INTERAFRICAN COMMITTEE FOR HYDRAULIC STUDIES

OUAGADOUGOU
UPPER VOLTA

SAVANNA REGIONAL WATER RESOURCES AND LAND USE

SAVANNA RESOURCES

VOLUME 1
REPORT

COMITE INTERAFRICAIN D'ETUDES HYDRAULIQUES

CIEH-USAID
Grant Agreements
625-11-120-712
and 698-0415

TAMS
ADG
345 Park Ave.
New York

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This SAVANNA RESOURCES Study consists of 4 Volumes:

VOLUME 1. REPORT

VOLUME 2. MAPFOLIO

VOLUME 3. APPENDICES

VOLUME 4. STUDY PROPOSALS

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INTRODUCTION

PURPOSE AND SCOPE

The studies which are presented in this report, and the accompanying mapfolio and appendices, are an initial step toward the design of an action program for water development in the Savanna Region of West and Central Africa. They provide a synthesis of existing information on Savanna natural resources and are intended to serve as a basis for subsequent integrated planning efforts at CIEH (Comitè Interafricain d'Etudes Hydrauliques*).

Carried out at CIEH in Ouagadougou as part of the "Savanna Regional Water Resources and Land Use Project", these studies were funded under Grant Agreements 625-11-120-712 and 698-0415 between USAID (United States Agency for International Development) and CIEH.

In the action program studies, scheduled to be carried out later, assessments must be made of the existing use of water and land as well as the regional water requirements of the Savanna. The subsequent step, to identify and design suitable projects for an overall program for rational development of the Savanna's water resources, will then be possible.

CONTENTS OF REPORT

The findings of these studies are presented in four volumes.

Volume 1 - Savanna Resources - Report, is a written review and analysis of available information on the land, water and human resources of the Savanna Region. The references consulted during this work are listed at the end of Volume 1. All references are available for consultation at CIEH's Documentation Center in Ouagadougou, Upper Volta.

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Volume 2 - Savanna Resources - Mapfolio, contains a map series supporting the report findings. The maps are at scale 1 : 5,000,000. At CIEH all these maps are also available at the scale 1 : 2,500,000 for further planning purposes.

Volume 3 - Savanna Resources - Appendices, presents detailed supporting material for Volume 1.

Volume 4 - Savanna Resources - Study Proposals, lists a series of proposals for further study. These study proposals were specified in order to eliminate certain gaps in scientific information identified in the course of the synthesis work carried out for Volume 1.

STUDY ORGANIZATION

These studies were undertaken by a multidisciplinary professional team provided to CIEH by TAMS Agricultural Development Group of New York, U.S.A., under U. S. Agency for International Development Contract AID-afr-C-1041. This team was supplemented by direct assignments of professional and support staff from CIEH. For certain elements of the work, special consultants, consulting firms and organizations were engaged. These included consultants in agroclimatology, water balance studies, hydrology, hydrogeology, and land resources.

The organization of the Savanna study staff was as shown on the accompanying figure. The studies were undertaken in the period January 1976 to January 1978, and all findings reported refer to conditions at that time unless otherwise stated.

CIEH SAVANNA REGIONAL WATER RESOURCES
AND LAND USE PROJECT
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ASSISTANCE AND COOPERATION OF OTHER ORGANIZATIONS

Several agencies were closely associated with CIEH in support of the work and offered particularly valuable assistance. These are the Land and Water Development Division of FAO, Rome, Italy, BURGEAP and ORSTOM in Paris, and BRGM in Orleans, France. (List of Abbreviations on page 7.)

Many governmental and nongovernmental agencies in West Africa contributed substantially to the work. They included:

Benin	- Ministère de l'Equipement
Cameroon	- Ministère de l'Agriculture - Ministère des Mines et de l'Energie - ONARES, ORSTOM, SNEC
Central African Empire	- Ministère de l'Agriculture, des Forêts et Chasse - Ministère du Développement - ENERCA, ORSTOM
Chad	- Ministère de l'Aménagement du Territoire et de l'Habitat - Ministère du Plan - CBLT, Institut National des Sciences Humaines, ONAREST, ORSTOM, SODELAC, Université du Chad
Gambia	- Ministry of Agriculture and National Resources - Ministry of Economic Planning

Ghana	- Ministry of Agriculture - Ministry of Lands and Natural Resources - Ministry of Works - FAO Regional Office - Ghana Institute of Engineers - Volta River Authority
Ivory Coast	- Ministère de l'Agriculture - Ministère du Plan - Ministère des Travaux Publics et de Transports - Forexi, AVB, BNETD, ORSTOM, SODEMI, Université d'Abidjan
Mali	- Ministère du Développement Industriel, de l'Hydraulique et du Tourisme - Ministère du Plan - Energie Mali, IRAT, ORSTOM
Mauritania	- Ministère de l'Equipement - SONELEC - FAO
Niger	- Ministère du Développement - Ministère de l'Economie Rurale - Ministère des Mines et de l'Hydraulique - Centre Nigerien de Recherches en Sciences Humaines, CFN, CTFT, ENA, IEMVT, OFEDES, ORSTOM, OUA

Senegal
- Ministère du Développement Rural
- Ministère des Travaux Publics
- ASECNA, BRGM-Dakar, Centre de la Recherche Agricole de Bambey, CTFT, EBAD, IDEP, IFAN, OMVS, ORSTOM, SAED

Togo
- Ministère des Mines, de l'Energie et des Ressources Hydrauliques
- Ministère du Plan
- ORSTOM

Upper Volta
- Ministère du Développement Rural
- Ministère du Plan
- AVV, CILSS, Liptako-Gourma, Programme de la Lutte contre l'Onchocercose

Valuable support, particularly in West Africa, was provided by missions of the United States Agency for International Development, Ministère de la Coopération (France), FED (Belgium), and the Overseas Development Ministry (United Kingdom).

In the United States, important information for the Human Resources Study was provided by the World Bank, the U.N. Population Division, G.E. Tempo, The Population Institute, USAID, and the U.S. Bureau of the Census. The OECD and The Club des Amis du Sahel in France, were also helpful.

Without the assistance and cooperation of many persons associated with all the above agencies, these studies would not have been possible. Their support is hereby gratefully acknowledged.

List of Abbreviations

ASECNA	=	Agence pour la Sécurité de la Navigation Aérienne en Afrique et à Madagascar
AVB	=	Autorité pour l'Aménagement de la Vallée du Bandama
AVV	=	Autorité des Aménagements des Vallées des Voltas
BNETD	=	Bureau National d'Etudes Techniques et de Développement
BRGM	=	Bureau de Recherches Géologiques et Minières
BURGEAP	=	Bureau d'Etudes de Géologie Appliquée
CBLT	=	Commission du Bassin du Lac Tchad
CFN	=	Commission du Fleuve Niger
CIEH	=	Comité Interafricain d'Etudes Hydrauliques
CILSS	=	Comité Permanent Interétats de Lutte contre la Sécheresse dans le Sahel
CTFT	=	Centre Technique Forestier Tropical
EBAD	=	Ecole des Bibliothécaires, des Archivistes, et des Documentalistes
ENA	=	Ecole Nationale d'Administration
ENERCA	=	Energie Centrafricain
FAC	=	Fonds d'Aide et de Coopération
FAO	=	Food and Agriculture Organization of the United Nations
FED	=	Fonds Européen de Développement
IDEP	=	Institut de Développement Economique et de la Planification
IEMVT	=	Institut d'Elevage et de Médecine Vétérinaire des Pays Tropicaux
IFAN	=	Institut Fondamental d'Afrique Noire
OAU	=	Organization of African Unity
OCDE	=	Organisation de la Coopération et du Développement Economique
OECD	=	Organization for Economic Cooperation and Development
OFEDES	=	Office de Développement de l'Energie Solaire
OMVS	=	Organisation pour la Mise en Valeur du Fleuve Sénégal
ONARES	=	Office National de la Recherche Scientifique et Technique
ONAREST	=	Office National de la Recherche Scientifique et Technique
ORSTOM	=	Office de la Recherche Scientifique et Technique d'Outre-Mer

List of Abbreviations (Cont'd)

SAED	=	Société d'Aménagement et d'Exploitation des Terres du Delta
SNEC	=	Société Nationale de l'Electricité
SODELAC	=	Société de Développement du Lac Tchad
SODEMI	=	Société pour le Développement Minier de la Côte d'Ivoire
SONELEC	=	Société Nationale de l'Electricité
USAID	=	United States Agency for International Development

CHAPTER 1

SAVANNA REGION

1.1 INTRODUCTION

The Savanna Region of West and Central Africa covering an area of about 4.5 million square kilometers, extends in a broad band between the Sahara desert and the tropical rain forest from the Atlantic Ocean in the west to the Sudan in the east (Fig. 1-1.)

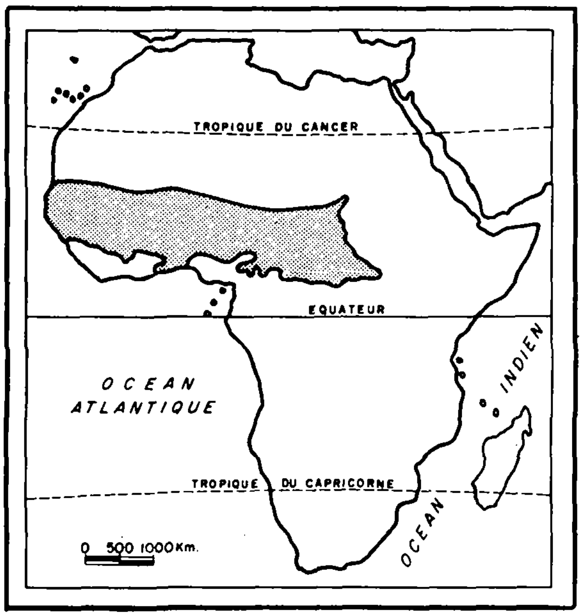

Fig. 1-1. The West and Central African Savanna Region in Africa.

1.2 DEFINITION OF REGION

According to Lanjouw (1936) the term savanna was first used in 1535 by Oviédo to describe the Llanos of Venezuela: "the savannas are the plains of northern South America and the Antilles covered with drought resistant grasses and bushes with some trees or shrubs". In tropical Africa, the term savanna has been applied to vegetative formations resembling those of South America.

Various hypotheses exist concerning the origin and evolution of the savanna. Most early authors and a few later ones considered the savanna to be of climatic origin (Goulissachvili, 1963). Some regard the savanna as an area of soils too poor to support forest (Beard, 1963). Others, such as Aubreville (1949) and Walter (1963), consider the savanna a direct result of human activity. Still another hypothesis exists, that a savanna results from paleoclimatic change (Schnell, 1971).

These genetic considerations do not provide for an unambiguous definition of the Savanna Region. Definitions based on actual observations are mostly given in terms of the savanna vegetation, but various points of view exist. At its 1956 conference in Yangambi, the Scientific Council for Africa South of the Sahara tried to reconcile the various definitions. However, numerous other definitions have since been put forth depending largely upon the authors' field of interest. (see also Hills, 1965).

The forester's approach is seen in the work of Vigne (1936), Sillans (1958), Keay (1959), and Taylor (1960) who based their descriptions of various savanna communities mainly on trees and shrubs, mentioning grasses and herbs only incidentally. Another approach is shown in attempts of grassland ecologists, Beard and Brammer (1956), Rattray (1960), and Hall and Denik (1968) to consider the savanna simply as grasslands and thus to define the various vegetation units in terms of the constituent grass species. The work of botanists lies between the above extremes by using classifications incorporating more or less floristic detail (Adjanohoun 1964; Trochain, 1940).

More recently, Collins (1975) considers the savanna as one of the major ecosystems or biomes on the surface of the earth, but, again defines the system in terms of its vegetation "which is characteristically herbaceous with some woody species".

In most definitions, even those expressed in purely vegetative terms, there is a tendency to include climatological parameters, the common denominator being the concept of savanna as a tropical ecosystem characterized by distinct wet and dry periods during the year (Eyre, 1968).

An excellent contribution to the problem of delimiting the Savanna Region of West Africa is given by Swami (1973) in a map compilation showing the extent of the similarities and differences in the savanna boundaries as given by Shantz (1923), Church (1957), Molard (1956), Keay (1959), Philips (1959) and Rattray (1960).

A suitable definition for water resource planning should emphasize these semi-arid aspects of the savanna, in contrast to the year-round humidity of the equatorial rainforest in the south and the aridity of the Sahara desert ecosystem in the north. In this report, therefore, the northern boundary of the savanna area is taken to be the 250 mm isohyet, the fringe of the Sahara desert and the limit of dry land cultivation. The southern boundary is the limit of the rainforest as shown on the World A. & O. Navigational charts for Africa (see also Jones and Wild, 1975).

The dominant climatic factors prevalent in this semi-arid Savanna Region have pronounced gradients along a north-south axis. The West and Central African Savanna, therefore, is an elongated strip nearly parallel with the equator. The western boundary is the Atlantic Ocean. For the purpose of this report, its eastern boundary is determined by the location of CIEH's* eastern most observer state and is therefore the border with the Sudan. The Savanna Region as such extends through the horn of Africa around the Ethiopian Highlands to the Indian Ocean.

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* Interafrican Committee for Hydraulic Studies

1.3 AREAL EXTENT AND SUBDIVISION OF REGION

The total area of the West and Central African Savanna Region as defined above is 4,562,547 km^2 or about 25% of the total 18 million km^2 savanna covering the surface of the earth (Budowski, 1956). It is a strip of territory some 4,500 km long and averaging about 1,000 km in width. The size of the area is about equal to 60% of the area of the continental United States.

Seventeen countries are included in this region, wholly or in part (see Map 1-1). Half of the region is taken up by the four states Nigeria, Central African Empire, Chad and Mali. Five other countries are completely in the Savanna Region: Upper Volta, Senegal, Togo, Guinea Bissau, and the Gambia.

An overview of the nations that constitute the Savanna Region, presented in Table 1-1, includes the total area of each country in the savanna, the percentage which this area takes up of the whole savanna, and the percentage of the total area of the country lying within the savanna.

Details as to the size of the various river basins that make up the Savanna Region are presented in Chapter 4.

1.4 MAPPING

The West and Central African Savanna Region is covered by numerous maps and map series of varying scale. Major small scale topographic maps, all of which are included in CIEH's map collection, are listed in Table 1-2.

Other important maps are contained in atlases available at CIEH. Several of these maps form a valuable supplement to those presented in Volume 2 of this report when considering the integrated Savanna resource base for

Table 1-1 POLITICAL SUBDIVISIONS OF THE SAVANNA REGION

COUNTRY	SAVANNA AREA (Km^2)	% OF TOTAL SAVANNA AREA	% OF COUNTRY IN SAVANNA
NIGERIA	780,402	17.1	84.4
CENTRAL AFRICAN EMPIRE	612,182	13.4	97.7
CHAD	560,062	12.3	43.6
MALI	526,561	11.5	43.7
NIGER	349,729	7.7	27.6
UPPER VOLTA	274,539	6.0	100.0
CAMEROON	254,393	5.6	53.6
GUINEA	233,631	5.1	95.0
SENEGAL	196,839	4.3	100.0
MAURITANIA	187,230	4.1	17.3
IVORY COAST	175,792	3.9	54.3
GHANA	170,463	3.7	71.5
BENIN	109,407	2.4	94.5
TOGO	56,980	1.2	100.0
GUINEA BISSAU	36,260	0.8	100.0
SIERRA LEONE	27,717	0.6	38.4
GAMBIA	10,360	0.2	100.0
TOTAL	4,562,547	100.0	-

Table 1-2 TOPOGRAPHIC MAPS OF THE SAVANNA REGION

Scale	Title	Publisher
2,000,000	Africa	Defense Mapping Agency (USA)
1,000,000	Carte internationale du monde, Afrique	Institut Géographique National (France)
1,000,000	World A. & O. Navigational Charts	Defense Mapping Agency
500,000	Cartes de l'Afrique de l'Ouest	Institut Géographique National
500,000	Cartes de l'Afrique Centrale	Institut Géographique National
250,000	Joint Operations Graphic	Army Map Service (USA)
200,000	Cartes topographiques	Institut Géographique National

the purpose of water resource planning. Key regional atlases were published by Organization of African Unity (1968), Davies (1973), Thompson (1965), Jeune Afrique (1973) and World Health Organization (1973). National atlases are available at CIEH for such countries as Cameroon (Institut de Recherches Scientifiques du Cameroun, 1957), Ivory Coast (Ivory Coast Ministry of Plan, 1971), Chad (Institut National Tchadien pour les Sciences Humaines, 1972), Ghana (Ghana Survey Department, 1969), and Upper Volta (Jeune Afrique, 1975).

CHAPTER 2

CLIMATIC RESOURCES

2.1 INTRODUCTION

In this chapter the climatic elements of the West African Savanna including rainfall, solar radiation, temperature and evapotranspiration are analyzed in relation to agricultural development. The major climatic constraint limiting year-round crop production in the West African Savanna Region is water availability. Consequently, an analysis of the period during which water availability does not limit crop growth, i.e., the growing period, forms the basis for this agroclimatological assessment.

Distinct Bioclimatic Regions of the Savanna are identified and discussed using vegetation maps and the length of the growing period as a basis for delineation. The Bioclimatic Regions are evaluated in terms of potential agricultural production.

2.2 DEFINITIONS AND MATERIALS STUDIED

2.2.1 Definitions

The growing period is defined as a continuous period during the year when the precipitation is greater than half the evapotranspiration (0.5 Et), calculated by Penman's method, plus a number of days required to evaporate an assumed 100 mm of soil water storage after the end of the rains. Further, the growing period must exhibit a humid period, i.e., a period when there is more precipitation than there is evapotranspiration.

The humid period is required not only to meet the full evapotranspiration demands of crops at a complete surface vegetation cover, but also to replenish the soil moisture deficit of the soil profile. Areas that do not exhibit the humid period in their hydrological cycle cannot be considered as suitable for rainfed crop production under normal management. However, these areas may be considered as marginal for dry land farming or for rangeland grazing.

The rainy season is defined as a number of days between the onset of the rains and their termination.

The onset of rains is defined as the first ten-day period during the year when precipitation is equal to or greater than one-half of the evapotranspiration rate using Penman's method. The first rains of the season fall on soil which is air dry at the surface and has a large soil moisture deficit in the soil profile. These rains are variable in their distribution, and the amount that falls cannot be relied upon to support the growth of crops in the absence of soil water reserves. They may be sufficient to allow for seed-bed preparation. However, once the precipitation exceeds half of the evapotranspiration in a unit time such as a ten-day period, sufficient moisture is present to support the growth of germinating crops. Furthermore, evaporation and transpiration from cultivated land with a germinating or incomplete cover is much lower than the full rate of evapotranspiration, and during the initial stages of growth, the evapotranspiration approximates about half of Penman's Et (Kowal and Kassam, 1977.) Therefore, the amount of precipitation during the ten-day period that is equal to or greater than one-half of the Et can be considered as sufficient to provide water requirements for establishing crops even in the absence of substantial soil moisture reserves.

The termination of the rains, which is relatively abrupt in the Savanna region, triggers pronounced changes in the environment and in the physiological response of crops. The transpiration rate declines as crops mature. Although the rate of transpiration varies considerably with cultivars during this time, experimental evidence (Kowal and Kassam, 1977) suggests that crops start drawing appreciably on the soil water reserves during the period when the rains decline to a level equivalent to about half evapotranspiration.

The termination of rains is therefore defined as the last ten-day period of the season in which precipitation is less than 0.5 Et.

The growing period for most crops extends beyond the rainy season. To a lesser or greater extent, crops mature during the post rainy period on water reserves stored in the soil profile. However, the amount of soil moisture stored in the soil profile that is available to crops varies with the depth of the soil profile, the soil's physical characteristics, the rooting patterns of various crops, and other factors. Furthermore, changes in soil moisture reserves lead to changes in the soil water potential, thus affecting the degree to which soil water is available to crops and consequently affecting the evapotranspiration rates.

In order to avoid these difficulties and conform to the initial definition of the growing period as "a period during which water availability does not limit crop growth," the contribution of soil moisture reserves to the length of the growing period is estimated as the number of days that are required to evaporate 100 mm of free water at the full evapotranspiration rate (Et). The choice of 100 mm is based on the experimental evidence from Samaru (Kowal and Kassam, 1977), which suggests that shallow rooted crops such as maize and sorghum deplete soil moisture reserves at harvest time by an amount equivalent to about 100 mm of rainfall. The post rainy period is therefore defined as the number of days after the end of the rainy season required to evaporate 100 mm of water, plus any additional rain which may fall during that time.

2.2.2 Materials Studied

The assessment of climatic resources of the West African Savanna Region for rainfed crop production is based on long-term climatic records (30-50 years of rainfall records) of some 179 stations. The source of the records available at C.I.E.H. (Comitė Interafricain d'Etudes Hydrauliques*) includes:

1. FAO (Land and Water Development Division), Rome - 143 stations; full climatic records.
2. ASECNA - 104 stations; computer printouts of rainfall and evaporation. These were used for the evaluation of the growing period using graphical solution.
3. COCHEME & FRANQUIN (1967) - 30 stations; these were used for evaluation of the growing period using graphical solution.
4. KOWAL & KNABE (1972) - 20 stations in Nigeria.

The data are not homogenous with respect to the recording period and particularly with respect to Et estimates. In order to assure higher accuracy, all the available data was included in the analysis. Consequently, there is a considerable overlap, and some stations include data from several sources.

The analyses include the following information:

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1. The coded numbers for the onset and termination of the growing period and their distribution throughout the region. Coded dates here represent the following periods:

1 = 1-10 January

2 = 11-20 January

3 = 21-31 January

4 = 1-10 February, etc.

2. The length of the growing period (in days) and its relationship to annual rainfall and the Bioclimatic Regions of the West African Savanna.

3. The following average values of climatic elements during the growing period:

a) The average seasonal global radiation ($Cal\ cm^{-2}\ day^{-1}$);

b) The average seasonal maximum and minimum screen temperatures (^{o}C);

c) The average seasonal day and night temperatures (^{o}C);

d) The rainfall (annual and seasonal) in mm;

e) The evapotranspiration in mm per season.

2.3 RESULTS

2.3.1 Climatic Elements

The outstanding climatic feature of the West African Savanna is the distribution pattern of climatic elements with respect to the North-South axis of the region. This is presented graphically on Maps 2-1, 2-2 and 2-3. The isolines of all climatic elements tend to run nearly parallel and exhibit a regular North-South gradient of distribution. Consequently, the distribution and intensity of climatic elements in space and time lend themselves to being analyzed using simple linear regressions. This facilitates the interpretation of the baseline data and forms a convenient basis for the comparison of phys ological crop requirements with climatic characteristics.

2.3.1.1 Mean Annual Rainfall

The principal features of rainfall in the Savanna are its seasonal and annual variability. The atmosphere in the tropics holds a large volume of moisture, and rainstorms are generally intensive and yield large volumes of water. The rainstorms are rarely prolonged with an average duration of 1 to 2 hours. Heavy storms producing 5 cm or more, and reaching 20 cm/hr over short periods, are not uncommon. This results in rain splash, soil compaction, surface crusting and sheet or gully erosion. Consequently, a special management of the soil and terrain that is largely unknown under the gentler rainfall conditions of temperate and mediterranean climates, is necessary.

Like other climatic elements of the Savanna, the rainfall pattern shows a distinct and fairly regular North-South gradient in which the mean annual rainfall increases from the North southwards. The isohyets run nearly parallel in the northernmost half of the area (Map 2-1).

