters in a Sub-Artic Lake Systems: M.Sc. Thesis, Department of Geography, McGill University, Montreal, Canada.

PEREIRA, H.C. (1958). The Limited Utility of Floodwater in the Perkerra River Irrigation Scheme, Kenya: East African Agricultural Journal Volume 23, pp. 246-253.

PUBLIC WORKS DEPARTMENT, (1955). Removal of Excess Fluorides from Potable Water: Hydraulic Branch, Technical Report No. 1.

PULFREY, W. (1969). The Geology and Mineral Resources of Kenya: Bulletin 9, Geological Survey of Kenya, 33 pp. Second Revision by Walsh, J.

PULFREY, W. (1960). Shape of the Sub-Miocene Erosion Bevel in Kenya: Bulletin No. 3, Geological Survey of Kenya.

PULFREY, W. (1958). Review of the Recent Work on the Gondwana Rocks of Kenya Colony: Commission Para la Correlecion del Sistema Karroo (Gondwana) pp. 41-55, XX International Geological Congress.

QUAGLIANO, J.V. (1958). Chemistry, 897 pages, Prentince Hall.

RAINWATER, F.H., and THATCHER, C.L. (1960). Methods for Collection and Analysis of Water Samples: United States Geological Survey, Water Supply Paper, 1454, 301 pages.

RICHARDS, L.A. (Editor) (1954). Diagnosis and Improvement of Saline and Alkaline Soils: United States Handbook No. 60, Department of Agriculture Salinity Laboratory Staff 160 pp.

RUSSEL, E.W. (1962). The Natural Resources of East Africa, 144 pp. E.A.L.B., Nairobi.

SAGGERSON, E.P. (-). Chemical Analysis of Igneous, Metamorphic and Sedimentary Rocks and Natural Gas from Kenya: Unpublished Bulletin of Geological Survey of Kenya.

SAGGERSON, E.P., and BAKER, B.H. (1965). Post-Jurassic Erision Surfaces in Kenya and their Formations in Relation to the Rift Structure: Quarterly Journal of the Geological Society of London, Volume 121, pp. 51-122.

SEABER, P.R. (1965). Variation in Chemical Character of Water in the English-town Formation New Jersey: United States Geological Survey Professional Paper, 498-B.

SCOTT, R.J.P. (1970). Fortran IV Programming Mannual Including ICL 1900, 92 pages, University of Nairobi.

SCOTT, R.J.P. (1970). The Development of a Fortran Programme on ICL 1900, 12 pages, University of Nairobi.

SHACKLETON, R.M. (1945). Geology of Nyeri Area: Geological Survey of Kenya, Report No. 12.

SHAW, D.M., and BANKIE, J.D. (1954). Statistical Methods Applied to Geochemistry: Geochemica et Cosmochimica Acta, Volume 5, pp. 111-123.

SIEVER, R. (1957). The Silica Budget in the Sedimentary Cycle: American Mineralogist, Volume 42, 826-841 pages.

SIKES, H.L. (1934). The Underground Water Resources of Kenya Colony, Government Printer, Nairobi.

SIKES, H.L. (1939). Notes on the Geology of the Country Surrounding Nairobi, Government Printer, Nairobi.

SIR ALEXANDER GIBB AND PARTNERS (1956). Kenya Nile Basin Water Resources Survey, 1956-1958, Nairobi Government Printer.

SIR ALEXANDER GIBB AND PARTNERS (1959). Upper Tana Catchment Water Resources Survey, 1958-1959, Nairobi Government Printer, 161 pages.

SOIL SURVEY UNIT (1968). Major Soil Distribution in Kenya, Department of Agriculture, National Agricultural Laboratories, Nairobi.

STEEL, W.E. (1960). Water Supply and Sewerage.

STEVENS, J.A. (1932). Lake Magadi and Its Alkaline Springs: Technical Report of the Magadi Soda Company.

SURVEY OF KENYA (1970). Kenya National Atlas.

SWARZENSKI, W.V. (1968). Fresh and Saline Groundwater Zones in the Punjab Region, West Pakistan: Geological Survey Water Supply Paper 1608-1, pp. I1-I24.

TAYLOR, L.M., and LAWES, E.F. (1971). Rainfall-Intensity-Duration-Frequency Data for Stations in East Africa, 30 pp. E.A.M.D. Technical Memorandum No. 17.

TEMPERLEY, B.N. (1960). Geology and Groundwater Conditions in the Kibwezi-Chyulu Area: Overseas Geology and Mineral Resources, Volume 8, No. 1, pp. 37-52.

TENANT, C.B., and WHITE, M.L. (1959). Study of the Distribution of Some Geochemical Data: Economic Geology, Volume 54, pp. 1281-1290.

THOMAS, W.L. (1956) (Editor). Man's Role in Changing the Face of the Earth: Chapter by Thomas, W.L. pp. 542-563.

THOMPSON, B.W. (1957). The Diurnal Variation of Precipitation in British East Africa: E.A.M.D. Technical Memorandum No. 8.

TODD, D.K. (1959). Groundwater Hydrology, 336 pages.

TOMSETT, J.E. (1969). Average Monthly and Annual Rainfall Maps of East Africa: E.A.M.D. Technical Memorondum No. 14.

UNITED NATIONS DEVELOPMENT PROGRAM AND WORLD METEOROLOGICAL ORGANISATION (1968). Hydrometeorological Survey of the Catchments of Lakes Victoria, Kyoga and Albert, 83 pages, Government Printer, Nairobi.

UNITED NATICNS EDUCATIONAL SCIENTIFIC AND CULTURAL ORGANISATICN (UNESCO) (1971). Ecological Survey of the Middle and Lower Nzoia River in Western Kenya: UNESCO Field Science Office for Africa, Nairobi.

UNITED STATES BOARD ON GEOGRAPHIC NAMES (1964). Kenya Official Standard Names Gazeteer, No. 78, Published by U.N.B.G.N. Office of Geography, Department of Interior, Washington.

VISTELIUS, A.B. (1960). The Skew Frequency Distributions and Fundamental Law of the Geochemical Processes: Journal of Geology, Volume 68, No. 1, pp. 1-22.

WALSH, J. (1969). Mineral and Thermal Waters of Kenya: XXIII International Geological Congress, Volume 19, pp. 105-110.

WARD, R.C. (1967). Principles of Hydrology, McGraw Hill, 403 pp.

WATER DEVELCPMENT DEPARTMENT (-). Superitending Hydrologist's Report 1953-1971, (Unpublished Reports of Water Development Department).

WATTERS (-) Fontran Programming, Heinemann.

WAYLAND, E.J., BRASNETT, N.V., BISSET, C.B., and MARTIN, W.S. (1938). Soil Erosion and Water Supplies in Uganda: Geological Survey of Uganda, Memoir No. IV, 89 pp. Government Printer, Entebbe.

WHISTON (-) Athi Basin: Unpublished Paper, Water Department, Kenya.

WILLIAMS, L.A.J. (1970). The Volcanoes of the Gregory Rift Valley, East Africa: Reprint from Bulletin Volcanoloque, Tome, XXXIV-2, pp. 439-465.

WORLD HEALTH ORGANISATION (1971). International Standards for Drinking Water, 3rd Edition, 1971.

YASUMISTU UZUMASHA (1965). Chemical Investigations of Hot Springs in Japan.