Kowal and Kassam (1977) have described the mean annual rainfall (Pa) in mm by a multiple regression equation with respect to its latitudinal (LA) and longitudinal (LO) position. The regression equation derived from the long term means at 52 stations within the region gives the following approximate relationship:

$$Pa = 2470 - 130.9\,(LA) - 8.6\,(LO)\ \text{mm}\quad (r^2 = 0.91)$$

This regression equation indicates the following:

(i) There is an average decrease in annual rainfall of 131 mm per degree latitude northwards, or 131/111 = 1.18 mm of rain per Km inland. This suggests that the distance from the sources of moisture is the dominant factor. The rain-bearing southerly airmass yields progressively less total rainfall inland. It is continually losing moisture in precipitation along its path northwards, and the duration of its influence decreases from south to north.

(ii) The isohyetal pattern described by the aforementioned equation results in an average decrease in rainfall of 8.6 mm per degree of change in longitude toward the east. Therefore, stations located at the same latitude exhibit equal day length variations but different annual rainfalls. For example, the 600 mm isohyet in West Senegal corresponds to a yearly variation of 100 minutes in daylength, whereas around Lake Chad, two degrees further south, it is 70 minutes.

(iii) The intercept of the regression line suggests that about 2,470 mm of rain per year would fall at the source of moisture if there were no other factors affecting precipitation.

The greater part of the region, extending north of the 1,300 mm isohyet, has a seasonal rainfall pattern characterized by a single peak (unimodal). Here the rains increase gradually in frequency and reach a maximum in August when the full effect of the inter-tropical convergence is felt. After this peak is reached there is a relatively rapid decline in rain followed by a termination of rains.

South of the 1,300 mm isohyet, there is a transitional zone with one or two annual rainfall peaks. The first peak occurs in June-July and the second peak in September, with August being relatively dry.

Significantly, the rainfall pattern with one peak characteristic has a far more reliable distribution than the two-peak rainfall pattern with crop water requirement than with a one-peak rainfall pattern.

Finally, an important aspect in the assessment of climatic resources for rainfed crop production is the relationship between the annual precipitation (Pa) and the length of the growing period (Ng). Using the available data of Pa and Ng, a regression analysis shows very high linear correlation ($r^2 = 0.968$) ($n = 201$) between the averages of annual precipitation and the averages of the length of the growing period (see Fig. 2-1).

The regression equation is: $Ng = 0.17\ Pa - 4.0$
It can be used to determine the length of the growing period using the more commonly available annual rainfall data in the region. This regression indicates that there is an average increase of 17 days in the growing season per 100 mm increase in the annual rainfall. It also shows that there is a zero growing period when the average annual rainfall is about 24 mm.

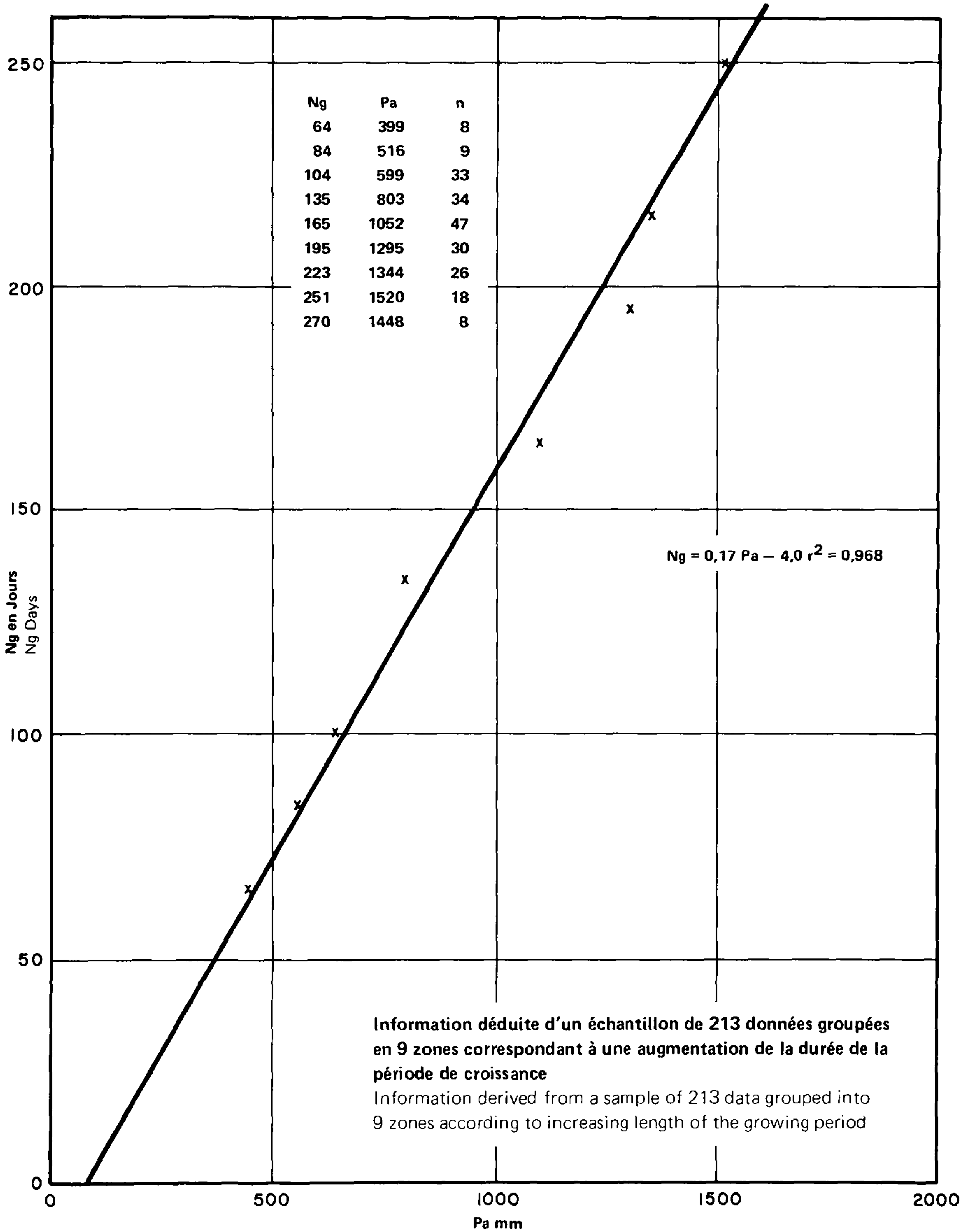
2.3.1.2 Onset of Rains

A reliable estimate of the start of the rainy season is very important in tropical agriculture. The start of rains coincides with the highest demand for labor and equipment, presenting a major constraint to management. In addition, the establishment of crops early in the season means higher yields, and there is a tendency in good farming to plant early. A reliable knowledge of the onset of the rains eliminates the risk of a poor crop establishment or crop failure where early planting is necessary.

The onset of the rains can be determined with adequate precision by regression analysis, relating coded dates of the start of the rains to such known parameters as latitude, longitude and annual rainfall.

RELATION ENTRE LA PRECIPITATION ANNUELLE MOYENNE (Pa) ET LA DUREE MOYENNE DE LA PERIODE DE CROISSANCE (Ng)

RELATIONSHIP BETWEEN THE AVERAGE ANNUAL PRECIPITATION (Pa) AND THE AVERAGE LENGTH OF THE GROWING PERIOD (Ng)



Ng	Pa	n
64	399	8
84	516	9
104	599	33
135	803	34
165	1052	47
195	1295	30
223	1344	26
251	1520	18
270	1448	8

$Ng = 0{,}17\ Pa - 4{,}0 \quad r^2 = 0{,}968$

Information déduite d'un échantillon de 213 données groupées en 9 zones correspondant à une augmentation de la durée de la période de croissance

Information derived from a sample of 213 data grouped into 9 zones according to increasing length of the growing period

Fig. 2-1

Here, the onset of the rains (Ps) was evaluated by grouping the length of the growing season (Ng) with the corresponding Pa and Ps values of individual stations into arbitrarily chosen intervals of 30 days. The average values of Ng, Pa and Ps in each 30-day interval group were then related by regression analysis.

The regression analysis between Pa and Ps, (Fig. 2-2) and between Ps and Ng shows a highly negative correlation of $r^2 = 0.933$ and $r^2 = 0.986$, respectively. This indicates that the onset of the rains occurs proportionately later in areas characterized by lower annual precipitation and shorter growing season.

The respective regression equations are:

$$Ps = 25.28 - 0.0107\ Pa$$

$$Ps = 25.15 - 0.0637\ Ng$$

The regression analysis indicates that the average onset of the rains in the southern parts of the Savanna (corresponding to the 1,550 mm rainfall isohyet or the 270-day growing period) occurs in early March. In the northern parts of the Savanna (corresponding to the 400 mm rainfall isohyet or the 64-day growing period), the rains begin during the middle of July. Thus, there is a difference of about 4 months in the start of the rains between the extreme southern and northern parts of the region (see Fig. 2-2).

2.3.1.3 Termination of Rains and the End of the Growing Season

The termination of the rains signals the approaching end of the growing season and is important for the planning of agricultural operations, e.g., lifting of groundnuts, incorporation of plant residues, land fallowing, etc. before the surface soil becomes too dry. The termination of the rains is abrupt and on the average occurs 30-40 days earlier than the end of the growing season. Crops which have not matured by the time the rains have ended have to rely partly or completely on residual soil moisture for yield formation and maturation. Photosensitive sorghums and millets form their yields and mature on residual soil moisture because they are susceptible to head mould and insect damage when they mature before the end of the rains. In cotton, the first boll-opening must occur as the rains are ending to avoid pest infestation and low quality lint. A large portion of the total yield in cotton is therefore formed on residual soil moisture. Crops such as groundnuts, cowpeas, maize and photoinsensitive Gero millet, when sown in time, do not generally rely on residual soil moisture for maturation in the Guinea Savanna areas. Where the rainy season is short, e.g., in parts of the Sudan Savanna or when sowing is late, these crops may rely on residual soil moisture for maturation. Gero millet is resistant to head mould, and maize cobs are protected against rain damage by husks. For good groundnut crops, maturation must occur as the rains are ending. If the yield is formed largely on the residual soil moisture, lifting of the crop becomes a problem.

An analysis of the end of the growing period is based on a similar technique to that described previously for the evaluation of the onset of the rains. The results show high positive correlations between the end of the growing period (Tg) and the Pa (see Fig. 2-2) or Ng. The r^2 values are 0.962 and 0.986, respectively. The respective regression equations are:

$$Tg = 0.00637\ Pa + 24.71$$

$$TG = 0.0373\ Ng + 24.87$$

The results indicate that the end of the growing period occurs about the middle of September in the northern parts of the Savanna, corresponding to the 400 mm rainfall isohyet or the 64-day growing period isoline. The growing period terminates early in December in areas corresponding to the 1,450 mm isohyet or the 270-day growing period isoline. Thus, there

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RELATIONSHIP BETWEEN THE AVERAGE ANNUAL PRECIPITATION (Pa), THE ONSET OF THE RAINS AND THE TERMINATION OF THE GROWING PERIOD

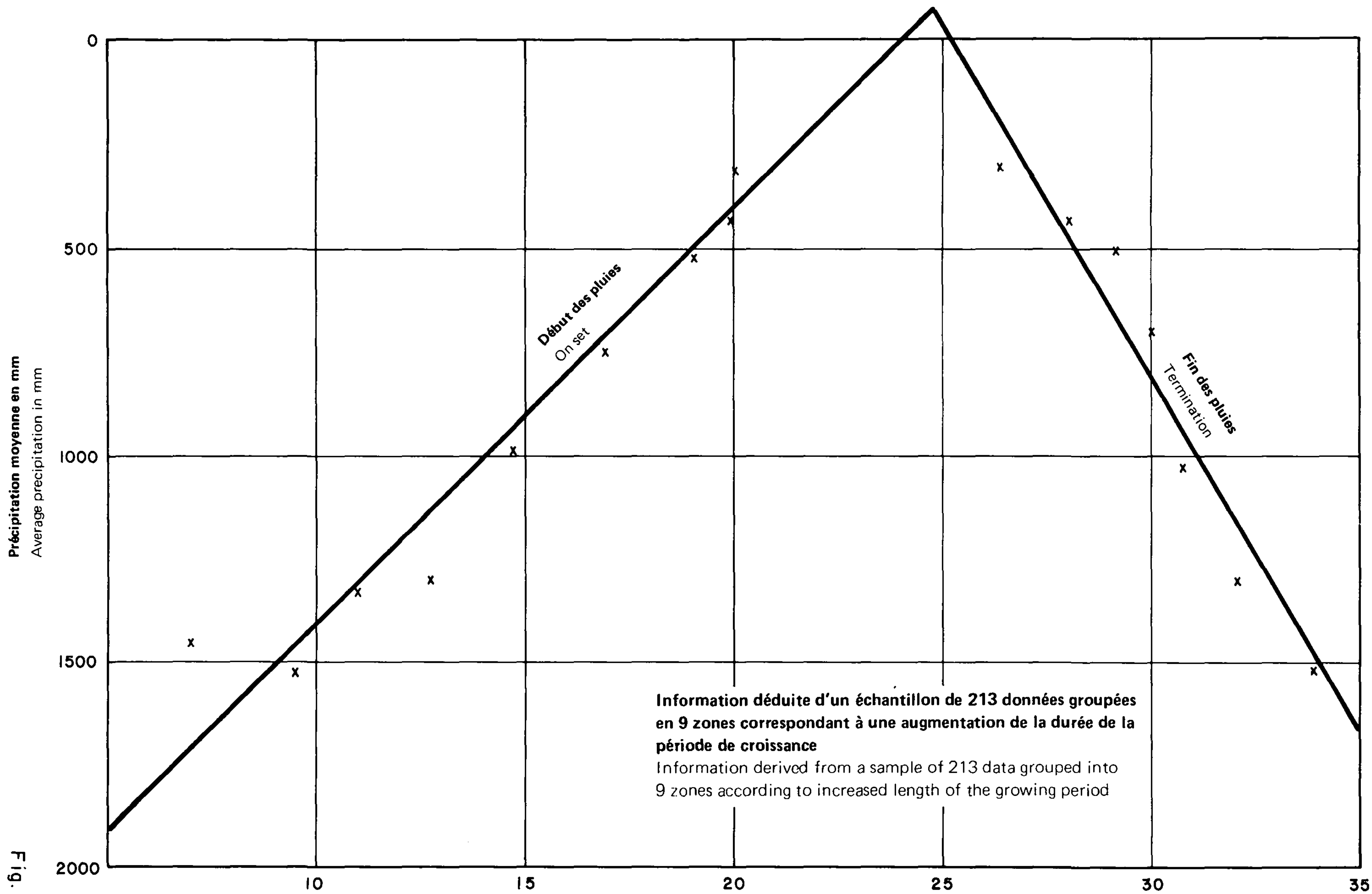


Fig. 2-2

is a difference of about 80 days in the end of the growing period between southern and northern parts of the Savanna (see Fig. 2-2).

The retreat of the rains and the termination of the growing period is a much faster process in comparison to the advance of the rains. According to Kowal and Kassam (1977) the average retreat of the rains is approximately 5.7 days per one degree of latitude, while the advance of the rains averages about 13.4 days per one degree of latitude.

2.3.1.4 Radiation and Thermal Regimes

Incoming solar radiation must be regarded as one of the most important climatic elements influencing crop production. Temperature, radiation and daylength largely determine crop adaptability and crop phenology (the developmental sequence of crop growth in relation to the calendar). Thus, a knowledge of the radiation and thermal regimes is essential for a rational selection of crops. When the climatic adaptability of crops is met (including phenological requirements), then quantitative information concerning the mean radiation during the growing season, the mean day time temperature and the mean seasonal temperature, forms a basis for the calculation of the upper limit of crop production.

An analysis of the data shows that with the increased length of the growing season there is a pronounced decrease in the incoming short-wave radiation (Rg), the mean screen temperature (TØ) and the day time temperature (Td). (See Fig. 2-3.)

The regression equation between the length of the growing season and the incoming short-wave radiation is:

$$Rg = 493 - 0.2932\ Ng\ \text{cal cm}^{-1}\ \text{day}^{-1}$$
$$(r^2 = 0.874)$$

The average daily radiation values range from about 482 cal cm^{-2} day^{-1} in the northern extremity of the Savanna, along the 400 mm isohyet or the 64-day growing period isoline, to about 414 cal cm^{-2} day in the southern parts of the Savanna, corresponding to the 1,600 mm isohyet or 270-day growing period isoline.

The differences in the radiation income between the extreme southern and northern parts of the region appear small, but they, in fact, reflect pronounced differences in illumination. Of particular interest to agriculture is the integrated radiation income received during the growing season. This appears to be positively correlated with the length of the growing season as shown in Fig. 2-4 and the following regression:

$$\text{Rg Seasonal} = (0.400\ \text{Ng} + 5.9) \times 10^{3}\ \text{cal cm}^{-2}\ \text{season}^{-1}$$
$$(r^{2} = 0.999)$$

The seasonal radiation (the total radiation during the growing period) ranges from about 31.5×10^{3} cal cm^{2} $season^{-1}$ at the 64-day growing period isoline to about 114×10^{3} cal cm^{2} $season^{-1}$ along the 270-day growing period isoline. These values are indicative of the potential productivity of the Savanna rainfed agriculture. Thus assuming a photosynthetic conversion efficiency of solar radiation into primary production as one per cent, the radiation income received at the 64 and 270-day growing period isolines corresponds to a potential yield of 7.88 tons and 28.5 tons of dry matter, respectively.

The thermal regime is characterized by steady temperatures which are negatively correlated with the length of the growing season; i.e., there is a slight decrease in temperature as the length of the growing season increases (see Fig. 2-5). The average seasonal screen temperature ranges from 28.6°C at the 64-day growing period isoline to 25.6°C at the 270-day isoline. The regression equation describing the distribution

RELATION ENTRE LA PERIODE DE CROISSANCE ET LES VALEURS MOYENNES QUOTIDIENNES DU RAYONNEMENT INCIDENT A FAIBLE LONGUEUR D'ONDE

RELATIONSHIP BETWEEN THE GROWING PERIOD AND THE AVERAGE DAILY VALUES OF INCOMING SHORT WAVE RADIATION

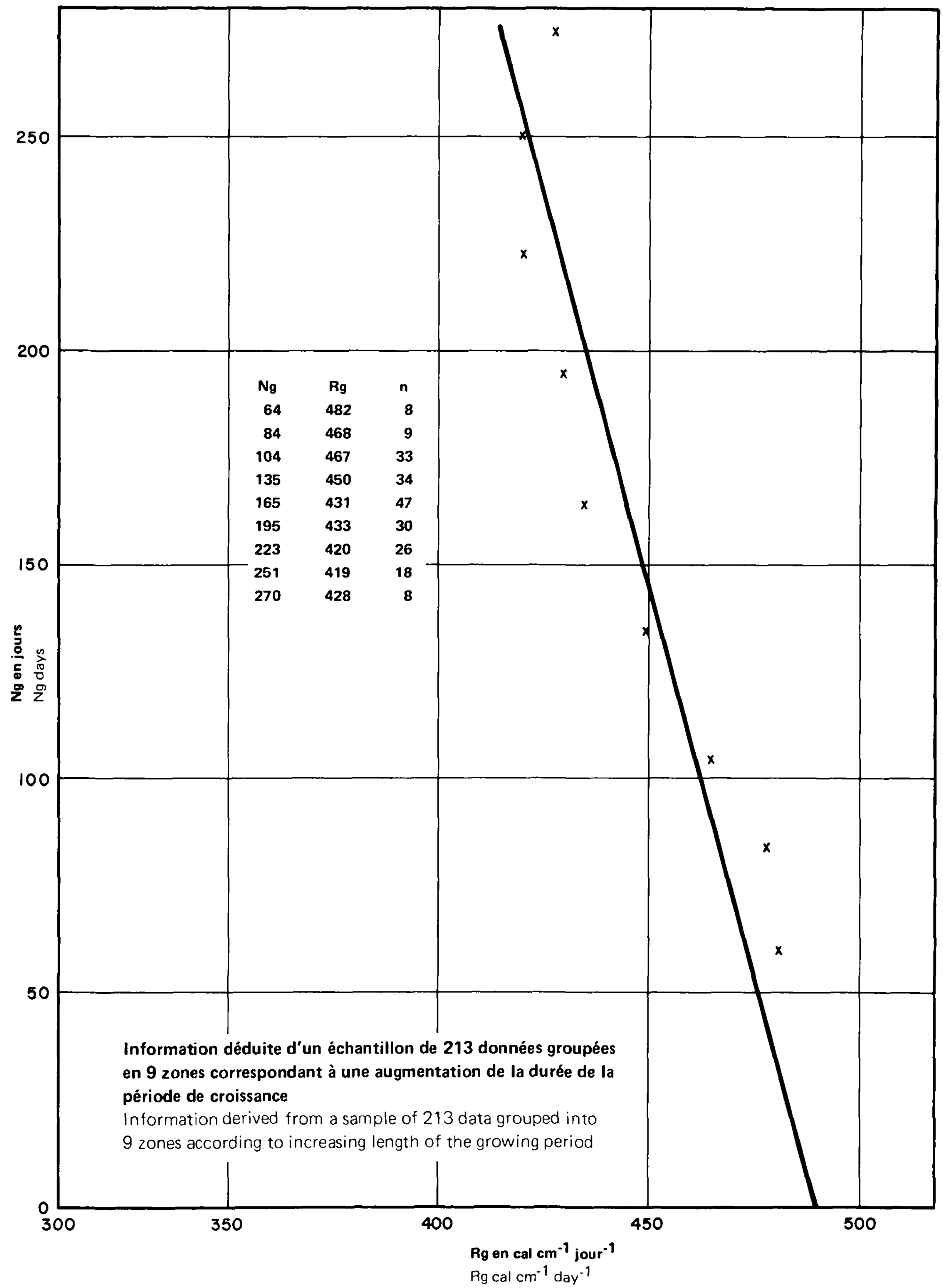
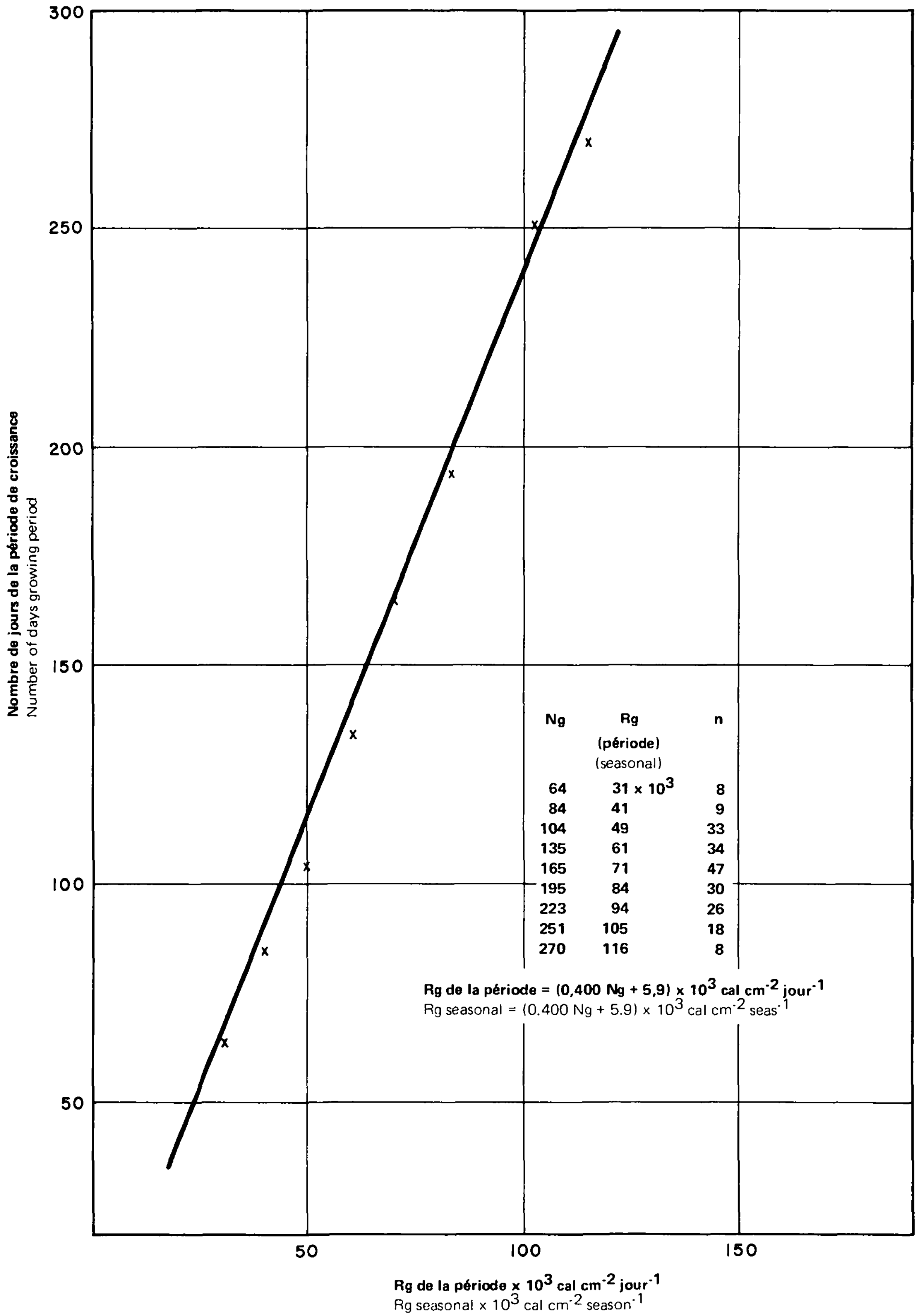


Fig. 2-3

RELATION ENTRE LA PERIODE DE CROISSANCE ET LA QUANTITE DE RAYONNEMENT INCIDENT RECU PENDANT CETTE PERIODE

RELATIONSHIP BETWEEN THE GROWING PERIOD AND THE AMOUNT OF INCOMING RADIATION RECEIVED DURING THE SEASON



Ng	Rg (période) (seasonal)	n
64	31×10^3	8
84	41	9
104	49	33
135	61	34
165	71	47
195	84	30
223	94	26
251	105	18
270	116	8

Rg de la période = (0,400 Ng + 5,9) x 10^3 cal cm^{-2} $jour^{-1}$

Rg seasonal = (0.400 Ng + 5.9) x 10^3 cal cm^{-2} $seas^{-1}$

Fig. 2-4

SOUS ABRIS MAXIMALES (TM) ET MINIMALES (Tm), LA TEMPERATURE DIURNE (Td) ET LA TEMPERATURE NOCTURNE (Tn)

RELATIONSHIP BETWEEN THE GROWING PERIOD AND THE MAXIMUM (TM) AND THE MINIMUM (Tm) SCREEN TEMPERATURES, DAY TIME TEMPERATURE (Td) AND NIGHT TIME TEMPERATURE (Tn)

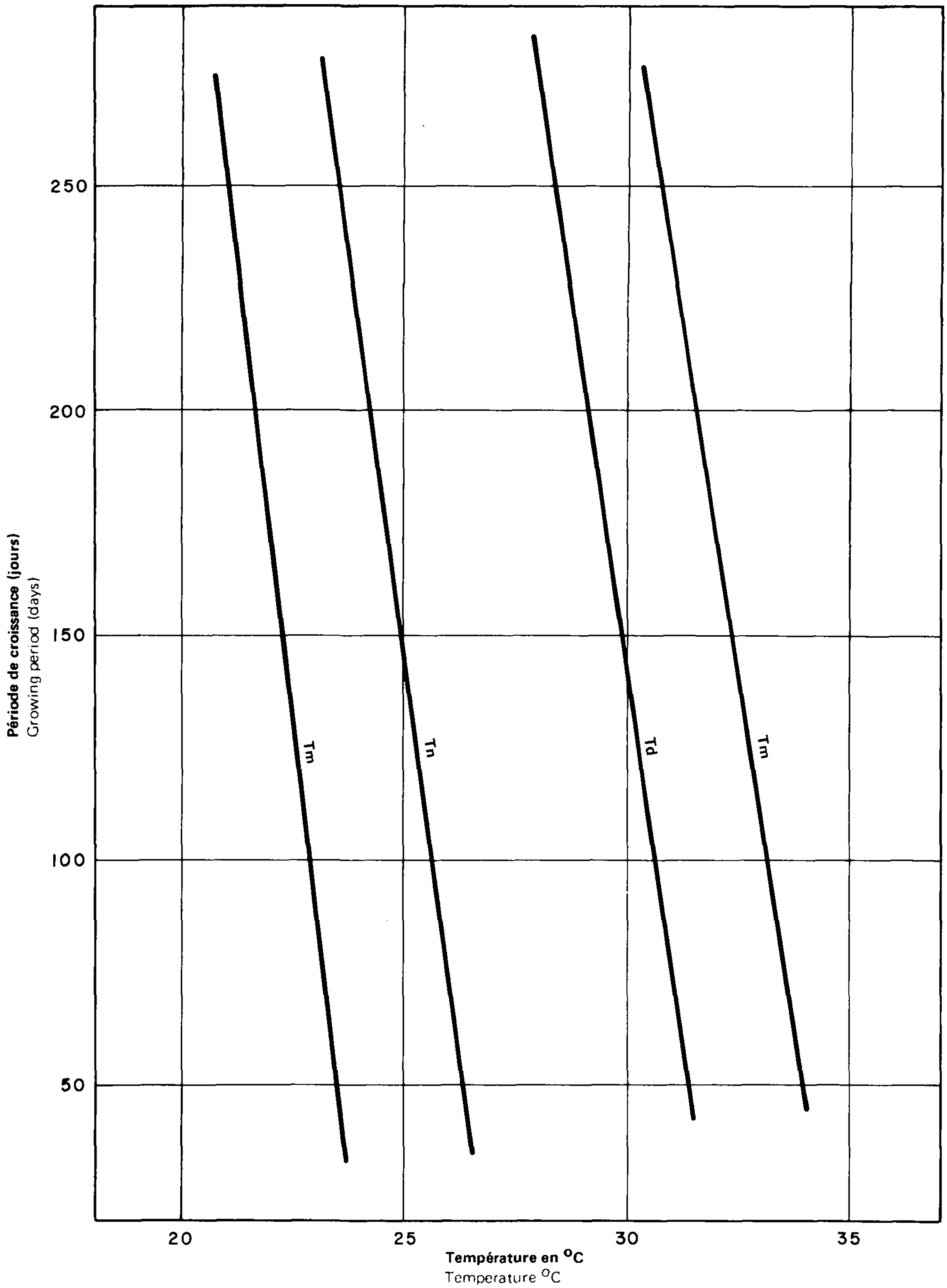


Fig. 2-5

of the average seasonal screen temperature of the region is:

$$T\emptyset = 29.5 - 0.01457\ Ng\ (r^2 = 0.89)$$

The diurnal range of temperatures during the growing season averages about 10°C. The regression equations describing the distribution of the mean maximum (TM) and the mean minimum (Tm) screen temperatures are:

$$TM = 34.89 - 0.01673\ Ng\ (r^2 = 0.76)$$

$$Tm = 24.16 - 0.01272\ Ng\ (r^2 = 0.98)$$

The range of TM and Tm temperatures corresponds to the following northern and southern parts of the Region:

- At the 64-day isoline of the growing season, TM = 33.8°C and Tm = 23.4°C.
- At the 270-day isoline of the growing season, TM = 30.4°C and Tm = 20.7°C.

The seasonal day time temperatures (Td) which directly determine the rate of photosynthesis, range from 31.2°C at the 64-day isoline to 28.0°C at the 270-day isoline.

The regression equation describing the average seasonal day time temperature in the region is:

$$Td = 32.18 - 0.01538\ Ng\ (r^2 = 0.81)$$

The above ranges of temperatures exclude the possible cultivation of such crops as wheat which are adapted to much lower temperatures.

The average night time temperatures are relatively high, ranging from 26°C at the 64-day growing period isoline to 23.2°C at the 270-day isoline. The regression equation describing the distribution of night time temperature in the region is:

$$Tn = 26.96 - 0.01394\ Ng\ (r^2 = 0.95)$$

These high night time temperatures are responsible for a considerable loss of the crop dry matter resulting from higher rates of respiration.

2.3.1.5 Evapotranspiration

There is a high negative correlation between the average daily potential evapotranspiration rate during the growing period (Etg/day) and the length of the growing period. The regression equation is:

$$Etg/day = 5.49 - 0.0062\ Ng\ mm\ day^{-1}\ (r^2 = 0.9)$$

The daily potential evapotranspiration rates within the Savanna range from about 3.8 mm per day at the 270-day growing period isoline to about 5.1 mm per day at the 64-day isoline. These rates are not too excessive. During the dry periods, however, the transpiration rates are much higher causing temporary crop water stress, closure of stomata and a consequent decrease in assimilation.

Of considerable interest is a comparison of the differences between the precipitation and evapotranspiration during the growing period. The Pg-Etg differences are negative in areas with the duration of the growing period of less than 110 days. For longer growing periods, the excess of precipitation over evapotranspiration demands increases rapidly with the increased length of the growing period reaching a maximum of about 420 mm when the duration of the growing period is about 200 days. Thereafter, the seasonal difference Pg-Etg is still positive but decreases with the increased length of the growing period (see Fig. 2-6).

The Pg-Egt differences indicate that conservation of soil moisture through agronomic practices such as tie-ridging, mulching, etc. is important or necessary in areas with growing periods of less than 110 days. During the dry years, rainfall may not be sufficient to replenish the assumed 100 mm soil moisture storage, thus shortening the growing period and resulting in yield reduction or crop failure. In contrast, areas with a growing period greater than 110 days have a sufficiently humid environment and do not require water conservation measures. Indeed, leaching and surface runoff increase with the increasing length of the growing period and

RELATION ENTRE L'EXCES DES PRECIPITATIONS PAR RAPPORT A LA DEMANDE EN EVAPOTRANSPIRATION PENDANT LA SAISON DE CROISSANCE (PG - ETG) ET LA DUREE DE LA PERIODE DE CROISSANCE

RELATIONSHIP BETWEEN THE EXCESS OF PRECIPITATION OVER EVAPOTRANSPIRATION DEMANDS DURING THE GROWING SEASON (PG - ETG) AND THE LENGTH OF THE GROWING PERIOD

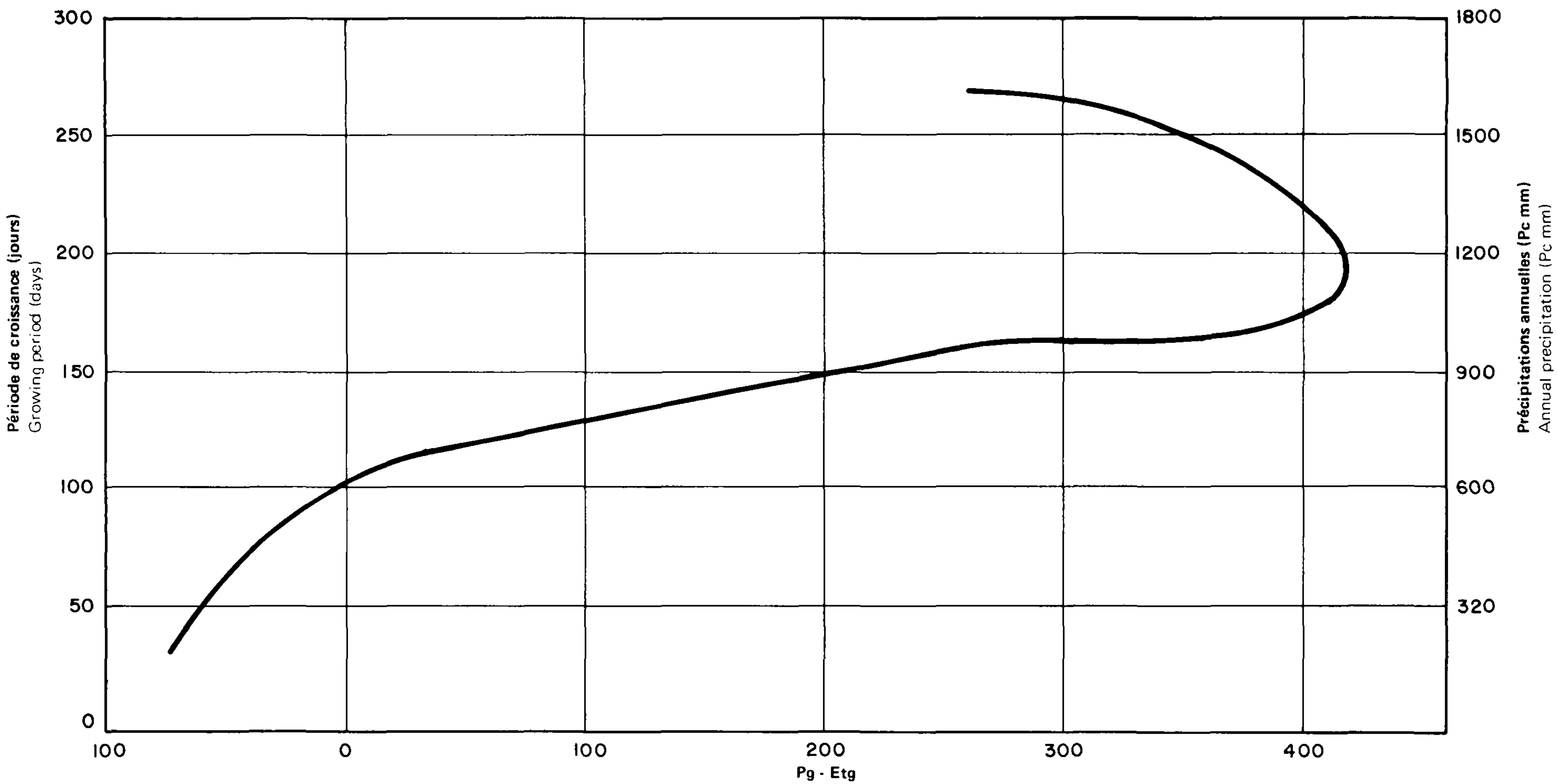


Fig. 2-6

become a significant factor in nutrient economy and soil conservation.

2.3.2 Climate and Rainfed Agriculture (Map 2-3)

The climatic resources of the West African Savanna are discussed below in relation to rainfed crop production.

2.3.2.1 Physical factors

The onset of the rains and termination of the growing period have been described in detail and their agronomic implication discussed. The relationships between the length of the growing period with the onset of rains, with the end of the growing season, and with annual precipitation have been described above. These relationships show on a broad scale, the exceptional regularity of the distribution patterns of climatic elements with respect to time and space and their amount and intensity.

In order to emphasize this important characteristic of the West African Savanna, a nomograph is presented which shows distribution gradients and identifies the growing season in time and space (see Map 2-3). The nomograph can be used to (1) identify the period of intense agricultural activity in the region; (2) correlate the length of the growing cycle of crops and their cultivars with the length of the growing season; (3) determine which crops can be grown in a particular area in relation to the levels of radiation and temperature; and (4) select the farming system, taking into account soil conditions, topography of the land, types of pests and diseases and social and economic considerations.

It is pertinent here to point out the very pronounced diversity of climatic characteristics of the region when the dry season is included. Temperature regimes and radiation are entirely different during the dry season, allowing for a wide range of crops to be grown under irrigation. High value crops, particularly those requiring high labor inputs such as tomatoes, onions, etc., have exceptionally good records of production under good irrigation management in the Savanna.

2.3.2.2 Biological Factors

There are three major considerations in relating the biological requirements of crops with the physical environment: 1) crop life, 2) photosynthetic crop requirements and 3) phenological crop requirements.

It is necessary to determine if the life of the crop can be completed within the growing period and if the crop can use as much of the favorable season as possible for yield-forming activities. Early or timely planting is essential for optimum yields, since higher temperatures and radiation income early in the season result in a rapid rate of growth and canopy formation. Crops having a life which does not correspond correctly with the length of the growing period, yield less, are often of poor quality, and may suffer from insect damage, diseases, poor nutrition and lack or excess of moisture.

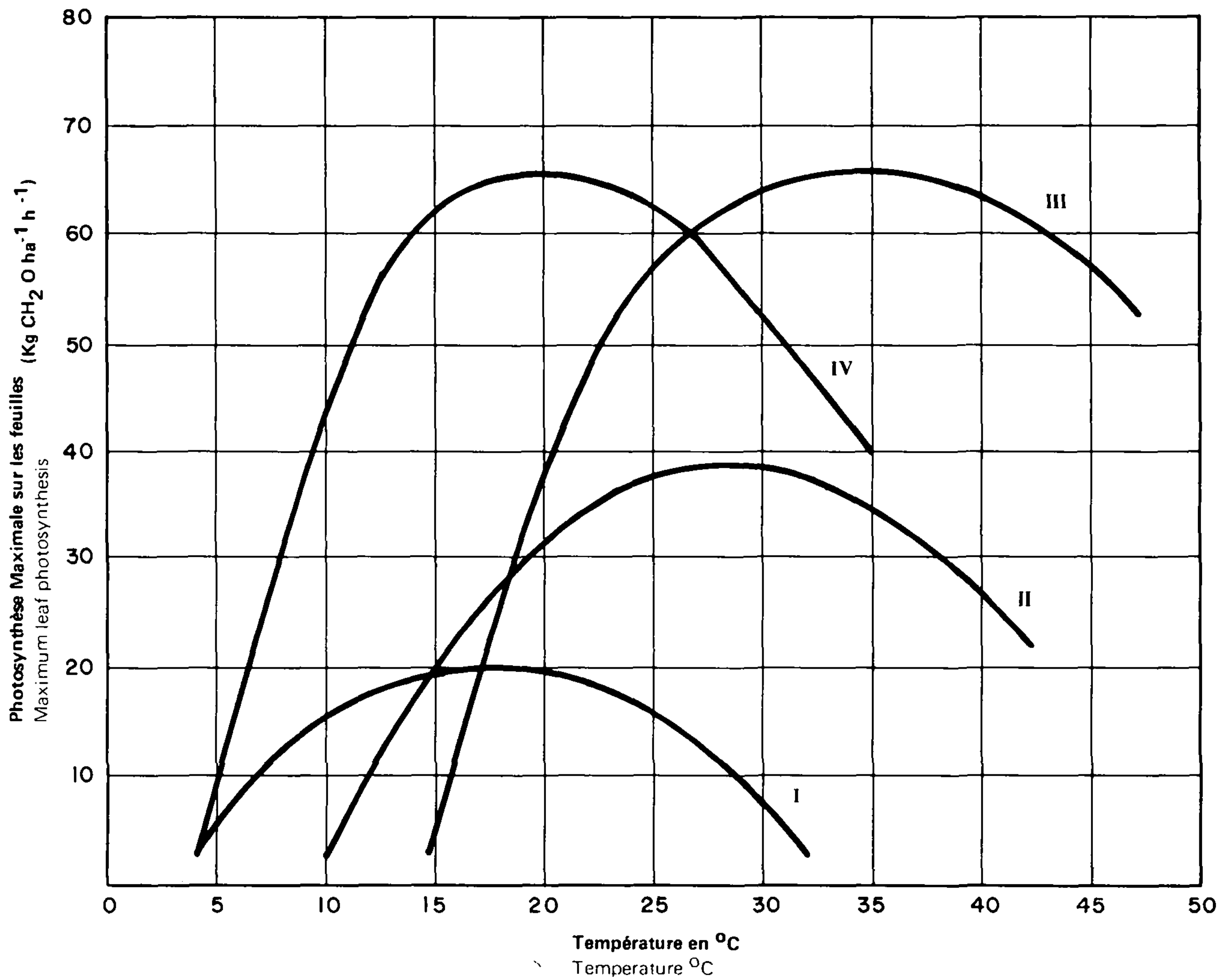
The physiological processes of crops operate at optimum rates only within a certain range of temperature and radiation. Consequently, it is possible to relate temperature and radiation regimes to crop productivity on the basis of the photosynthetic responses to temperature and radiation (Fig. 2-7, 2-8) and from the known effects of temperature on respiration. Since the photosynthetic response to temperature and radiation depends on the photosynthesis pathway, crop species can be classified according to their assimilation pathways and their photosynthesis capabilities.

The two major pathways of photosynthesis are:

(a) The C_3 assimilation pathway adapted to operate at an optimum rate under conditions of low temperature (15-20^{o}C) and characterized by relatively low rates of CO_2 exchange (in the range 15-30 mg CO_2 dm^{-2} h^{-1} with light saturation at 0.2 - 0.6 cal cm^{-2} min^{-1}); and

RELATION MOYENNE ENTRE LE TAUX MAXIMAL DE PHOTOSYNTHESE ET LA TEMPERATURE

AVERAGE RELATIONSHIP BETWEEN MAXIMUM PHOTOSYNTHESIS RATE AND TEMPERATURE



I Cultures à niveau d'assimilation C_3 adaptées à des températures basses
I Crops with C_3 assimilation pathway adapted to low temperatures

II Cultures à niveau d'assimilation C_3 adaptées à des températures élevées
II Crops with C_3 assimilation pathway adapted to high temperatures

III Cultures à niveau d'assimilation C_4 adaptées à des températures élevées
III Crops with C_4 assimilation pathway adapted to high temperatures

IV Cultures à niveau d'assimilation C_4 adaptées à des températures basses
IV Crops with C_4 assimilation pathway adapted to low temperatures

Fig. 2-7

RELATION ENTRE LA PHOTOSYNTHESE SUR LES FEUILLES, A UNE TEMPERATURE OPTIMALE, ET LE RAYONNEMENT DE PHOTOSYNTHESE ACTIF

RELATIONSHIP BETWEEN LEAF PHOTOSYNTHESIS RATE AT OPTIMUM TEMPERATURE AND PHOTOSYNTHETICALLY ACTIVE RADIATION

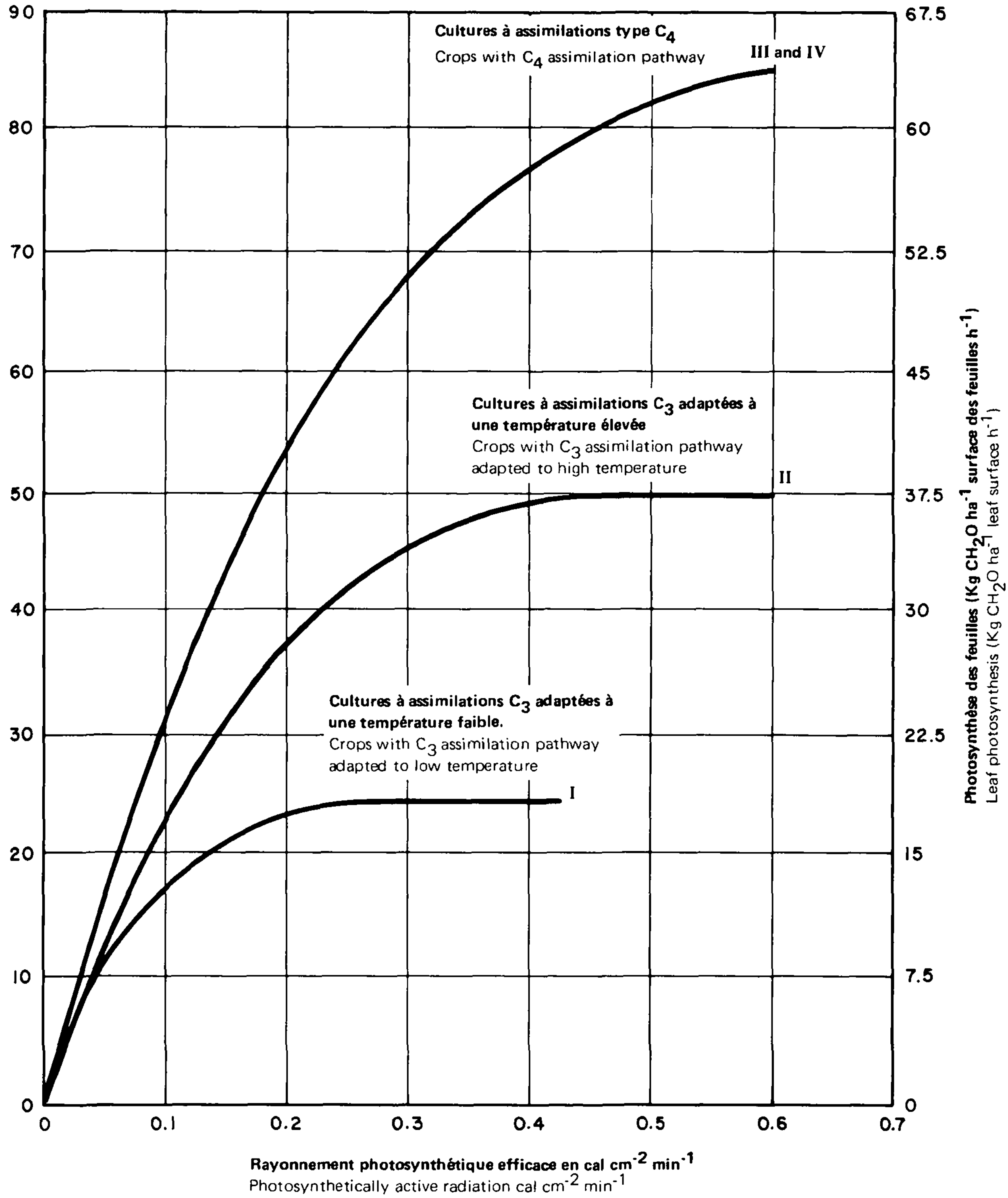


Fig. 2-8

(b) The C_4 assimilation pathway adapted to operate under conditions of high temperature (30-35°C) and characterized by high rates of CO_2 exchange (in the range 70-100 mg CO_2 dm^{-2} h^{-1} with light saturation at 1.0 - 1.4 cal cm^{-2} min^{-1}). However, breeding and selection have changed the temperature responses of some C_3 and C_4 species, and consequently there are C_3 species (e.g., cotton, groundnut) whose optimum temperature is in the medium to high range (25-30°C). Likewise, certain C_4 species (e.g., maize, sorghum) have been adapted to temperate and highland cultivars with optimum temperatures in the medium to low range (15-25°C).

In addition, there is another group of species which operates under xerophytic conditions with a C.A.M. metabolism. These CAM species are able to capture the light energy during the day time and fix CO_2 during the night. Consequently, they have very high water use efficiencies compared to the C_3 and C_4 species. There are only two species of agricultural importance in this group: the pineapple and sisal.

The physiological characteristics of the plant species described above are tabulated in Table 2-1 for a convenient reference.

The seasonal temperature and radiation regimes of the Savanna environment (range of day time temperature 31-28°C, and high density of radiation 480-410 cal cm^2 day^{-1} over relatively short day time) correspond well with the temperature and radiation requirements of C_4 species (30-35°C and radiation density of 1.0 - 1.4 cal cm^2 min^{-1}). The major C_4 assimilation pathway.

In addition, there is a large number of C_3 crops that are adapted to the medium-high range of temperatures (25-30°C). They can be expected to do well under environmental conditions of the Savanna. These include:

Table 2-1

ADAPTABILITY GROUPS OF CROPS ACCORDING TO SIMILARITIES IN ASSIMILATION PATHWAY AND EQUAL PHOTOSYNTHESIS ABILITY

Characteristics	Adapted to low temperature	Adapted to high temperature	Adapted to high temperature	Adapted to low temperature	Adapted to high temperature
Photosynthesis Pathway	C-3	C-3	C-4	C-4	CAM
Rate of photosynthesis at light saturation at optimum temperature mg CO_2 $dm^{-2}h^{-1}$ kg CH_2O $ha^{-1}h^{-1}$	 20 - 30 15 - 22.5	 45 - 55 33.75 - 41.25	 70 - 100 52.5 - 75	 70 - 100 52.5 - 75	 20 - 50 15 - 37.5
Optimum temp. (^{o}C) for maximum photosynthesis Cal cm^{-2} min^{-1}	15 - 20	25 - 30	30 - 35	15 - 30	25 - 35

Table 2-1 (Cont.)

ADAPTABILITY GROUPS OF CROPS ACCORDING TO SIMILARITIES IN ASSIMILATION PATHWAY AND EQUAL PHOTOSYNTHESIS ABILITY

Characteristics	Adapted to low temperature	Adapted to high temperature	Adapted to high temperature	Adapted to low temperature	Adapted to high temperature
Radiation intensity at maximum photosynthesis Cal cm^{-2} min^{-1}	0.2 - 0.6	0.3 - 0.8	1.0 - 1.4	1.0 - 1.4	0.6 - 1.4
Water use efficiency g water/g dm	350 - 900	400 - 600	150 - 350		50 - 200
Major crops	Wheat Potato Phaseolus bean (temperate and tropical high land cultivars)	Phaseolus bean (tropical cultivars) Soya bean Rice Cotton Cassava, Yams Sweet potatoes	Pennisetum millet* Maize* Sugar cane Sorghum* Tropical Cultivars	Sorghum Maize (temperate and tropical high land cultivars)	Sisal Pineapple

groundnuts, cotton, cowpeas, soyabeans, rice, sesamum, sunflower, tobacco, sweet-potato, jute, kenaf and roselle.

Most plants have innate biological clocks which determine the sequential developmental pattern of their life cycle, such as the length of vegetative growth, the time of flowering, seed or fruit setting, leaf shedding, etc. This developmental sequence of crop growth in relation to the calendar is referred to as crop phenology. The timing of phenological events is controlled by climatic factors, especially day length. Temperature may also determine whether a particular developmental process will begin or not (e.g., tuberization in potatoes), the time it will begin, the subsequent rate of development, and the time when the process stops. In some crops both day length and temperature may stimulate the plant and determine the time at which it will flower while in other crops only day length may stimulate the time of flowering.

Plants have an obligatory developmental pattern which must be followed if the photosynthetic assimilates are to be converted into economically useful yields of the right quantity and quality. It is therefore necessary to take into account the specific climatic requirements for yield quality in addition to those for photosynthesis, in order to define the climatic adaptability of specific crops. Different crops accumulate economic yield at different stages of their life cycles or use different proportions of their life span to form yield. Botanically they fall into three broad phenological classes.

Plants with determinate growth: yield produced in terminal or late formed inflorescence, as the last phase in the life of an annual crop, or of the annual shoots of a perennial crop. In these crops, no more leaves can be formed once the epical bud of the shoot has become reproductive and grain-filling is dependent on the last formed leaves. The dominant members of this class are cereals and plants such as bananas and plantains.

Plants with indeterminate growth: growth of stems, branch or shoot not limited or stopped by development of terminal bud. Yield is produced during a greater or smaller fraction of the life of the crop; in fruits and seeds borne on lateral inflorescenes which may be formed early in the crop's life. This class of crops includes tomatoes, cotton, tree crops grown for their fruit and the leguminous pulses and oil seeds.

Plants with determinate or indeterminate growth: yield accumulated throughout much or all of the period in which growth is possible, because it is accumulated in the vegetative parts of a sufficiently long-lived perennial or biennial crop. This group of crops includes fodder grasses and other forage and silage plants, sugarcane, root and tuber crops, sweet potatoes, yams, cassava and tobacco.

The following four tables (2-2, 2-3, 2-4, 2-5) present schematically those plant species important in the Savanna, along with photosynthesis pathway, growing period and phenological classification. Each table relates to one of the Savanna bioclimatic regions.

2.3.3 Bioclimatic Regions

The major ecological units in West Africa have been identified, described and referred to in terms of natural vegetation (for details see Swani, 1973). A quantitative and qualitative description of the major ecological units, in terms of various climatic elements and allowing for the recognition of Bioclimatic Regions of the West African Savanna has several important implications.

Firstly, it is useful for planning purposes to show relative climatic resources, identify various forms of constraints and assess potential productivity.

Secondly, choice of crops, adaptability of crop associations or introduction of farming systems can be more rationally and more conveniently dealt with if related to environmental conditions represented by a specific Bioclimate.

Kowal and Kassam (1977) have shown that vegetation zones can be used to describe a number of Bioclimatic Regions. In this report Bioclimatic Regions of West African Savanna are identified and described using vegetation maps and the length of the growing period.

In Table 2-6 the climatic characteristics of the various Bioclimatic Regions are summarized. Map 2-4 gives the geographic distribution of these Regions. Below each of the Regions is described in detail.

2.3.3.1 Sahel Bioclimate

This can best defined as a transitional zone from the desert to the savanna. The southern boundary of this region is difficult to define precisely since it changes according to the weather cycles and is affected by years which may be drier or wetter than the average. However, according to most vegetation maps, the southern boundary of the Sahel roughly corresponds to the 90-day growing period isoline or the 550 mm isohyet of annual rainfall.

From the agricultural point of view, the Sahel Bioclimate can be conveniently divided into two distinct subregions: the Northern and

TABLE 2-2 SOUTHERN SAHEL BIOCLIMATE AND CROP ADAPTABILITY

SOUTHERN SAHEL BIOCLIMATE CHARACTERISTICS	CROP ADAPTABILITY INVENTORY				
	PHOTOSYNTHESIS CHARACTERISTICS	DAYS TO MATURITY	PHENOLOGICAL CLASSIFICATION*		CROP SPECIES
			Photoperiodic sensitivity	Growth habit	
Growing period: 75-90 days Average daytime	<u>Photosynthesis pathway C-4</u>	50-90	Day neutral	Determinate	Echinochloa frumentacea (Japanese barnyard millet)
temperature: 30.8-31.0°C	Temperature response of photosynthesis: Optimum	70-90	Day neutral	Determinate	Setaria italica (Foxtail millet)
Average seasonal radiation:	temperature : 30-35°C Operative range: 15-45°C	70-90	Day neutral	Determinate	Eleusine coracana (Finger millet)
467-471 cal cm^{-2} day^{-1}	Radiation intensity at maximum photosynthesis:	70-90		Determinate	Panicum miliacum (Common millet)
Average daylength: 761-775 minutes	1.0-1.4 cal cm^{-2} min^{-1}	70-90	Day neutral	Determinate	Pennisetum typhoides (Pearl millet) (Gero)
Average intensity of radiation: 0.60-0.62 cal cm^{-2} min^{-1}	Maximum net rate of CO_2 exchange at light saturation: 70-100 mg $dm^{-2}h^{-1}$	90	Day neutral	Determinate	Digitaria exilis (Hungry rice)
Average annual	Maximum crop growth rate:	90	Day neutral	Determinate	Sorghum bicolor (Sorghum)
rainfall: 450-550 mm	30-60 g m^{-2} day^{-1}	80-90	Day neutral	Determinate	Zea mays (Maize) early cultivars

Table 2-2 (Cont.) SOUTHERN SAHEL BIOCLIMATE AND CROP ADAPTABILITY

SOUTHERN SAHEL BIOCLIMATE CHARACTERISTICS	CROP ADAPTABILITY INVENTORY				
	PHOTOSYNTHESIS CHARACTERISTICS	DAYS TO MATURITY	PHENOLOGICAL CLASSIFICATION*		CROP SPECIES
			Photoperiodic sensitivity	Growth habit	
	Water use efficiency: 150-300 g/g	50-90	Day neutral	Determinate or Indeterminate	Annual grasses and legumes harvested mainly in vegetative stage, e.g. Amaranthus spp. African spinach
	Photosynthesis pathway C-3 adapted to high temperature environment	90	Day neutral	Indeterminate	Arachis hypogaea (groundnut, early cultivars)
		90	Day neutral	Determinate	Vigna uniquiculata (cowpea, early cultivars)
	Temperature response of photosynthesis: Optimum temperature : 25-30°C Operative range: 10-35°C	90	Day neutral	Determinate	Glycine max (soyabean, early cultivars)
	Radiation intensity at maximum photosynthesis: 0.3-0.8 cal cm^{-2} min^{-1}	90	Day neutral	Determinate	Phaseolus vulgaris (French bean, early cultivars)
	Maximum net rate of CO_2 exchange at light saturation: 40-50 mg dm^{-2} h^{-1}	up to 90	Day neutral/ short day	Determinate or Indeterminate	Annual grasses and legumes harvested in vegatative stage.
	Maximum crop growth rate: 30-40 g m^{-2} day^{-1} Water use efficiency: 300-700 g/ς				

*All species listed have an annual life span.

Table 2-3

SUDAN BIOCLIMATE AND CROP ADAPTABILITY

B I O C L I M A T E   C H A R A C T E R I S T I C S

Growing period:	Average daytime temperature:	Average seasonal radiation:	Average daylength:	Average intensity of radiation:	Average annual rainfall:
90-165 days	29.6-30.8°C	445-467 cal cm^{-2} day^{-1}	756-760 minutes	0.59-0.61 cal cm^{-2} $min.^{-1}$	550-1,000 mm

CROP ADAPTABILITY INVENTORY

PHOTOSYNTHESIS CHARACTERISTICS	DAYS TO MATURITY	PHENOLOGICAL CLASSIFICATION			CROP SPECIES	REMARKS
		Photoperiodic sensitivity	Growth habit	Life span		
Photosynthesis pathway C-4	50-90	Day neutral	Determinate	Annual	Echinochloa frumentacea (Japanese barnyard millet)	
Temperature response of	70-90	Day neutral	Determinate	Annual	Setaria italica (Foxtail millet)	
photosynthesis:	70-90	Day neutral	Determinate	Annual	Eleusine coracana (Finger millet)	
Optimum temperature: 30-35°C	70-100	?	Determinate	Annual	Panicum maliacum (Common millet)	
Operative range : 15-45°C	75-100	Day neutral	Determinate	Annual	Pennisetum americana (Pearl millet)	Does not tolerate waterlogged conditions. Because of
Radiation intensity at maximum	120-165	Short day	-		short season cultivars (Gero)	heavy basal tillering more than 1 crop can be taken.
photosynthesis:					long season cultivars (Maiwa)	
1.0 - 1.4 cal cm^{-2} min^{-1}	90-130	?	Determinate	Annual	Digitaria elixis (Hungry rice)	
	90-110	Day neutral	Determinate	Annual	Sorghum bicolor (Sorghum)	Flowering must coincide with the end of the rains to
Maximum net rate of CO_2	120-130	Day neutral/	-		short season cultivars	obtain good quality grain.
exchange at light saturation:		short			medium season cultivars	
70 - 100 mg d m^{-2} h^{-1}	140-165	Short day	-		long season cultivars	
Maximum crop growth rate:	80-100	Day neutral	Determinate	Annual	Zea mays (Maize short/medium	Average experimental yields of maize are 2 to 3 times
30-60 g m^{-2} day^{-1}	110-130	Day neutral	-		season cultivars	greater than average yields of improved cultivars of
Water use efficiency:						either sorghum or millet. However, high soil
150 - 300 g/g						fertility is essential.
	90-165	Day neutral/	Determinate/	Annual	Annual grasses and legumes	
		short	Indeterminate		harvested in vegetative stage	
	90-110	Day neutral	Indeterminate	Annual	Arachis hypogaea (Groundnut)	Harvest must coincide with the end of the rains to
	90-120	Day neutral	Determinate	Annual	Vigna sinensis (Cowpea)	obtain good quality kernels -- control of Cerospora
	140-165	Short day	Determinate	Annual	short/long season cultivars	greatly increases yield. Well tolerates hot and
						relatively dry conditions of the Sudan Savanna.

Table 2-3 (Cont.)

	90-130	Day neutral	Determinate	Annual	Glycine max (Soyabean)	In Nigeria yields of over 3 tons/acre have been obtained.
	140-165	Short day	-		short/long season cultivars	
	90-140	Day neutral	Determinate	Annual	Phaseolus vulgaris (French beans)	
	160-165	Day short/neutr	Indeterminate		bush/pole cultivars	
	100-130	Day short/neutr	Determinate	Annual	Nicotiana tabacum (Tobacco)	
	100-120	Day short/neutr	Determinate	Annual	Helianthus annuus (Sunflower)	
	130-160	Variable			branched/long season cultivar	
					unbranched cultivar/early cultivar	
	100-130	Day short/long	Indeterminate	Annual	Sesamum indicum (Sesame)	
	140-165				unbranched/early/branched/long season cultivar	
	110-130	Day neutral	Determinate	Annual	Lycopersicum esculentum (Tomato)	Optimum yields and better quality obtained during the the dry season under irrigation due to lower night temperatures and lower incidence of stem and leaf diseases
	120-140	Day neutral	Determinate/ Indeterminate		upright tomato cultivar	
					potato leaf cultivar	
<u>Photosynthesis pathway C-3 adapted to high temperature environment</u>:	110-130	?	Determinate	Annual	Carthamus tinctorius (Safflower)	
	140-165				early/long season cultivars	
	110-130	Day neutral			Oryza sativa (Rice)	Upland cultivars must have adequate water supply and are usually grown in areas with high water table or river banks which are seasonally flooded - 3-4 tons per hectare can be expected when adequately fertilized.
Temperature response of photosynthesis: Optimum temperature: 25-30°C Operative range: 10-35°C	140-165	Short day	Determinate	Annual	early cultivar	
					long season cultivar	
Radiation intensity at maximum photosynthesis: 0.3-0.8 cal cm^{-2} min.$^{-1}$	110-130	Day short/long	Indeterminate	Annual	Lablab purpureus (Hyacinth bean)	
	140-165				early cultivar	
Maximum net rate of CO_2 exchange at light saturation:					long season cultivar	
40-50 mg dm^{-2} h^{-1}	120-150	Short day	Indeterminate	Annual	Hibiscus sabdarifa (Roselle)	Yields up to 3 tons/hectare of dry fibre under good management. The time of first boll opening must coincide with the end of the rains to obtain good quality lint.
	120-150	Short day	Indeterminate	Annual	Hibiscus cannabinus (Kenaf)	
Maximum crop growth rate:	130-140	Day short/neutr	Indeterminate	Annual	Gossypium hirsutum (Cotton)	
30-40 g m^{-2} day^{-1}	160+ marginally suitable				ocra leaf cotton cultivar	
					normal leaf cotton cultivar	
Water use efficiency: 300-700 g/g	130-160	?	Indeterminate	Annual	Ricinus Communis (Castor bean) early cultivar	
	90-165	Day neutral/ Short	Determinate Indeterminate	Annual	Annual grasses and legumes harvested in vegetative stage.	Range of vegetables and fodders.

Table 2-4

NORTHERN GUINEA BIOCLIMATE AND CROP ADAPTABILITY

NORTHERN GUINEA BIOCLIMATE CHARACTERISTICS	CROP ADAPTABILITY INVENTORY: PHOTOSYNTHESIS CHARACTERISTICS	DAYS TO MATURITY	Photoperiodic sensitivity	Growth habit	Life span	CROP SPECIES
	Photosynthesis pathway C-4					Crop species and cultivars listed under Sudan Bioclimate that have growing season greater than 110 days, but particularly:
	Temperature response of photosynthesis:					
	Optimum temperature: 30-35°C	70-100	Day neutral	Determinate	Annual	Pennisetum americana (Pearl millet)
	Operative range: 15-45°C	120-210	Short day			short season cultivars (Gero)
	Radiation intensity at maximum photosynthesis:					long season cultivars (Maiwa)
		90-110	Day neutral	Determinate	Annual	Sorghum bicolor (Sorghum)
	$1.0-1.4$ cal cm^{-2} min^{-1}	120-130	Day neutral/short			short season cultivars
	Maximum net rate of CO_2 exchange at light saturation:	140-210	Short day			medium season cultivars
						long season cultivars
		110-130	Day neutral	Determinate	Annual	Zea mays (Maize)
	70-100 mg d m^{-2} h^{-1}					Note: High reliability of rainfall and very favorable length of the growing season and thermal regimes result in a very high potential of biomass and grain production in this region.
	Maximum crop growth rate: 30-60 g m^{-2} day^{-1}					
	Water use efficiency: 150-300 g/g					Crop species and cultivars listed under Sudan Bioclimate that have growing season greater than 110 days but shorter than 210 days.
Growing period: 165-210 days						
Average daytime temperature: 29.0-29.6°C						
Average seasonal radiation: 431-444 cal cm^{-2} day^{-1}						

Table 2-4 (Cont.) NORTHERN GUINEA BIOCLIMATE AND CROP ADAPTABILITY

NORTHERN GUINEA BIOCLIMATE CHARACTERISTICS	CROP ADAPTABILITY INVENTORY: PHOTOSYNTHESIS CHARACTERISTICS	DAYS TO MATURITY	Photoperiodic sensitivity	Growth habit	Life span	CROP SPECIES
	Photosynthesis pathway C-3	105-135	Day neutral	Indeterminate	Annual	Arachis hypogaea (Groundnut)
	adapted to high temper-	90-120	Day neutral	Determinate		Vigna unquiculata (Cowpea)
	ature environment	140-180	Short day	Indeterminate	Annual	early cultivar
	Temperature response of	90-130	Day neutral	Determinate		late cultivar
	photosynthesis:	140-180	Short day	Indeterminate	Annual	Glycine max (Soyabean) early/late cultivars
	Optimum temperature: 25-30°	100-120	Day neutral	Determinate		
	Operative range: 10-35°	130-160	Short day	Determinate	Annual	Helianthus annus (Sunflower) early/late cultivars
	Radiation intensity at maxi-	140-180	Day short/long	Indeterminate	Annual	Sesamum indicum (Sesame)
	mum photosynthesis:	140-180		Determinate	Annual	Cartamus tinctorius (Safflower)
	0.3-0.8 cal cm^{-2} min^{-1}	140-180	Day neutral	Determinate	Annual	Oryza sativa (rice)
	Maximum net rate of CO_2	140-210	Day short/long	Indeterminate	Annual	Lab-Lab pupureus (Hyacinth bean)
	exchange at light			Indeterminate	Annual	Hibiscus sabdarifa (Roselle)
	saturation:	120-150	Short day	Indeterminate	Annual	Hibiscus cannabinus (Kenaf)
	40-50 mg dm^{-2} h^{-1}	120-150	Day short/neutral	Indeterminate	Annual	Gossypium hirsutum (Cotton)
	Maximum crop growth rate:	160-180				Ricinus communis (Castor bean)
	30-40 g m^{-2} day^{-1}	170-210	Short day	Indeterminate	Annual	Ipomoea batatas (Sweet potatoes)
Average daylength:	Water use efficiency:	150-210	Short day	Indeterminate	Annual	Manihot esculenta (Cassava)
742-760 minutes	150-300 g/g	180-210	Day short/neutral	-	-	Annual and perennial grasses and legumes harvested
		up to 210				in vegetative stage.
Average intensity of radiation:						
0.57-0.60 cal cm^{-2} min^{-1}						
Average rainfall:						
1000-1250 mm						

Table 2-5 SOUTHERN GUINEA BIOCLIMATE AND CROP ADAPTABILITY

BIOCLIMATE CHARACTERISTICS:			
	Growing period: 210-270 days (1)	Average daytime temperature: 28.0-29.0°C	Average seasonal radiation: 414-431 cal cm^{-2} day^{-1}
	Average daylength: 738-742 minutes	Average annual rainfall: 1250-1400/1600 mm	Average intensity of radiation: 0.56-0.58 cal cm^{-2} min^{-1}

CROP ADAPTABILITY INVENTORY

PHOTOSYNTHESIS CHARACTERISTICS	DAYS TO MATURITY	PHENOLOGICAL CLASSIFICATION			CROP SPECIES
		Photoperiodic sensitivity	Growth habit	Life span	
Photosynthesis pathway: C-4					
Temperature response of photosynthesis: Optimum	270	Day short/ neutral	Determinate	Annual/ Biennial	Saccarum officinarum (Sugar cane)
temperature: 30-35°C	210-240	Short day	Determinate	Annual	Sorghum bicolor (Sorghum)
Operative range: 15-45°C	210-240	Short day	Determinate	Annual	Pennisetum americana (Pearl millet)
Radiation intensity at maximum photosynthesis: 1.0-1.4 cal cm^{-2} min^{-1}					Crop species and cultivars listed under Sudan Bioclimate that match growing period of binominal distribution of rains (See 2)
Maximum net rate of CO_2 exchange at light saturation: 70-100 mg d $m^{-2}h^{-1}$					Alternatively, because of the prolonged growing season, the highest returns in terms of biomass production are achieved by growing crops that are harvested in vegetative stage.
Maximum crop growth rate: 30-60 gm^{-2} day^{-1}					
Water use efficiency: 150-300 g/g					

Table 2-5 (Cont.) SOUTHERN GUINEA BIOCLIMATE AND CROP ADAPTABILITY

BIOCLIMATE CHARACTERISTICS:	Growing period: 210-270 days (1)	Average daytime temperature: 28.0-29.0°C	Average seasonal radiation: 414-431 cal cm^{-2} day^{-1}
	Average daylength: 738-742 minutes	Average annual rainfall: 1250-1400/1600 mm	Average intensity of radiation: 0.56-0.58 cal cm^{-2} min^{-1}

Photosynthesis pathway : C-3 adapted to high temperature environment	210-270	Short day	Indeterminate	Annual	Manihot esculenta (Cassava)
Temperature response of photo-synthesis: Optimum	210-270	Variable	Indeterminate	Annual	Dioscorea alata (Yams)
temperature: 25-30°C Operative range: 10-35°C	minimum 240		Indeterminate	Perennial	Citrus sinensis (Sweet orange)
Radiation intensity at maximum photosynthesis: 0.3-0.8 cal cm^{-2} min^{-1}	minimum 240		Indeterminate	Perennial	Citrus limon (Lemon)
Maximum rate of CO_2 exchange at light saturation: 40-50 mg d m^{-2} h^{-1} Maximum crop growth rate: 30-40 g m^{-2} day^{-1} Water use efficiency: 300-700 g/g					Crop species and cultivars listed under Northern Guinea Savanna Bio-climate that match suitably the length of the growing period utilizing bimodal distribution of rains (See 2)
Photosynthesis pathway : C.A.M.					
Temperature response of photo-synthesis: Optimum temperature: 25-35°C Operative range: 10-45°C Radiation intensity at maximum photosynthesis: 0.6-1.4 cal cm^{-2} min^{-1} Maximum rate of CO_2 exchange at light saturation: 20-50 mg d m^{-2} h^{-1} Maximum crop growth rate: 20-30 g m^{-2} day^{-1} Water use efficiency: 50-200 g/g	270		Determinate	Biennial	Agave sisalana (Sisal)

TABLE 2-6

CLIMATIC CHARACTERISTICS OF THE BIOCLIMATIC REGIONS

Bioclimatic Region	(days)	Annual Rainfall (mm)	Radiation (cal $cm^{-2} day^{-1}$)	SEASONAL MEAN TEMPERATURE (°C)					Potential Dry Matter Production	VEGETATION CHARACTERISTICS	
				Day Time	Average	Night Time	Maximum Range	Minimum Range		Grassland	Woody
Northern Sahel	0 - 75	0 - 450	470 - 500	31.0 - 32.2	28.4 - 29.3	25.9 - 27.0	33.6 - 34.9	23.2 - 24.2	To be Calculated	Aristidia	Acacia & Shrubs
Southern Sahel	75 - 90	450 - 550	467 - 470	30.8 - 31.0	28.2 - 28.4	25.7 - 25.9	33.3 - 33.6	23.0 - 23.2		Cenchrus	Acacia dominant
Sudan	90 - 165	550 - 1000	445 - 467	29.6 - 30.8	27.1 - 28.8	24.7 - 25.7	32.1 - 33.4	22.0 - 23.0	To be Calculated	Andropogon	Baobab and shea butter most characteristic
Northern Guinea	165 - 210	1000 - 1250	431 - 44	29.0 - 29.6	26.4 - 27.9	24.0 - 24.7	31.4 - 32.1	19.8 - 21.5	To be Calculated	Andropogon spp. cominate	Isoberlinia spp. most characteristic
Southern Guinea	210 - 270	1250 - 1400/1600	414 - 431	28.0 - 29.0	25.6 - 26.4	23.2 - 24.0	30.4 - 31.4	20.7 - 21.5	To be Calculated	Hyparrhenia spp. & Imperata cylindrica	Isoberlinia Brachystegia Woodland

Southern Sahel.

The Northern Sahel includes areas bordering the desert where the rainfall and growing season are insufficient in amount and duration for crop production. Pastoral (nomadic) agriculture is the dominant form of land use. However, the vegetation cover is very sparse, plant growth is seasonal and land can therefore support only a limited amount of livestock. For this reason, the area must be considered of marginal value agriculturally.

The Southern Sahel includes areas bordering woodland savanna where sedentary agriculture is the main source of livelihood. The boundary delineating the areas of sedentary and pastoral agriculture is based on the climatic characteristics required for millet production, i.e., a minimum length of the growing period of 75 days, corresponding approximately to the 450 mm rainfall isohyet.

2.3.3.2 The Sudan Bioclimate

This area extends south of the Sahel, between isohyets 550/600 and 1,000 mm annual rainfall. The amount of rainfall, its greater reliability and the duration of the growing period (ranging from 90-165 days), allow a wide range of crops to be grown. The drought hazards are relatively low. Most of the region is under fairly intensive cultivation, particularly in Nigeria where continuous cultivation of land is practiced. Soil fertility is low. Yields can be improved by timely and early sowing, the application of fertilizers, and the choice of suitable cultivars whose life cycle corresponds with the rather short duration of the rainy period.

Natural vegetation here consists of an open grassland with scattered deciduous trees, comprised of a mixture of broadleaved and fine-leaved species. In the drier parts of the Sudan, baobab and tamarind are the most characteristic species while the shea butter tree dominates the wetter parts of the region.

The climatic characteristics of the region are suitable for production of short season crops (grains and legumes). The major crop association of the region is millet-sorghum-groundnut-cowpeas.

2.3.3.3 The Northern Guinea Bioclimate

Agriculturally, this is the most interesting region because it has the highest photosynthetic potential for one crop per season. It has a reliable rainfall with unimodal distribution within the range 1,000-1,250 mm isohyets and is virtually free of drought hazards. There is a large water surplus and, therefore, soils are strongly leached. The average duration of the growing season ranges from 165-210 days, allowing for a wide choice of crops and intensive arable production.

It is apparent that the radiation and temperature regimes of the region favor production of C_4 crops but also those C_3 crops adapted to high temperatures. The area is particularly suitable for the production of maize, sorghum, soya, groundnut, cowpeas and cotton. The region is also suitable for the production of plantation forests using such species as Eucalyptus and Pinus spp. At present cattle are excluded from this region because of the presence of tse-tse flies. However, the area may have a high potential for livestock production if it could be associated with intensive grain and silage production and the control of animal diseases.

2.3.3.4 The Southern Guinea Bioclimate

In contrast with other bioclimatic regions, which are characterized by a unimodal distribution of rains, Southern Guinea is a transitional area with a pronounced bimodal distribution which implies two dry seasons and two wet seasons per year.

The two rainfall peaks in June and September are separated by a relatively dry period in August often referred to as the "little dry season." Although the little dry season in the southern Guinea region is not very long, it does separate the rainy season into two growing seasons of unequal duration. This effect becomes more pronounced in the Southern parts of the region where it affects the cropping pattern of arable crops. Neither the amount of rainfall nor the duration of the two rainy seasons can be easily correlated with crop water requirements. Because of the lower radiation and higher night temperatures, the potential photosynthesis per day is lower than in the Northern Guinea Savanna. Also, because of the prolonged total growing period and the less severe main dry season, pests and diseases have a a more detrimental effect on crops and livestock.

The region has a great diversity in agricultural use. The temperature regime is suitable for the production of C_4 crops, both short season crops such as maize and long season crops such as sugarcane. In addition, a number of C_3 crops with high temperature requirements have optimum or near optimum climatic conditions here. These include tuber crops such as yams and cassava as well as grain crops that can be adapted to the bimodal distribution of rainfall such as rice, soybeans, sesame and others. Fibre crops include: cotton, kenaf, jute and roselle.

Because of the prolonged growing season and the climatic suitability for the production of high yielding crops, the region could be very suitable for livestock production if parasites and diseases could be adequately controlled.

Afforestation, particularly in areas which are less accessible or have poorer soils, presents economic development possibilities through proper plantation management.

2.3.4 Net Biomass Production and Yield of Crops

Recently the FAO has developed a methodology for estimating the net biomass and yield of crops and reflecting the potential crop performance as set by the climatic factors and crop adaptability characteristics. It has been used for assessing the relative crop performance in various locations of Africa by Kowal et al., 1977. Some of the results of this study show the expected net biomass production and yield of crops in various Bioclimatic Regions of the Savanna. They are presented in Tables 2-7 and 2-8.

It must be stressed that the results of the study do not represent a theoretical upper limit of crop performance but a real crop performance possible when non-climatic constraints (edaphic and biotic) are minimal. These conditions often prevail at experimental research stations where crop yields measured from specifically designed maximum yield trials are often in the range predicted by the model.

Referring to Table 2-7, it will be noted that the biomass production of non-leguminous crops is much greater than leguminous crops under similar climatic conditions. It appears that it is more expensive in terms of energy use to produce protein-rich crops (Legumes) compared with starchy crops (non-Legumes).

Crops with a C-4 assimilation pathway have higher capacity for net biomass production under West African climate conditions than crops with a C-3 assimilation pathway adapted to a high temperature environment. The difference is about 25 per cent.

TOTAL NET BIOMASS PRODUCTION FOR THE GROWING SEASON AND AVERAGE RATE OF NET BIOMASS PRODUCTION PER DAY FOR FIVE LOCATIONS IN WEST AFRICA

Table 2-7

Location	Crop Group	Net Biomass ton/ha/season		Net Biomass kg/ha/day	
		Legume	Non-Legume	Legume	Non-Legume
Kano (Sudan Bioclimate)	A	12.9	17.8	93.5	129.0
	B	-	24.4	-	175.4
Samaru (Northern Guinea Bioclimate)	A	15.7	22.5	84.0	120.3
	B	-	29.6	-	158.3
Minna (Southern Guinea Bioclimate)	A	15.8	23.8	73.0	110.7
	B	-	33.3	-	154.9
Ibadan (Tropical Moist Forest Bioclimate)	A	16.4	27.5	59.4	99.6
	B	-	35.6	-	129.0
P. Harcourt (Tropical Rain forest Bioclimate	A	15.7	26.1	47.4	78.9
	B	-	34.6	-	104.5

Crop groups:

A = Crops with C-3 assimilation pathway adapted to high temperature environment

B = Crops with C-4 assimilation pathway adapted to high temperature environment

Table 2-8

TOTAL NET BIOMASS PRODUCTION AND YIELD OF SELECTED CROPS

	Total Net Biomass Production (ton/ha)				Yield (ton/ha)			
	P	M	Ca	Ca'	P	M	Ca	Ca'
Kano (Sudan Bioclimate)	10.8	22.0	17.8	42.7	4.3	9.9	-	24.5
Samaru (Northern Guinea Bioclimate)	10.9	21.0	22.5	37.2	4.4	10.5	12.4	20.5
Minna (Southern Guinea Bioclimate)	10.3	20.0	23.8	33.6	4.1	9.1	13.1	18.5
Ibadan (Tropical Moist Forest Bioclimate)	9.7	19.5	27.5	31.2	3.9	7.8	15.1	17.1
P. Harcourt (Tropical Rain forest Bioclimate	8.7	17.1	26.1	29.3	3.4	6.8	14.4	16.1

P = 100-day Phaseolus bean

M = 120-day maize

Ca = cassava utilising full growing season

Ca' = cassava utilising whole year with irrigation

Further, the results show pronounced differences in net biomass production between various Bioclimatic Regions. The most striking differences, particularly in the rates of biomass production, are between Savanna and Forest Bioclimates. The Savanna Bioclimates offer higher rates of biomass production for both Leguminous and non-Leguminous crops. Thus, for example, the rate of biomass production for a Legume crop at Kano is 93.5 Kg ha^{-1} day^{-1}. Less pronounced but probably significant are the differences in the rate of biomass production between Savanna Bioclimates. These reflect the pattern of radiation and daytime temperatures of Savanna Bioclimate Regions.

The total net biomass production is influenced by two variables, the average rate of net biomass production and the number of days in the growing season. Depending on how well the growing period is utilized, the introduction of these two variables modifies the trend which is not accurately reflected in Table 2-7. The derived values assume full utilization of the growing period which is difficult to achieve in practice. Nonetheless, the magnitude of the values for total biomass production in Table 2-7 may reflect accurately the potential production of crops harvested in the vegetative stage. However, an assessment of good crops requires a careful interpretation of values.

Reference to Table 2-8 shows a typical pattern of net biomass production and the yield of some specific crops in relation to Bioclimatic Regions. Thus a 100-day phaseolus bean at Kano and Samaru can be expected to yield 4.3 - 4.4 ton ha^{-1}, while the same crop at Ibadan and Port Harcourt would yield 3.4 to 3.9 ton ha^{-1}, a difference of about 23 per cent. Similarly, the corresponding figures for a 120-day maize are 9.9 to 10.5 ton ha^{-1} and 6.8 to 7.8 ton ha^{-1} respectively, a difference of about 40 per cent.

The yield of a cassava crop utilizing the full growing season ranges from 12.4 ton ha^{-1} at Samaru to 14.4 - 15.1 ton ha^{-1} at Ibadan and Port Harcourt, a difference of about 33 per cent. However, the difference in the length of the growing season between Samaru and Ibadan/Port Harcourt is about 63 per cent. To illustrate what would happen to cassava yields if it were possible to utilize the whole year with irrigation, Kano/Samaru would be capable of producing 21 to 24 ton ha^{-1} while Ibadan/Port Harcourt would be capable of producing 16 - 17 ton ha^{-1}. The above demonstrates the extent of the climatic superiority of the Savanna Bioclimates over Forest Bioclimates for intensive food production (particularly grain production) and justifies further detailed analysis of Bioclimatic Regions of the Savanna.

CHAPTER 3

WATER BALANCE

3.1 INTRODUCTION

In the savanna countries, the "10-day rainfall" and "soil" factors, determine vegetation growth.

The possible low rooting depth together with the irregular rainfall often results in vegetation growth stoppage.

An empiric system or model simulating the soil-water relationship has been designed to study this relationship.

The lay of soil needed for rooting has been set at 1 meter on the average, which corresponds to soils with good crop aptitude. The model presented in this chapter has three advantages.

a) Having been prepared for savanna-type stations, (see Table 3-1), it provides a series of chronological information which may improve the knowledge of the relationship between vegetation and climatological factors;

b) Since the results have been treated statistically, the model forms a means of reference which enable the zone-by-zone comparison of the estimated values for the variables and this at a given probability level. (See Listings of Results in Appendices, Volume 3.)

Table 3-1. List of Rainfall Stations Used

Benin

- Bohicon
- Kandi
- Natitingou
- Parakou
- Savé

The Cameroons

- Garoua
- Mamfé
- Maroua
- Ngaoundere
- Yoko

Ivory Coast

- Bouaké
- Bondoukou
- Bouna
- Boundiali
- Ferkessedougou
- Man
- Odiénné

Central African Empire

- Bambari
- Birao
- Bossangoa
- N'Delé

Upper Volta

- Bobo-Dioulasso
- Boromo
- Dédougou
- Djibo
- Dori
- Fada N'Gourma
- Gaoua
- Kaya
- Ouagadougou
- Ouahigouya
- Po

Mali

- Bafoulabé
- Bamako
- Banamba
- Bougouni
- Diéma
- Douentza
- Gao
- Hombori
- Kayes
- Kéniéba
- Kita
- Koutiala
- Ménaka
- Mopti
- Nara
- Niafounké
- Niono
- Nioro du Sahel
- San

Table 3-1. List of Rainfall Stations Used (cont'd)

	Ségou		Kedougou
	Sikasso		Kolda
	Sokolo		Koungheul
	Tombouctou		Linguère
Mauritania			Matam
	Aïoun-El-Atrouss		Podor
	Boutilimit		St. Louis
	Kiffa		Tambacounda
	Néma		Ziguinchor
	Nouakchott	Chad	
Niger			Abéché
	Birni-Nkonni		Am Timan
	Dogodoutchi		Ati
	Filingue		Baïbokoum
	Gaya		Bol
	Gouré		Bousso
	Mainé Soroa		Moissala
	Maradi		Moundou
	Nguigmi		N'Djamena
	Niamey		Pala
	Tahoua		Sarh
	Tanout	Togo	
	Tillabery		Anié Mano
	Zinder		Atakpamé
Senegal			Sansanne-Mango
	Bakel		Sokodé
	Dakar		
	Kaolack		

c) If a hydro-agricultural project is to be developed, the model can be modified by adjusting the parameters in such a way that they correspond to the field measurements. Thus, the model enables simulations with valuable results on the technical, managerial and economic levels.

This model, developed by ORSTOM in cooperation with CIEH*, was applied to one hundred stations of the area surveyed (Franquin and Forest, 1977). The original results, as well as the program listing, are available from these institutions. The model is identified as ORBVCR (ORSTOM BILAN HYDRIQUE D'UN COUVERT VEGETAL [CROP] EN CONDITIONS VARIABLES DE RESERVE D'HUMIDITE UTILISABLE**). The statistical results are given in appendices 3-1 to 3-11.

3.2 PROGRAM FOR THE EVALUATION AND FREQUENTIAL ANALYSIS OF THE ORBVCR SYSTEM WATER BALANCE ELEMENTS

The ORBVCR system cannot claim to explain the hydrological balance of the watershed which comprises a complex series of slopes, soils, subsoils, vegatation groups and modes of utilization by man and stock.

Having been developed for agriculture, this system determines the water balance of the farmed parcel which is characterized by a soil and its crop for a certain period of the year. The water balance is represented as follows:

$$P + (I) \mp R - D \mp \Delta H - ETR = 0$$

P = rainfall; (I) = possible irrigation; R = runoff; D = drainage; ΔH = soil moisture variation; ETR = actual evapotranspiration.

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* Interafrican Committee for Hydraulic Studies

**(Water Balance for Plant Cover [Crop] Under Various Conditions of Usable Soil Moisture)

The system evaluates the elements of the balance for successive intervals of 5, 7 or 10 days. In other words, it does not simulate the actual physical phenomena of the soil/plant/atmosphere (weather) relationship, some of which have time constants of less than 24 hours. Although the system is not very flexible, it may be adapted to specific soil and vegetation conditions (observed or theoretical) by factor adjustment. The adjustment will be made on the basis of the measured soil moisture variations (ΔH) for the time intervals considered.

In this case, which covers the various conditions at 100 stations, any adjustment was excluded in the absence of observations and due to the necessity to have average conditions.

Moreover, the system was designed, not in the light of what is nowadays known as African agriculture - which would not have made sense - but of what it should become in order to overcome its role of subsistence agriculture and to form the driving force towards progress. Cultivated soils, planting at the right time, adequate density, care of crops and, most of all, conservation of water and soil are then compulsory. In particular, all means (anti-erosion techniques, burying of crop residues, surface work against battance crust) must strive to avoid runoff (R), in order to form a moisture reserve, mainly at the beginning of the season, when rainfall (P) is most uncertain.

Finally, even though the application of the system is here directed towards rainfall agriculture (dry farming) which is presently, and for a long time to come, the essence of African agriculture, ORBVCR may find use in irrigation to complement the annual rainfall. For irrigation of permanent crops (sugar cane, for instance), another system, ORBKCR, which operates with a constant RU, would be more suitable. Indeed, it will be noted that

ORBVCR operates with an increasing RU, as is required for annual crops.

3.2.1 Characteristics of the System

3.2.1.1 Increasing Usable Soil Moisture (RU)

The balance models operate usually with a constant RU, defined for a z dm rooting depth for a H_c% field capacity soil (dry soil weight), a H_f% permanent withering point and a d_a apparent density:

$$RU\ mm = (H_c - H_f)\, d_a\ .z$$

In humid areas, this soil portion z never dries out - except for the surface horizon - to the withering point since the dry season is short and not absolute. The constant RU formula is then justified for a crop which covers the soil constantly, (bushes, meadows, sugar cane, natural vegetation...). Under the same conditions, it is less well justified for a yearly crop, planted in bare soil, for which the RU will increase with the progression of its root front.

In drier areas where the soil moisture reaches the withering point (and exceeds it for the surface horizon) during the dry season, a constant RU doesn't make any sense. Whether a permanent vegetation with an underground growth that survives due to residual moisture, or a farmed or natural annual vegetation, the RU is zero (and even negative) when rainfall returns. Consequently, it is important to simulate its increase as the rainy (wet) season progresses.

In case of an annual vegetation, it is appropriate to simulate the progression of the root front which would require, though, the development of various models in accordance with the species. For permanent vegetation, the solution is simpler if one accepts the principle according to which a rehumidification front at elevation z would only progress by Δz if the profile is already moistened up to depth z at the field retention capacity.

Since the profile moisture is supposed to be adjusted to the withering point value at the beginning of the wet season, the first rainfall, considered as fully infiltrated and not precipitated in depth through cracks, shall determine the value of the initial RU. After that, the RU shall progress whenever the available volume of moisture present in the soil will exceed the real RU value, taking into account the precipitation and the actual evapotranspiration (ETR); and this, up to the maximum set value, considering the estimated root depth and the moisture characteristics of the soil. From this point onwards, the infiltrated excess, with respect to this maximum RU, will be drained or run off away from the roots.

On the basis of this principle, the RU increase in the ORBVCR system has been simulated, whether we are dealing with a permanent or with an annual vegetation. In the latter case, without being severe, the process is an improvement with respect to the constant RU practice.

3.2.1.2 System Inputs

Inputs consist of rainfall (P), possible evapotranspiration (ETP), maximum evapotranspiration (ETM) K coefficients and the maximum RU value.

Rainfall (P)

The numerical value of the rainfall sample determines the statistical interest of the operation. The system establishes a series of 10-day balances for each year of rainfall surveying which enables a frequential analysis of the rainfall itself and of the output variables. In the best instances, this sample was limited to 50 years, counting backwards from 1972 or 1973, the last two years of the 5 or 6 drought years suffered by the Sahel, South of the Sahara.

Rainfall, entered on computer cards in daily amounts by the ORSTOM Hydrology Department, is totalled by 10 or 11 calendar day periods (8 or 9 days for the 3rd February 10-day period). To the rainfall total (P) of the i 10-day period, the residual moisture (RS) of the i-1 10-day period is added to form the available moisture (HD) during the i 10-day period. If HD during i is higher than RU during i-1, its value determines the one for the new RU, which, however, cannot exceed the maximal RU of the input. Once this value is reached, HD cannot exceed it, while the excess is run off/drained (RDR).

Hereinafter, we will see that the system also provides a frequential analysis of the 10-day rainfall totals.

Potential Evapotranspirations (ETP)

The ETP values are not calculated by the system. They are directly entered as 10-day values, preferably proposed by the interested party who assumes full responsibility. In this case, they have been calculated according to PENMAN for the meteorological and agronomical stations which produce the data for length of sunshine, temperature, vapor pressure and wind velocity. Spatial interpolations have permitted us to estimate the ETP values for the common rainfall stations.

These monthly values have been obtained on the basis of a 0.20 albedo. The Angstrom relationship coefficients have been considered as equal to 0.18 for a and 0.62 for b, with the exception of Upper Volta for which the OMM agrometeorologist had proposed ETP values calculated with a = 0.30 and b = 0.50, resulting in values which are 5 to 10% higher.

The 10-day ETP values were finally interpolated on the basis of the monthly values, which introduces another source of errors. These errors compensate each other to a certain extent, since they are not of the same type. They are, in the end, of little importance considering the very large variability of rainfall.

Maximum Evapotranspiration (ETM=K.ETP) K Coefficients

The actual evapotranspiration (ETR) is determined by the available water volume, the degree of availability of this water and by ETP on the one hand, all requirements which the EAGLEMAN ETR calculation relationship (1971) incorporated into the system, takes into account. On the other hand, it can be limited by the foliage surface area, from whence the necessity to introduce an ETP modulation K factor. This factor is variable according to the degree of vegetation cover growth. Two cases must be considered, namely, whether we are dealing with an annual crop, planted at the beginning of the rainy season, or with a permanent cover (permanent crop or natural vegetation).

The water balance of an annual crop follows the bare soil water balance from the time of sowing. As far as a given crop is concerned, sowing takes place at a date which varies according to the year. ORBVCR can initiate the crop balance from the first 10-day period with a rainfall volume set as desired. In this case, this procedure was not applicable since one was required to adopt an average situation for all of the crops. The solution consisted in adopting a fixed average sowing date.

Together with certain specialists, one will accept that in tropical areas the evaporation of the bare soil at the beginning of the rainy season when rainfall is not frequent enough to keep the surface moistened, is, on the average, equal to 1/3 of the evaporation of a free water surface. This evaporation will be equated to Penman E_o calculated with a 0.05 albedo. But, $1/3.E_o$ is equivalent to 0.40-0.45 Penman E_T calculated with a 0.20 albedo. As a safety margin, we will here consider that at the beginning of the rainy season, the bare soil evaporates on the average 1/2.ETP evaluated according to Penman. Since all excess moisture is then stored in the soil, bare or slightly covered with vegetation, sowing ceases to be uncertain from the moment when the rainfall curve exceeds the ETP/2 (Fig. 3-1) curve and remains there.

The average 10-day period for which P becomes higher than ETP/2 has been determined by intersecting the average P and ETP/2 curves. This 10-day period has been considered for sowing, irrespective of the year. This approximation would be rough if one were to take a particular crop, such as sorghum or peanuts for instance. It becomes less rough if one takes into account that the farmer grows in fact several crops, some much earlier (food crops generally), others later (very often cash crops): preparing the soil and sowing are spread over 2 months or more.

As of the 10-day sowing period - which is thus the period when on the average P exceeds ETP/2 - the K values assigned to the successive 10-day periods are as follows: 0.50 - 0.50 - 0.60 - 0.70 - 0.80 - 1.0 - ... The crop supposedly planted at adequate density in adequately fertile soil, evapotranspires to ETP after 50 or 60 days. Rainfall has become by then so frequent that the soil, even if not fully covered yet (as would be required to ensure optimal photosynthetic efficiency of the moisture) evaporates to ETP

DETERMINATION DE LA PERIODE DE CROISSANCE VEGETALE
DETERMINING THE PERIOD OF VEGETATION GROWTH

LIEU
LOCATION
OUAGADOUGOU-VILLE

PAYS
COUNTRY
HAUTE-VOLTA

PERIODE
PERIOD
1931 - 1960

MOYENNE PLUVIOMETRIQUE
AVERAGE RAINFALL
860 mm.

LATITUDE: 12° - 21′ N

LONGITUDE: 01° 31′ W

ALTITUDE: 304 METRES

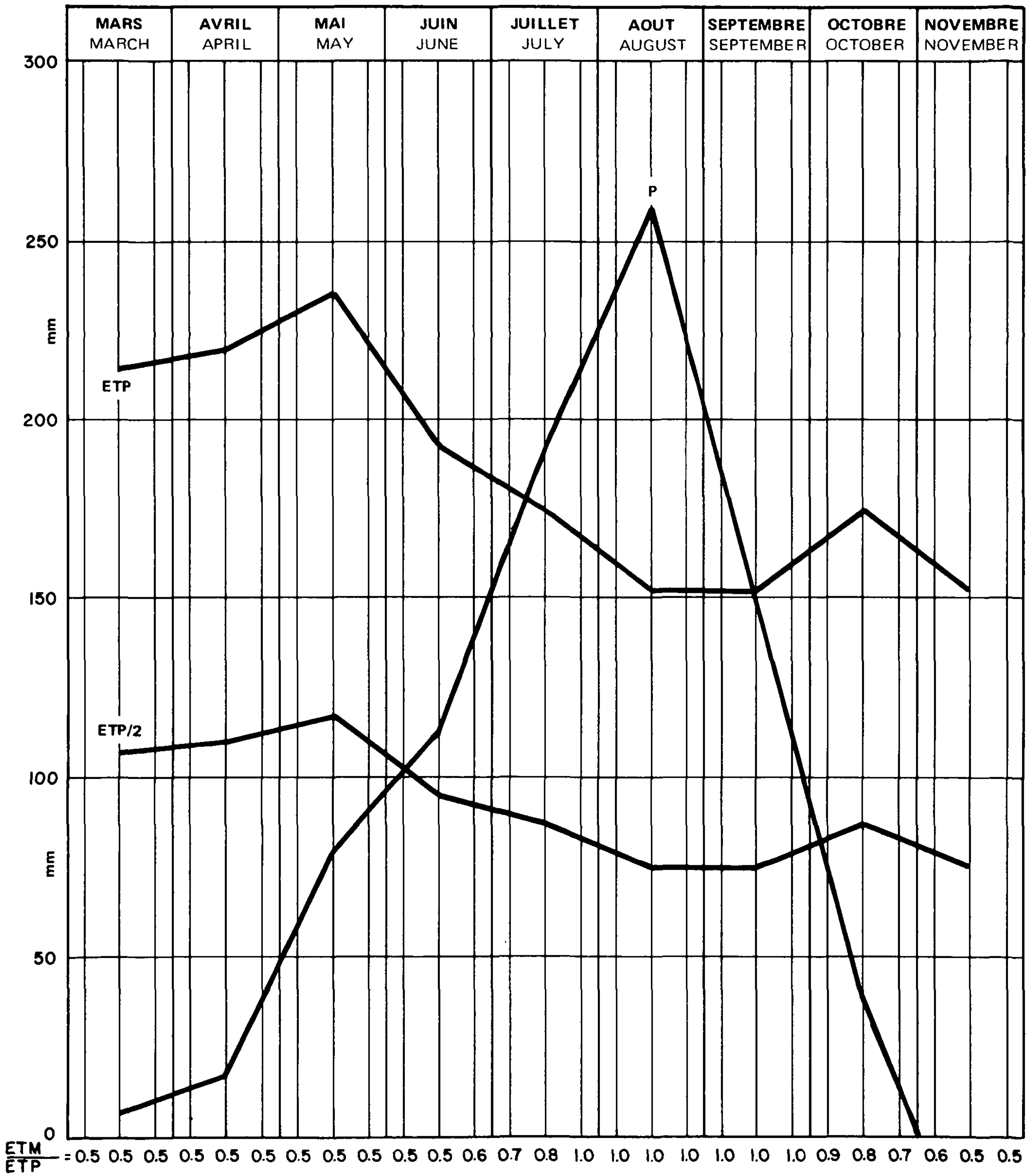


Fig. 3-1

(or approximately $0.80.E_o$ Penman). The K coefficient remains then equal to 1.0 until the 10-day period when, on the average, the rainfall curve falls again below ETP/2, then it decreases linearly to 0.50, as follows: ... - 1.0 - 0.90 - 0.80 - 0.70 - 0.60 - 0.50 -, in accordance with the maturation process of the plant. For the remainder of the year, K remains set at 0.50, a value which is supposed to correspond with the evaporation of the bare soil (or $1/3.E_o$) sporadically moistened by rainfall.

However, this general diagram comprises exceptions which coincide with the rainfall differences. In the case of MAMFE, N'GAOUNDERE and YOKO stations in the Cameroons, of MAN in the Ivory Coast and BAMBARI in the Central African Republic, sowing is supposed to take place not during the 10-day period when P climbs above ETP/2 since this period falls too early or doesn't even exist, but during the 10-day period when P exceeds ETP. For the BOUAKE and BONDOUKOU stations in the Ivory Coast, characterized by two rainfall highs separated by a short dry season, two successive crop cycles have been programmed. Finally, there are the Sahel stations which can be described as pre-Saharan for which the average rainfall curve remains lower than the ETP value and sometimes even lower than ETP/2: AIOUN, BOUTILIMIT, KIFFA, NEMA, NOUAKCHOTT in Mauretania, N'GUIGMI, TAHOUA, TANOUT in Niger, GAO, MENAKA, NIAFUNKE, TIMBUKTU in Mali and BOL in Tchad.

The duration and the timing of the vegetation period vary considerably in these areas, to the extent that the MIL rainy monocrop is only very uncertain and this balance simulation does not apply to it at all. At best one could consider the programming of an irrigated crop with an arbitrary vegetation cycle duration or even the development of a natural annual vegetation growth (grasslands). This last solution has been adopted.

But the water balance considered above for an annual crop generally, can also be considered for a permanent crop or for a perennial natural vegetation. One may then accept that prior to the 10-day period for which P exceeds ETP, the fully consumed rainfall forms ETR; the remainder of the cycle remains unchanged with respect to an annual crop which was supposed to fully use the soil moisture by the end of the season.

Maximum Usable Soil Moisture (RU)

RU is evaluated on the basis of the root development type, of the soil depth and of the moisture and hydrodynamic characteristics (permeability above all) of the soil. Whenever these data are lacking, 100 mm forms generally the average value retained. It corresponds to a 80 to 120 cm soil thickness for which the available moisture interval $H_c - H_f$, varies from 5 to 10%, with an apparent density of 1.3 to 1.6. For soil with an average coarse texture, one would obtain: 5 x 1.6 x 12 = 96 mm. For a soil with an average fine texture (also less pervious): 10 x 1.3 x 8 = 104 mm.

As we have seen above, ORBVCR operates with an increasing RU value. Consequently, the errors included in the RU evaluation only affect its maximum value and thus interfere only from the time when this value is reached, which corresponds in essence to the duration of the vegetation period. One will see that it is possible to interpret what would have been a balance on the basis of a higher or lower maximum RU value.

Thus, in order to take into account that the RU value depends also on rainfall, the values considered are 120 mm for Sudan areas and 80 mm for Sahel areas; the difference is somewhat arbitrary in the area between these two.

3.2.1.3 System Outputs

These comprise mainly: actual evapotranspiration (ETR), residual moisture (RS), runoff/drainage (RDR), relative evapotranspiration (ETR/ETM) and the crop moisture deficit (ETM/ETR).

Actual Evapotranspiration (ETR)

Therefore, where the balance components of interest to the hydrologist are runoff (R) and drainage (DR), the main worry of the agronomist is the actual evapotranspiration (ETR) which represents the moisture consumption by the crop. The fundamental problem is thus the evaluation of the ETR without having to make measurements at the soil level nor at the plant level (unless for inspections or adjustments) nor at the atmospheric (weather) level (except for the standard meteorological observations enabling the evaluation of ETP). It is the raison d'être of the water balance models.

Almost all empirical models use:

$$ETR/ETP = f(HR) \qquad HR = HD/RU \qquad 0 \leq HR \leq 1$$

in which RU is the maximum usable moisture reserve in the root growing area of the soil; HD is the actual available moisture within the boundaries of this RU. In most models, one has even:

$$ETR/ETP = HR,$$

with the restriction that if the relative humidity of the soil (HR) is higher than a certain threshold (0.70 - 0.60 - 0.50 - ...) which depends on the soil makeup and which is the bottom of the RFU (easily usable reserve), then ETR = ETP.

This RFU, for which no static definition can be given, then remains to be estimated: for the same RU value on the same soil with the same root density, the RFU value decreases with the soil drying speed, and thus, with the climatological demand value (ETP). A solution for this problem may be provided by the EAGLEMAN relationship (Agr. Meteorol. 8, 1971, 385-394), a cubic relationship for which the four parameters are themselves usually decreasing functions of ETP:

$$ETR/ETP = A + B(HR) + C(HR)^2 + D(HR)^3$$

$$A = -0.05 + 0.732\ (ETP)$$

$$B = 4.97 - 0.661\ (ETP)$$

$$C = -8.57 + 1.560\ (ETP)$$

$$D = 4.35 - 0.880\ (ETP)$$

This EAGLEMAN relationship forms the ETR evaluation function of the ORBVCR system.

Residual Moisture of the Soil (RS)

This is the remaining volume of water after removing ETR from the available water (HD) volume:

$$RS = HD - ETR$$

But one cannot say that RS represents the groundwater for the 10-day period considered. This HS volume present in the soil during the 10-day period is on the average:

$$HS = \frac{HD + RS}{2}$$

Runoff/Drainage (RDR)

The system does not comprise a runoff function as such. Except for steep slopes (requiring an anti-erosive device), there is no runoff in good agriculture during the first part of the season, when rainfall is most uncertain and when it is necessary to store all of the rainfall in order to form a moisture reserve.

Later, from the moment when the (maximum RU) usable moisture capacity for the crop is reached, the excess may be drained or run off. It seems that the simulation is better when the excess is run off before removing ETR rather than drained afterwards. This solution has been adopted. Whether run off or drained, the excess does not go to the crop, thus forming what has been called runoff/drainage (RDR). This RDR is cumulated in the RDRC column.

This being said for a crop, it is certain that the same is not true for natural vegetation, a more or less considerable runoff according to the slope, the nature of the soil, the nature of the vegetation (annual or permanent) occurs with the first rainfall.

Soil Deficit and Relative Soil Deficit

This deficit is calculated for the 10-day period i on the basis of the present RU and RS:

$$D(RS)_i = RU_i - RS_i$$

But the average deficit is in reality:

$$D(HS)i = RU_i - \frac{(HD+RS)_i}{2}$$

The relative deficit is the ration between the deficit and the RU:

$$D(HS)_i / RU_i$$

Relative Evapotranspiration (ETR/ETM)

The ORBVCR system can, as desired, provide the relative evapotranspiration with respect to ETP (in other words ETR/ETP) or with respect to ETM (in other words ETR/ETM).

ETR/ETM is usually more interesting to know in order to compare the annual balances, as in this case. ETR/ETP is required, on the other hand, for station comparison.

In either case, it is a production index of the dry product, the relationship being considered as linear, while all other components are otherwise equal.

Moisture Deficit of the Crop (ETM/ETR)

This is the consumption deficit of the crop, in relation to its maximum evapotranspiration (ETM), a deficit to be made up through irrigation by taking action against the soil deficit D(RS).

For instance, given a certain quantity of available irrigation water, one may attempt to investigate what its distribution would be in column 1 to reduce ETM/ETR, taking into account the crop requirements during its successive growth phases, taking also into account, possibly, the price of this water.

3.2.2 Statistical Analysis of the Information

The input and output data can be analyzed frequentially for each 10-day period. Since the distribution laws are various according to the variable considered (gamma function for rainfall, beta for ETR/ETM, ...), the statistical treatment takes place by simple frequential classification into tenths, quarters and twentieths.

In this case, the following have been treated statistically: rainfall (P), ETR, runoff/drainage (RDR) and the crop deficit (ETM/ETR). The results are shown on a special table for each variable (see appendices 3-1 to 3-11).

3.2.3 Basic Information

All of the water balance and statistical analysis tables form a data bank. This bank provides the climatology users of certain sectors of activity with basic and detailed information.

Basic information refers to rainfall and to possible evapotranspiration (ETP).

3.2.3.1 Rainfall (P)

The rainfall data for 100 stations have been reduced to a 10-day scale based on daily observations transferred onto perforated computer cards by the Hydrology Department of ORSTOM. These data were carefully checked by a specialist. Thus, gross errors were corrected and the years with incomplete or doubtful observations were removed.

For the 100 stations - as well as for the other rainfall stations of French-speaking Africa - the daily observations and their monthly totals were published by ORSTOM since the beginning up to 1965; from 1966 onwards, this was done by ASECNA. For the 100 stations in question, this study repeats thus the data, reduced to a 10-day scale, for the last 50 years (maximum) ending in 1972, 1973 or 1974.

Except for some rare instances when the rainfall of certain years is of interest (for instance, drought years from 1968 to 1973), the interest goes usually to their frequential aspects. The 10-day pluviometry has thus been described statistically on the frequential classification tables in deciles, quartiles and vigintiles annexed to the water balance interannual series.

Even though the quality of this statistical treatment mode is not as good as the one with an adjustment of the theoretical distribution law data (in particular, incomplete gamma function on which the ORSTOM rainfall frequential analysis model is based), its usage for agricultural purposes is the same, namely:

- Definition of the beginning and the end (thus the duration) of the useful rainy season, based on the thresholds, repeated or not, of rainfall and probability.
- Evaluation of the deficit frequency (possibly made up through irrigation) or the excess (to be stored or drained or run off), in successive 10-day periods with respect to any ETP fraction.
- Estimation of the occurrence risk, in position and duration, of successively dry or wet periods, with respect to the critical crop phases.
- Whether ETP is taken into account or not, construction of frequential models of the vegetation period, for: the setting of the vegetation cycles of the cultivars, photoperiodic or not, with determination of the optimal sowing date; setting with or without irrigation of two crop cycles on the same lot during the same year; determination of climatological relative productivity indexes, taking ETP into account.

3.2.3.2 Potential Evapotranspiration (ETP)

As indicated above (3.2.1.2), ETP has been calculated on a monthly basis according to Penman for the meteorological stations, with a 0.20 albedo and, for the Angstrom relationship coefficients, a = 0.18 and b = 0.62; except for Upper Volta, with a = 0.30 and b = 0.50, resulting in values which are 5 to 10% higher.

These monthly ETP values for the meteorological stations have been spacially interpolated for the rainfall stations. Then, the monthly values have been interpolated in time in 10-day period values.

They are average ETP values derived from averages of length of sunshine, temperature, vapor pressure, wind velocity established for periods which are as long as possible (the average temperatures are standard). The very wide variability of rainfall warrants the acceptance of average ETP values when establishing the balances.

Since the ORBVCR system is only one of many systems, it should be possible for anyone who has the means to reutilize these same data for rainfall and ETP in water balance models with higher performance, on the basis of various hypotheses (such as runoff, for instance), with respect to well-determined crops for which one would have more precise knowledge of the ETM K values and sowings at variable dates rather than average dates, on soils with well-known moisture characteristics.

3.3 ORBVCR SYSTEM RESULTS

3.3.1 Model Control and Validity

The ORBVCR system is a black-box model requiring inputs which are in accordance with the actual observations and experiences.

The model has been tested by comparing the results obtained with the observations made by neutron probe measurements.

Fig. 3-2 shows that there is a proper agreement between the "Water reserve in the soil" measured and that computed by the model. Without special modifications to the model, it is evident that the results are in agreement. A precise agreement is then obtained by adjusting certain parameters.

3.3.2 Runoff/Drainage Period Expected for One Year Out of Two (Map 3-1)

One of the frequential analysis results is shown on Map 3-1.

The curves represent the periods (in days) of runoff/drainage of equal duration with a 0.5 probability threshold. For Ouagadougou, one has for instance a maximal period of 50 days. The drainage corresponds to the percolation below 1 meter in depth. However, it is not possible to distinguish drainage from runoff. The figure next to the dot indicating the rainfall station thus shows the yearly volume of water (in mm), drained and/or run off during the period shown by the curve. It is accepted that surface runoff takes place at the beginning of the season; later, drainage prevails due to the protective effect of the soil. For Ouagadougou, there is a 68 mm runoff/drainage for a 50-day period.

The map shows the disturbances caused by the central delta of the Niger and the Atakoro range in Togo.

In the case of the central delta of the Niger, there is low runoff/drainage. Indeed, due to the size of this lake area, the convection phenomena are less sizeable and result in fewer cloud formations. Consequently, there is less rainfall, especially during August, when the relative humidity of the area is high.

In the case of Atakoro, another phenomenon takes place: rainfall is much higher on the East side of the range than on the range itself.

COMPARAISON ENTRE LE BILAN HYDRIQUE SIMULE ET LES MESURES IN SITU (SONDE A NEUTRONS)
COMPARISON BETWEEN SIMULATED WATER BALANCE AND IN SITU MEASUREMENTS (NEUTRON PROBE)

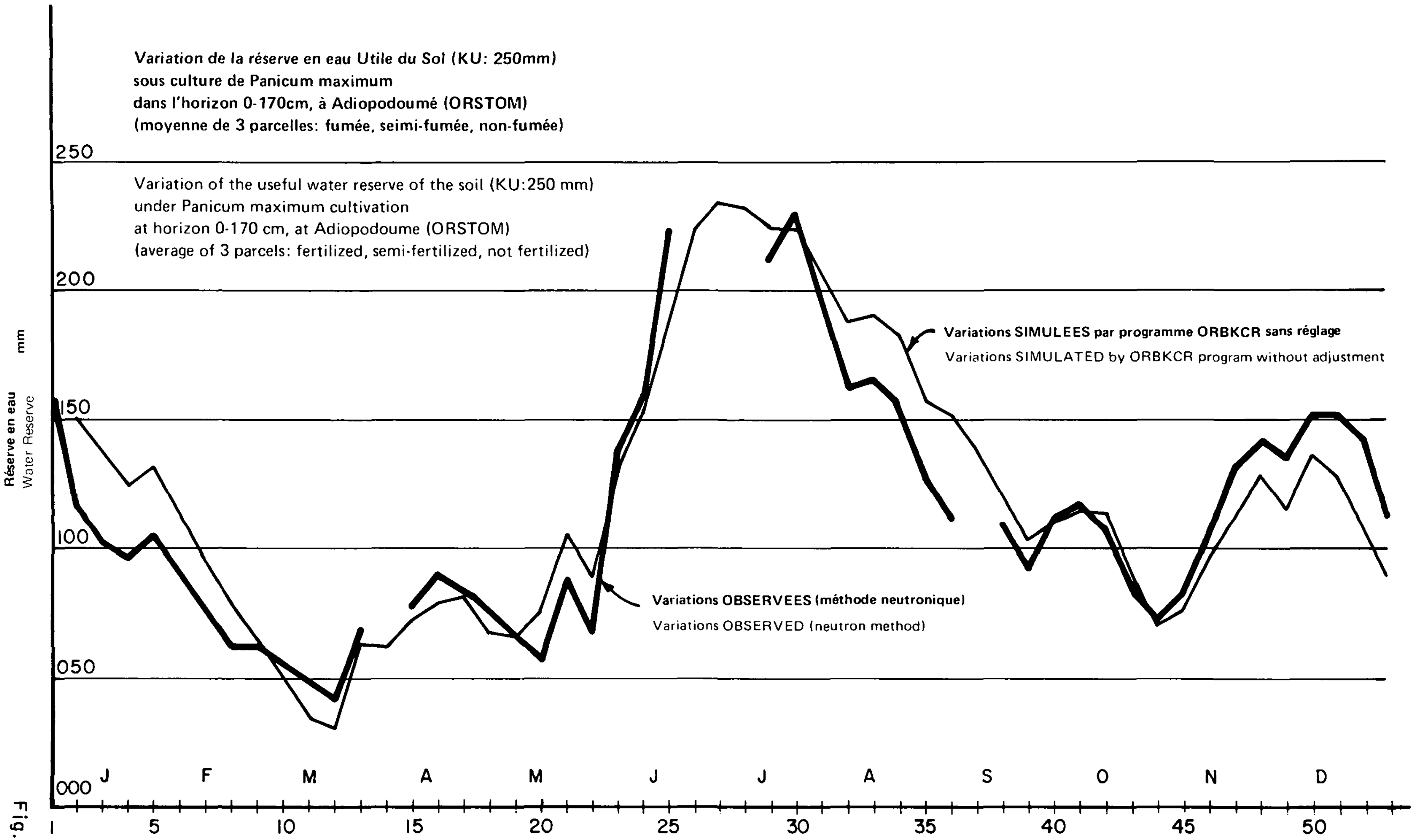


Fig. 3-2

Consequently, the runoff/drainage is higher on the Eastern edge of Atakoro. This is due to the fact that the large cloud formations move generally in an East-to-West direction.

3.3.3 Rainwater Supply for Grasslands (Map 3-2)

Map 3-2 shows 3 types of information with a 0.5 probability:

a) The total annual deficits to keep the vegetation cover alive during the year (its growth phase takes place during the rainy season). This is a theoretical minimum deficit. The water needs during the dry season are estimated at 1/2 ETP, with the soil reservoir at a depth of 1 m. The information is given in mm of water.

b) The irrigation proportions to ensure maximum production during the rainy season (complementary irrigation) and the dry season (total irrigation). In this case for instance, the production expectations for a variety of Panicum maximum can be estimated at 50 tons of dry product per hectare. The water needs during the dry season are estimated at ETP. The information is shown in the Map and expressed in 1000 m^3/hectare.

c) The duration observed, one year out of two, during which there is no rainwater supply deficit for the crops. This value thus indicates the optimal duration of the adaptable crop cycle under natural local climate conditions.

The isolines characterize homogenous areas where the development and growth phase of the crop is ensured by rainfall on the one hand, and by the stored moisture in the soil on the other hand. Generally speaking, the North-South gradient is homogenous. At the planning level, the values for the periods enable the identification of vegetation which is adaptable to the climatological conditions linked to rainfall crops.

The estimated complementary irrigation required must be related to the local available water (bottom water, underground water, ...).

In order to obtain more precise information, the user is invited to analyze the chronological 10-day period results for the ETM/ETR tables computed for the 100 stations for the savanna area (see Appendices 3-1 to 3-11).

3.4 ORBVCR SYSTEM APPLICATIONS

The system outputs consist of information which may be of interest not only to the agronomist (generalist, agroclimatologist, phytotechnician, pedologist, etc.) but also to the phytoecologist and, to a certain extent, the hydrologist and the hydrogeologist.

3.4.1 <u>Agronomy</u>

In agronomy, all applications cannot be listed extensively. First of all, the K sequence of ETM (0.50 - 0.50 - 0.60 - 0.70 - 0.80 - 1.0 ... - 1.0 - 0.90 - 0.80 - 0.70 - 0.60) is a measurement, in 10-day periods, for each station, namely of the average duration and position of the physical period of vegetation; of the maximal length of the cultivar vegetation cycles.

The average physical vegetation period comprises three sub-periods:

- a pre-humid period, during which the average rainfall curve goes from ETP/2 to ETP; it corresponds to the "installation" phase of the crop, supposedly sown during the 10-day period when P becomes higher than ETP/2 and is supposed to develop according to the sequence: 0.50 - 0.50 - 0.60 - 0.70 - 0.80 - 1.0 -
- a humid period during which P is on the average higher than ETP. During this period the crop is supposed to evapotranspire to ETP (the excess being stored in the soil or partially run off/drained) and during which the phenomena take place which lead to fructification.
- a post-humid period during which the average rainfall curve goes from ETP/2 to 0. The complement required to satisfy ETM is requested from soil moisture. It is the maturation phase of a crop for which the earing (for a grass-type with a defined blooming type) or the useful blooming end (for a species with an axillary blooming type - cotton tree, peanut, niebe ... - is supposed to coincide with the 10-day period when P falls again below ETP. The K sequence for ETM, as of the beginning of the maturation phenomena, is supposed to be as follows: 1.0 - 0.90 - 0.80 - 0.70 - 0.60.

It is to be observed that in this case, the K coefficients have been rather well fixed in general (even though somewhat variable with the minor features of the rainfall pattern) with respect to the occurrence dates of the remarkable events considered (P becoming higher than ETP/2, then lower than ETP, then lower than ETP/2). On the other hand, the maturation phase should be considered as ended when coefficient K = 0.70, totalling about 40 days.

The variable sequence of the ETR values, but above all, the one for indexes ETR/ETM and the one for the ETM/ETR deficits, shall then make it possible to point out to what extent each special year differs from the standard year computed by the ETM variable sequence.

It will then be possible to perform statistical work on these features (in particular for ETR/ETM, an index for which there is no frequential classification table), regarding:

- any special event considered as interesting (ETM = 0.5.ETP); first ETM = ETP; last ETM = ETP; average and variable positions of the lowest ETM/ETR deficit during the wet sub-period; last ETM (ETM = 0.70) of the maturation phase ... ;
- any special 10-day period: ETR and ETM/ETR are analyzed statistically in the attached classification tables, in which the 10-day periods are numbered from 1 to 36. For irrigated farming, one will consider for instance, the excess probabilities of such deficit levels, and, namely the peak demand probability as well as its size and position in time.

Generally speaking, all ways of utilization mentioned above in 3.2.3 (Basic Information) regarding rainfall data are applicable here, but on the basis of better developed, and thus more precise information.

Finally, one is in a position to imagine what would have been the vegetation period for any year if the maximum RU value had been higher or lower. One observes that if RU is made to vary, then, for the years when an excess can be run off/drained, a 40 mm increase of the RU value only extends the vegetation period by about 10 days while slightly reducing the deficit for the 10-day periods immediately preceding. It will also be observed that as a matter of fact, an RU increase of n mm reduces the total quantity of runoff/drainage (RDRC) by the same proportions.

3.4.2 Phytoecology

The phytoecologist is above all interested in natural vegetation. Consequently, he will be able to consider that prior to the values K = 1.0, all of the rainfall, except for runoff, has been consumed by this vegetation to ensure the actual evapotranspiration (ETR).

Since the ETR/ETM values form a dry product production index, their annual total can be studied statistically as corresponding roughly to the possibilities of feeding the herds, in a relative rather than an absolute value.

3.4.3 Hydrology and Hydrogeology

It is certain that the ORBVCR system, which was not designed for these objectives, cannot for certain give an account of the runoff nor of the makeup of the groundwater. But the same may not be true in the relative sense.

Hydrologically, the major objections to the system is that there is no runoff as long as the maximum RU estimated for the crops or the natural vegetation is not reached. However, on a non cultivated soil, on a badly cultivated soil and in certain instances (steep slopes, very heavy rainfall, battance of the soil surface, mass impermeability...) even on a well-cultivated soil, runoff occurs with the first heavy rainfall.

At SOKODE (Northern Togo), a tropical station with heavy rainfall (1450 mm), the average beginning of rainfall runoff is observed around March 15, while in our system, on the basis of a 120 mm maximum RU, the average beginning of the runoff/drainage (RDR) takes place around May 31 and its average termination around October 10. In DORI (Northern Upper Volta) a dry tropical station (540 mm), with an average beginning of the rainfall around May 15, RDR with an average beginning around July 31 and an average termination around August 31; for 5 years out of 45, there is no RDR on the basis of an 80 mm RU.

Against this point, one may object that a good deal of the precipitation, not run off by the system at the beginning of the season, accumulates in the soil (even more since the system evapotranspires to ETR and not to ETP as so many runoff models do) and is found back at the end of the season in the cumulated runoff/drainage (RDRC). In SOKODE, this RDRC represents on the average, on the basis of a 120 mm RU, 40% of the total rainfall. In DORI, with a 80 mm RU, this is only 20%. But in SOKODE, the drainage portion in the RDRC is higher than the runoff portion, while in DORI, it is the runoff that dominates, without being able to be more precise.

Another major problem with the ORBVCR system is that it does not distinguish between runoff and drainage. If one accepts however that RDRC provides a rough idea of the runoff at the outlet of a basin of adequate dimension, the hydrogeologist may be able to form an idea about the frequency of the aquifer recharge in accordance with the hypotheses he will make regarding the runoff percentage (% RDRC) and in accordance also with the values he will assign to RU: any RU increase by x mm will only result in a drainage reduction by x mm, except in some very unusual years when a long period without continuing rainfall will ensure that this drainage reduction will be 2x mm.

CHAPTER 4

SURFACE WATER RESOURCES

4.1 DESCRIPTION OF AREA

The Savanna Zone of West Africa is an area which, despite the well publicized problems of the drought, has considerable surface water resources. A large amount of research and data acquisition have already been carried out concerning water resources within this zone. The purpose of this chapter is to summarize and supplement this water resource information on a regional basis to provide a baseline document for regional planning.

For this study, the Savanna Zone has been divided into six major river basins which include the Chad Basin, with the Chari and Logone sub-basins; the Niger, the Volta, the Senegal, and the Gambia. The Benue Basin has unfortunately not been included, except for a few representative values, because of the difficulty in obtaining data from Nigeria. In analyzing the surface water resource data of these basins, emphasis was placed on calculating reliable estimates of the annual flows, flood flows and low flows for varying return periods of the major rivers and their tributaries. Flow values have been calculated for all gauging stations within the Savanna Zone with sufficient length of record.

In general, the most striking feature of the Savanna River basins is the variability of flow within the rivers and their tributaries, not only within a given year, but also from one year to another. Another feature of the Savanna Basins is the large amount of water which is lost to evaporation and evapotranspiration. In the following section, a short description of each basin is presented as well as brief discussions on small watershed runoff, sedimentation and water quality.

4.1.1 Chad Basin

The Chad Basin has a total surface area of 2,335,000 km^2 and is one of the largest closed river basins in the world. Instead of emptying into the sea, the river basin drains into Lake Chad. The surface area of the basin and Lake Chad extends over portions of six countries: Chad, Niger, Cameroon, Nigeria and the Central African Empire (CAE), and Sudan.

The principal source of the Chad Basin is the Chari River. The headwaters of the Chari River originate in the humid highlands of western Central African Empire. The upper reaches of the Chari Watershed are located at elevations of 600 to 800 meters (m) and receive an average of more than 1,400 millimeters (mm) of rainfall per year. It is estimated that the Chari River discharges a total of about 38.4 billion cubic meters ($10^9 m^3$) per year into Lake Chad.

The largest of all the Chari tributaries is the Logone River which joins the Chari near N'Djamena, about 75 km. from Lake Chad. The Logone River originates in the mountains of eastern Cameroon. The upper reaches of its basin range in elevation from 1,100 to 1,900 m. Like the headwaters of the Chari, the headwaters of the Logone receive an average of more than 1,400 mm. of rainfall per year. The high rainfall and the steep slopes favor high rates of runoff. Specifically, the annual flow of the Logone, as measured at Lai, is $16.1 \times 10^9 m^3$. Below Lai, the flow of the Logone is augmented by about $0.5 \times 10^9 m^3$, by water discharged into it from the Tandile River. Consequently, the total discharge of the Upper Logone Basin is $16.6 \times 10^9 m^3$ per year.

Another major tributary of the Chari is the Bahr Sara. The Bahr Sara joins the Chari River just below Sarh in southwestern Chad. The annual flow of the Bahr Sara into the Chari, as measured at Manda, is $16.6 \times 10^9 m^3$.

The eastern and southern tributaries of the Chari individually contribute much less annual flow than the Logone or the Bahr Sara. Specifically, the four eastern tributaries (Salamat, Bahr Keita, Mya and Bahr) supply only about 9.3×10^9 m^3, although they drain about 50 percent of the Chari-Logone watershed. The southern tributaries (Bangoran, Bamingui, and Gribingui) probably contribute an estimated 4.0×10^9 m^3 annually.

By adding the flows of all of its tributaries (i.e. 16.6×10^9 m^3 from the Logone, 16.6×10^9 m^3 from Bahr Sara, 9.3×10^9 m^3 from the eastern tributaries and 4.0×10^9 m^3 from the southern tributaries) it would appear that the total yearly flow of the Chari, just below N'Djamena should be 46.5×10^9 m^3. However, the total volume of water emptying into Lake Chad from the Chari River is 38.4×10^9 m^3/year. Thus, the difference between the expected and actual flows is 8.1×10^9 m^3. It is believed that about 6.0×10^9 m^3 of this 8.1×10^9 m^3 is lost to evapotranspiration and that about 2.1×10^9 m^3 overflows into an adjacent watershed during periods of high flow. It is thought that the El Beid River, located just west of the Chari-Logone watershed in Northern Cameroon, receives this 2.1×10^9 m^3 of overflow, which it then discharges into Lake Chad. Flow records indicate that the Logone loses about 28 percent of its flow between Lai and Logone Gana; and the Chari loses 12 percent of its flow between the Salamat confluence and N'Djamena.

Very little is known about the area which is flooded by the Chari River or about the frequency and duration of the flooding. No detailed studies have been made of stage versus flooded area. From year to year the maximum area flooded may be 20 to 30 times the minimum.

4.1.1.1 Lake Chad

Lake Chad is unusual in that, although lying in an apparently closed drainage basin and subject to intense evaporation, it is a fresh water lake. Salinity of the lake's water as measured by electrical conductivity has been studied by several researchers (Bouchardeau, 1958; Carmouze, 1971, 1972 and 1976). Salinity is least in the southern portion of the lake because of dilution from the Chari and increases gradually to the north. Nevertheless, the maximum salinity does not exceed (k^{20} 1,000 umhos) which is well within the freshwater range. The salinities of Lakes Tanganyika, Albert, Edward and Rudolf in Tropical Africa are all higher than this and they all support a rich and variable flora and fauna (Beadle, 1974).

As noted previously, the Chari River contributes approximately 38.4×10^9 m^3 of water per year to Lake Chad . Additional contributions are received from the El Beid, the Yedseram, and Komadugu Yobe amounting annually to 2.1, 0.1, and 0.5×10^9 m^3, respectively. The amount of water coming into Lake Chad has varied considerably over time. During this century alone, the surface area of Lake Chad has fluctuated between 10,000 and 25,000 km^2. Today, the lake has an average depth of about four meters and a maximum depth of 7 to 12 meters. Inflow from tributary streams and rainfall on the lake average about 2,330 mm/year. This amount is largely offset by an evaporation rate of about 2,100 mm/year.

Efforts to determine the area of the lake as a function of depth have not been very successful. Part of the difficulty stems from the fact that the shoreline is difficult to define as much of it consists of swampy wetlands. Also, numerous small islands on the north and northeast sections of the lake obscure portions of the lake's shoreline.

Water balance studies (as reviewed by Roche in 1970), have given estimates that over 90 percent of the lake inflow is evaporated. Normally, such an evaporation rate would result in a very saline lake.

There are three possible explanations of the mechanism whereby salts are removed from the lake. It is believed that a small amount of salt is precipitated out of the water and is absorbed by organisms, especially mollusks. Some salt is believed to be removed from the lake during flooding. During the seasonal rise in the lake's volume, water fills the northeastern bays and inlets. As the lake level falls, these saline bays are isolated from the lake and left to evaporate. However, most of the salt removed from the lake is believed to be deposited in the desert sands located at the northern rim of the lake. Although quantitative values are lacking, it is thought that there is constant seepage of water from the lake into the clay and water bearing sandy layers of the northern rim. The salinity of wells in this area has been found to be 10 times that which is discharged by the rivers. Therefore, it is thought that subterranean seepage is probably the main route by which salt is lost from the lake. Given the amount of salt which is brought into the lake, it is estimated that possibly 65 to 165 m^3 per second (2 to 5 x 10^9 m^3 annually) of saline water seeps out of the lake.

4.1.2 Niger Basin

The Niger River Basin encompasses the major portions of four countries, Guinea, Mali, Niger and Nigeria, and minor portions of five other countries, Ivory Coast, Upper Volta, Benin, Chad and Cameroon.

The Niger River Basin is about 4,000 km. long, but only 300 to 500 km. wide. Its drainage area is difficult to delineate because a significant part of it consists of intermittent streams in Mali and Niger. The area known to contribute potential runoff to the Niger River is estimated to be 1,000,000 km^2, although the total basin is about 1,900,000 km^2. Hydrologically, the basin is divided into four sections: the Guinea and Mali headwaters, the Interior Delta, the Sahelian section, and the humid Nigerian section below Niamey. Each hydrologic section is discussed below.

Four streams, the Mafou, the Niandan, the Milo and the Tinkisso are the sources of the Niger. They flow into the Niger in the Fouta Djallon Mountains of Guinea, where the average annual rainfall is 2,500 mm. All of these streams have been gauged, but no information has been available from the Guinean stations since 1957. However, since the data from the Guinean stations are believed to correlate well with data which are available from Malian stations downstream, it has been possible to extend the Guinean flow data from the flow readings available in Mali.

Another tributary of the Niger which originates in Guinea is the Sankarani. It joins the Niger downstream of the Malian border. The key gauging station for measuring flows of the upper Niger is at Koulikoro. With 70 years of continuous readings, this station provides an excellent historical record of flow patterns in the upper Niger. The average annual flow at Koulikoro is 47.9×10^9 m^3.

In addition to the four streams constituting the source of the Niger and the Sankarani, the other principal water resource in the Guinea and Mali headwaters of the Niger River Basin is the Bani. The Bani drains a basin of 129,500 km^2, located to the east of the Niger upper basin. The Bani is formed by the Baoule, Bagoe, and Bafing. Its headwaters are located in the Ivory Coast in an area which is similar to the Fouta Djallon Mountains in that it has an average annual rainfall of 2,500 mm. However, this area is located at lower altitudes than the Fouta Djallon Mountains. Consequently, the potential for runoff into the Bani is less than the runoff of the Niger headwaters. Therefore, although the Bani drains a large area, its contribution to the Niger as measured at a key station in Douna is 18.5×10^9 m^3. Below Douna, the runoff of the Bani decreases significantly in volume as a result of evapotranspiration.

The second hydrologic section of the Niger River Basin, the interior Delta, has a great influence on the flow of the Niger River. The Delta is an immense natural reservoir consisting of swamps, multiple channels and lakes. It varies in size with the seasons, occasionally reaching a maximum area of up to 80,000 km^2. The effect of this reservoir on the flow of the Niger is both beneficial and adverse. On the one hand, the Interior Delta moderates flood flows by acting as a vast retention basin, thereby beneficially regulating downstream flows. On the other hand, the retention of river water promotes considerable evaporation and evapotranspiration losses. Specifically, it is estimated that, based on the flow data measured at both Koulikoro and Douna, an average of 49 percent or a range of 40 to 54 percent of the total river flow is lost in the Interior Delta.

The third hydrologic section, the Sahelian section, extends from Timbuctou to Niamey. In this section, the Niger River flows east along the "bend" and then south. For the 700 km. between Timbuctou and the Niger border, the Niger River maintains a constant flow, although about 10 percent of its volume is lost to evaporation. The Niger River is the only water resource in this arid region between Timbuctou and the Niger border.

South of the Niger border, several tributaries, which originate in Upper Volta, pour into the river and virtually offset evaporation losses. From the Niger border to Niamey, the river flow is relatively uniform. Usually, maximum flow levels (i.e. the flood peak) are recorded at Niamey during January or February, some four months after the end of the local rains.

The fourth hydrologic section extending from Niamey to the Atlantic, is characterized by a large increase in flows. Below Niamey, tributaries originating in Benin augment the flows in the Niger River such that at Gaya, near the Nigeria border, the annual flow of Niger River flow is 14 percent greater than that measured at Niamey.

At Gaya two flood peaks occur in the year, one in September following the local rains, and another in February when the flood waters from the other hydrologic sections reach Gaya.

Below Sokota, the local rains contribute more water to the river than do the upstream flood waters which arrive in February. One reason why flows increase rapidly downstream is that the Niger River flows through the Jos Plateau, which has steep slopes and high rainfall. Also, in the downstream reach of the Niger River, flows are augmented by runoff from the Benue Basin. The mean annual flow of the Benue is greater than that of the Niger above the confluence at Lokoja. Although the scarcity of recent hydrologic data at CIEH from Nigeria has precluded detailed analysis of the section of the river which transects Nigeria, it is known that the Niger discharges some 175×10^9 m^3. of water annually into the Gulf of Guinea.

In 1968 the Kainji dam was completed on the Niger. The dam is 8.3 km. long, and 65.5 m. high. The Kainji Lake which is formed by this dam has a surface area of about 1,250 km^2, and a volume of 15×10^9 m^3. The annual inflow is at least three times the storage, resulting in a very rapid flow-through. The annual drawdown of the lake averages 10 meters. The area of land which is exposed when the lake is drawn down and then flooded when the lake is refilled is extensive. However, it is not suitable for cultivation because of the pattern of drying and flooding.

4.1.3 Volta Basin

The Volta River Basin extends over 398,860 km^2. Eighty-five percent of the basin is located in Upper Volta and Ghana, although it also transects four other countries: Ivory Coast, Benin, Togo and Mali. The headwaters of the basin are in Upper Volta ; the mouth is in the Gulf of Guinea. The total distance from the headwaters to the Gulf of Guinea is 1,520 km. The basin consists of several independent sub-basins: the Black Volta, the White Volta and its tributary, the Red Volta; the Oti, and the Volta River itself.

4.1.3.1 Black Volta

The Black Volta rises in the Banfora Plateau, in western Upper Volta, and flows 1,105 km. before reaching Lake Volta in Ghana. Like most Sahelian streams it first flows north and then turns southward. In this case, the river turns south at its confluence with the Sourou. In addition to serving as a tributary to the Black Volta throughout the year, the Sourou acts as a retention basin for water which overflows into it from the Black Volta during the flood season. It is estimated that 250 million m^3 of water overflow into the Sourou from the Black Volta. Because the Sourou is large and shallow, approximately half of this flood water is evaporated, while the other half reenters the Black Volta at the confluence of the Sourou and the Black Volta.

A key gauging station of the Black Volta is located at Bui, which is about 130 km. from Lake Volta. The average annual flow of the Black Volta as measured at Bui is 7.78×10^9 m^3, of which about 3.6×10^9 m^3 comes from the Upper Volta. The annual runoff at Bui is equivalent to about six percent of the total volume of precipitation occuring in the Black Volta Basin. During periods of high flow (usually in September), the average monthly flow measured at Bui is about 940 m^3/s. During low flows (usually in March), the average monthly flow is 4 m^3/s.

4.1.3.2 White Volta

The White Volta rises in the Sahelian Zone and therefore flows only after periods of heavy rainfall. The river bed slopes gently, thereby promoting the formation of a series of shallow pools. These pools are filled with water during the flood season, but are empty during the dry season. The pools vary in size, up to one km. in width, in the upper reaches of the White Volta Basin.

Two important tributaries, the Sissili and the Red Volta, join the White Volta in Ghana and raise the average annual flow measured at Nawuni to $7.8 \times 10^9\ m^3$. The total discharge of the White Volta represents only about 10 percent of the rainfall which falls within the Volta River Basin.

4.1.3.3 Oti

The Oti has its source in northern Benin where mountains with altitudes above 600 meters, combined with steep slopes, cause high runoff. The annual runoff for the Oti, as measured at Sabari, averages $13.1 \times 10^9\ m^3$ which is equivalent to about 16 percent of the total volume of rainfall on the contributing area.

4.1.3.4 Volta

Prior to the construction of the Akosombo Dam in 1964, and the subsequent creation of Lake Volta, the Volta River originated at the confluence of the Black Volta and White Volta. Since 1964, this confluence and most of the Volta River have been inundated by the reservoir. Below the Akosombo Dam, the Volta River continues a distance of 99 km. to the sea.

Lake Volta is 400 km. long and covers an area of $8,730\ km^2$ at an average depth of 17 m. when full. It is primarily fed by the Black Volta, the White Volta, and the Oti; although, several smaller tributaries, the Daka, the Pru, the Afram and the Gbanhou also empty into it. The total capacity of Lake Volta has been estimated at $148 \times 10^9\ m^3$. About one fourth of the entire flow from the Volta River Basin is retained in Lake Volta. The remainder of the flow is discharged into the Gulf of Guinea, less minor diversions to the Asutsuare irrigation scheme and evaporation and seepage losses en route.

4.1.4 Senegal Basin

The Senegal River is over 1,800 km. long and drains a basin of 290,000 km^2. The river discharges an annual average of 20×10^9 m^3 into the Atlantic Ocean. The Senegal River proper begins about 1,060 km. upstream from the Atlantic Ocean at the confluence of the Bafing and Bakoye Rivers. Almost all of the flow in the Senegal River, a total of 830 m^3/s during May, comes from its principal tributaries: the Bafing, the Bakoye, and the Falema, together with its minor tributaries: the Kolombe and the Karakoro.

4.1.5 Gambia Basin

The Gambia Basin has a total area of 77,850 km^2. About 77 percent of the basin lies in Senegal, 14 percent in Gambia, and 9 percent in Guinea. The principal water resource within the basin is the Gambia River.

Like the Senegal and Niger Rivers, the Gambia River has its source in the Fouta Djallon Mountains. The total length of the river is 1,184 km. About 500 km. of the river (as measured upstream from the mouth), are tidal. During the dry season, about 250 km. of this estuary is saline.

Along its course from the Fouta Djallon Mountains to the Atlantic Ocean, the character of the river changes considerably. Beginning at an altitude of 1,500 m., the river falls rapidly for 300 km. to an altitude of 75 m. at Mako, Senegal. It then meanders slowly across 300 km. of "Continental Basin" to Gouloumbo which is located virtually at sea level. Finally, it flows 500 km. under tidal conditions at sea level to the Atlantic Ocean.

Reports by Howard Humphreys (1974) and ORSTOM (1974) provide the basic hydrologic information for the Gambia River Basin. Only one gauging station, Gouloumbo, has more than six years of record and before 1970 data gathering at this station was very intermittent. Since 1970, many gauging stations have been installed in the basin, in particular in the Continental Basin (see Map 4-1). The records to date have been influenced by the drought and are not representative of average conditions. However, preliminary analysis suggests that data from the Senegal River could be used to extrapolate flow data for the Gambia River, thereby compensating for gaps in the Gambia River flow data.

According to data obtained from the gauging station at Gouloumbo, the average annual flow of the Gambia River is about 305 m^3/s and the 10-year frequency high flow is 450 m^3/s. About 95 percent of the annual flow measured at Gouloumbo occurs during the months of July to November.

4.1.6 Lesser Basins

To complete the descriptions of the main basins, mention must be made of the relatively small but important rivers which flow south and westwards directly into the Gulf of Guinea, and the Atlantic Ocean.

The principal ones are:

Senegal - Casamance
Guinea Bissau - Corubal, Cacheu
Guinea - Lopa, St. Paul, Konkoure, Sangan
Ivory Coast - Komoe, Bandama, Sassandra

The total drainage area of these rivers within the savanna is about 290.000 Km^2.

Referring to Map 4-2 it can be seen that, whereas most of the west-flowing rivers run entirely through the Savanna region, those flowing to the southwest and south leave the Savanna region and enter the Guinea forest zone before reaching the ocean.

No detailed analysis of these areas was made. However, it appears that yields in the southwest (Fouta Djallon) are very high, more than 600 mm per year (19.2 $l/sec/km^2$), whereas these in the Senegal (Casamance) areas are much lower, probably less than half of this value.

Finally, mention must be made of the catchment areas to the south of Lake Chad basin, where most of the rivers drain to the Oubangui River. All of the rivers within the Central African Empire are relatively small. To the west, a larger one, the Mambere flows directly to the Zaire River (Congo) and further west again, those which rise in the vicinity of the Mbang Mountains, flow into the Gulf of Guinea. The total drainage area of these rivers exceeds 400,000 km^2.

Further east there are high yield rivers which discharge into the Zaire River. Typical tentative specific yields are 500 mm at least, (16.$l/sec/km^2$) reducing to 200 mm and less (6.4 $l/sec/km^2$) in the east.

4.2 MATERIAL STUDIED

Surface Water data were obtained primarily from three sources. First, published monographs by ORSTOM were obtained and studied for the Chari, Logone, Niger, Senegal, and Senegal portion of the Gambia River. A monograph for the Volta River system has also been completed but is not yet published. The upper basin portion of the Gambia River is discussed in a report prepared by Howard Humphreys (1974) for the UNDP. The ORSTOM studies are exhaustive and generally of excellent quality. However, except for the Volta and Gambia studies, the data reported do not incorporate the last nine to thirteen years and do not include the recent drought years.

Second, recent yearbooks of discharge data, published by the national hydrologic services of individual countries or by the national services in conjunction with ORSTOM, were examined. The relative input of ORSTOM varies among countries. The quality of the yearbook data information was found to be highly variable from country to country (see Table 4-1). This data was supplemented by published reports from various organizations on specific projects. Whenever publications were found to report conflicting data, the information found in the most recent source was retained.

In general, the standard of ORSTOM stream gauging is very high and is based on multi-point exposure of the current-meter. The daily mean discharge is calculated using a computer program in which the rating curve is represented by a series of quadratic equations fitted mathematically to the measured flows. This method, introduced only a few years ago, has been used in all recent publications of streamflow data and accounts to some degree for the divergence between these publications and the earlier published data.

The third source of surface water data was the national hydrologic services of the individual countries. The availability and accessibility of data varied considerably among countries. The data obtained from these sources undoubtedly contain some errors. Quality checks for individual stations were obviously warranted because of questionable reporting but were impracticable to check because of time considerations. The expected up-dating of rating curves for certain stations will also likely introduce some differences from the data used in this study for the most recent years of record. In spite of possible future revisions the compilation of all discharge data, especially the inclusion of the 1969 to 1974 drought years, is believed to be justified.

TABLEAU/TABLE 4-1

ANNUAIRES HYDROLOGIQUES DISPONIBLES AU C.I.E.H.

HYDROLOGIC YEARBOOKS AVAILABLE AT C.I.E.H.

PAYS/COUNTRY	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77
FRANCE D'OUTRE MER/ AFRIQUE FRANCOPHONE	(1) X	X	X	X	X	X	X	X	X	X	X	X								
BENIN				X(2)	X(2)	X(2)	X(2)	X(2)												
CAMEROUN					X	X	X	X	X	X	X	X	X	X	X	X	X			
COTE D'IVOIRE								X(3)	X X(3)	X X(3)	X X(4)	X X(5)	X X(6)	X X(7)	X X(7)	X X(7)				
EMP. CENTRAFRICAIN		X(8)	X	X	X	X	X	X	X	X	X	X	X	X(8)						
GAMBIA																				
GHANA		X(9)	X(9)	X(9)	X	X	X	X	X	X	X									
GUINEE																				
HAUTE-VOLTA								X	X	X	X	X	X	X	X	X	X	X		
MALI												X	X	X						
NIGER									X	X	X	X	X	X	X (10)	X (11) X (12)	X (13)	X (14)	X (15)	
NIGERIA (Kano State)							X	X	X	X	X	X	X	X						
SENEGAL																		X	X	
TCHAD			X	X	X	X	X	X	X	X	X	X	X	X	X(16)	X(16)	X	X	X	
TOGO		X(17)	X	X X	X X	X X	X X	X X	X X	X	X	X	X	X(17)						

Notes pour le Tableau 4-1/Footnotes to Table 4-1

1. CIEH a les annuaires des années 1949 à 1957/CIEH holds yearbooks for the years 1949 - 1957.

2. ORSTOM. Annuaires hydrologique du Dahomey, années 1961, 1962, 1963, 1964, 1965. Cotonou, 1967.

3. ORSTOM. Mesures de débits, années 1965, 1966, 1967. Adiopodoumé, 1969.

4. ORSTOM. Mesures de débits, année 1968. Adiopodoumé, 1969.

5. ORSTOM. Mesures de débits, année 1969. Adiopodoumé, 1970.

6. ORSTOM. Mesures de débits, année 1970. Adiopodoumé, 1971.

7. ORSTOM. Mesures de débits, années 1971, 1972, 1973. Adiopodoumé, 1974.

8. ORSTOM. Annuaire de la République Centrafricaine. (2 vols.). Bangui, 1971, 1972.

9. Ghana. Hydrological Services. The Volta River Basin hydrological data book. Accra, 1966.

10. ORSTOM. Annuaire hydrologique du Niger (le réseau Est-Nigérien). Niamey, 1973.

11. Niger. Service du Génie Rural. Section Hydrologique. Rapport Niger-Moyen. Niamey, 1973.

12. ORSTOM. Annuaire hydrologique du Niger (le réseau Est-Nigérien). Niamey, 1974.

13. Niger. Service du Génie Rural. Section Hydrologique. Rapport Niger-Moyen. Niamey, 1974.

14. Niger. Service du Génie Rural. Section Hydrologie. Rapport Niger-Moyen. Niamey, 1975.

15. Niger. Service du Génie Rural. Section Hydrologie. Rapport Niger-Moyen. Niamey, 1976.

16. ORSTOM. Annuaire hydrologique de la République du Tchad, année 1972. N'Djaména, 1973.

17. ORSTOM. Annales hydrologiques du Togo depuis la création des stations jusqu'à l'année hydrologique 1970-71. (2 vols.). Lomé, 1973, 1974.

The discharge data of some 340 stations (Map 4-1) were examined and about half were judged to contain an adequate length of record for the derivation of dependable averages and for frequency analyses.

Streamflow data are assembled in Appendix 4 (Volume 3) in the form of monthly and annual flows for the complete period of observation at all stations offering a significant period of observation. The Appendix also includes chronological tables of the average annual discharge, the annual volume, the equivalent depth of runoff, and the specific yields. These tables also contain flood and low flows, both of which are treated in another section of the present chapter.

It should be emphasized that these tables are intended to provide an overall indication of the time and space distribution of surface water in the area and that they do not present daily mean discharges essential for operational studies of water development projects. These basic data must be sought from ORSTOM or the national hydrological services of the respective countries.

4.3 METHODS AND RESULTS

4.3.1 Annual Stream Flow

Values of long-term annual streamflow at all stations having a significant length of record are listed together with the volumes, equivalent depth of runoff and specific yields in Tables 4-2 to 4-7(pages 4-18 through 4-23). These tables also furnish values of the streamflow which can be expected in wet and dry years for five and ten-year return periods. The mean, ten-year wet, and ten-year dry streamflow are also presented on Map 4-2.

4.3.1.1 Reference Period

In order that the mean values be statistically homogenous within each main river basin, these values have been reduced to the common time base by upstream-downstream regression or by regression with stations in neighboring watersheds. Stations for which correlation coefficients were not found to be significant within the 95 percent confidence limits have not been included in Tables 4-2 to 4-7 or on Map 4-2. However, the mean annual discharge for the full period of observation at these stations may be found in the Appendix. Figure 4-1 shows the chronological distribution of annual mean discharges of key gauging stations on the Niger, Chari, Senegal and Black Volta Rivers.

Long-term annual means of the observation series have been determined by adding the monthly mean discharges. Thus, information gathered during those years for which flow data records were incomplete is included in this analysis.

4.3.1.2 Variability

Values of the expected five - and ten-year annual flows were determined by fitting frequency distributions to the annual flow series.

These distributions were generally normal but in a number of cases a better fit was obtained with the log-normal distribution. The coefficient of variation, equal to the standard deviation divided by the mean, has been calculated for each of the stations and will be found in Tables 4-2 to 4-7.

4.3.1.3 Equivalent Depth of Runoff

The mean equivalent depth of runoff on the complete catchment area upstream of each gauging station is included in Tables 4-2 to 4-7. The runoff depths on catchments situated between gauging stations are also presented on Map 4-3. Annual isohyets are also indicated on this map.

The runoff values on Map 4-3 were calculated as the difference between the discharges of the two stations divided by the difference in watershed areas. Negative values indicate areas in the Chari, Logone, Volta and Senegal basins where overbank flow gives rise to evaporation losses which are not compensated for by rainfall and runoff. Losses in the lower reaches of the Chari and Logone basins are not indicated on this map because the values obtained for these areas were not compatible with the upstream watersheds.

4.3.1.4 Water Balance

No attempt will be made here to assign numerical values to the

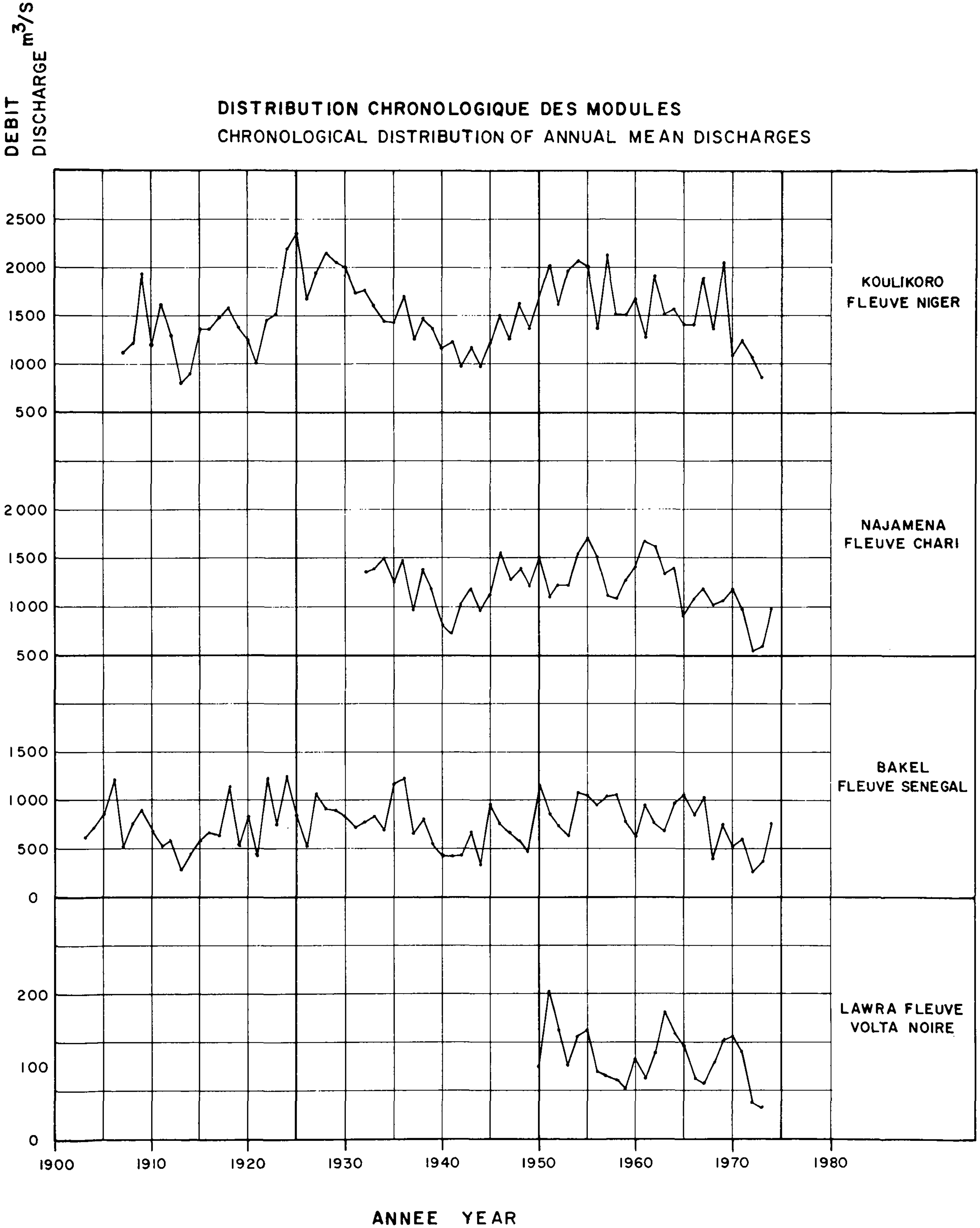

DEBIT
DISCHARGE m^3/S
DISTRIBUTION CHRONOLOGIQUE DES MODULES
CHRONOLOGICAL DISTRIBUTION OF ANNUAL MEAN DISCHARGES
2500
2000
1500
1000
500
KOULIKORO
FLEUVE NIGER
2000
1500
1000
500
NAJAMENA
FLEUVE CHARI
1500
1000
500
0
BAKEL
FLEUVE SENEGAL
200
100
0
LAWRA FLEUVE
VOLTA NOIRE
1900
1910
1920
1930
1940
1950
1960
1970
1980
ANNEE YEAR

Fig. 4-1

Table 4-2 Annual Streamflow Chari Basin 1932 - 1974

River	Station	discharge ($m^3 s^{-I}$) return period (years) dry 10	5	mean	5	wet 10	Volume Mm^3	mean runoff mm	sp. runoff $l\ s^{-I}\ Km^{-2}$	Coeff. of var. CV	area Km^2
Bahr Aouk	Golongosso	45	53	75	94	105	2365	25	0.8	.29	96000
Bahr Azoum	Am Timan	10	15	29	42	50	915	11	0.4	.39	80000
Bahr Sara	Moissala	260	320	495	610	690	15600	230	7.3	.34	67700
Bamingui	Bamingui	8	11	21	30	36	662	151	4.8	.47	4380
	Manda	280	350	525	620	700	16600	209	6.6	.33	79600
Fafa	Bouca	25	30	46	55	60	1450	215	6.8	.35	6750
Gzibingui	Crampel	18	21	27	34	38	851	150	4.8	.25	5680
Ouham	Bozoum	70	76	90	110	120	2840	350	11.1	.20	8100
	Bossangou	180	195	232	275	300	7320	321	10.2	.19	22800
	Batangafo	260	270	316	390	440	9970	223	7.1	.21	44700
Chari	Sarh *	150	190	299	365	400	9430	49	1.6	.34	193000
	Bousso	550	620	832	1020	1130	26200	58	1.8	.26	450000
	Guelendeng	670	720	820	1020	1170	25900	55	1.7	.21	470000
	Mailao	440	550	834	1020	1170	26300	53	1.7	.34	500000
	N'Djamena *	880	990	1217	1460	1600	38400	64	2.0	.25	600000

Table 4-3 Annual Streamflow Logone Basin 1932-1974

River	Station	discharge ($m^3 s^{-1}$) return period (years) dry 10	5	Mean	wet 5	10	Volume Mm^3	Mean runoff mm	sp. runoff $l\ s^{-1}\ Km^{-2}$	Coeff. of var. CV	area Km^2
Pendé	Begouladge	60	64	72	86	95	2270	402	12.9	.17	5640
	Gore	55	75	129	165	185	4070	339	10.7	.41	12020
	Doba C.	60	80	135	165	180	4260	298	9.4	.37	14300
M'Béré	M'Béré	65	78	109	140	165	3440	463	14.7	.30	7430
Tandile	Tchoa	7.0	8.7	13.3	17.2	20	419	71	2.3	.37	5870
Logone	Moundou	260	300	383	440	475	12100	356	11.3	.21	33970
	Lai	320	375	510	620	690	16100	284	9.0	.29	56700
	Bongor	365	420	539	620	660	17000	231	7.3	.21	73700
	Logone G.	240	280	382	430	455	12000	160	5.1	.23	75000

Table 4-4 Annual Streamflow Volta Basin

River	Station	discharge ($m^3 s^{-1}$) return period (years) dry 10	5	Mean	5	wet 10	Volume Mm^3	Mean runoff mm	Sp. runoff $l\ s^{-1}\ Km^{-2}$	Coeff. of var. CV	area Km^2
I. Volta Noire											
Kou	Nasso	3.0	3.7	5.5	6.4	7.0	173	428	13.5	.24	405
Volta Noire	Samendeni	11	13	19	23	25	599	131	4.1	.24	4580
	Nwokuy	15	20	36	42	45	1140	77	2.4	.38	14800
	Kouri	18	22	32	43	50	1010	49	1.5	.36	20800
	Manimenso	18	21	30	36	40	946	30	0.9	.29	32000
	Boromo	28	32	43	50	55	1360	27	0.9	.26	50000
	Ouessa	43	51	72	86	95	2270	37	1.2	.29	62000
	Lawra	57	72	113	140	160	3560	38	1.2	.37	93965
	Bui	150	180	243	340	400	7660	61	1.9	.40	125000
	Bamboi	120	152	254	345	410	8010	60	1.9	.39	134200
2. White Volta											
	Nawuni	160	185	248	310	350	7820	84	2.7	.29	92950
	Yapei	180	210	275	340	370	8670	90	2.9	.26	96320
3. Oti											
Pendjari	Porga	35	45	71	87	100	2240	101	3.2	.35	22280
Magou	Tiele	2	3	5	7	8	156	187	6.0	.49	836
Keran	Titira	25	30	42	54	60	1320	357	11.4	.31	3695
Oti	Mandouri	55	68	102	125	140	3220	111	3.5	.37	29100
	Sansanne M.	60	80	138	180	210	4350	122	3.9	.42	35650

cont'd overleaf

Table 4-5 Annual Streamflow Niger Basin 1907-1973 (I)

River	Station	discharge ($m^3 s^{-1}$) return period (years) dry 10	5	Mean	5	wet 10	Volume Mm^3	Mean runoff mm	Sp. runoff $l\ s^{-1} Km^{-2}$	Coeff. of var. CV	area Km^2
Milo	Kankan	160	170	195	235	260	6150	621	19.7	.19	9900
Niandau	Baro	180	200	246	300	340	7760	616	19.5	.20	12600
Baoulé	Bougouni	95	105	128	155	175	4040	257	8.2	.22	15700
Bagoé	Guinguerini	9	11	15	19	22	473	454	14.4	.28	1042
	Pankourou	110	150	256	310	350	8070	254	8.1	.37	31800
Bani	Douna *	320	400	587	780	900	18500	182	5.8	.32	101600
Niger	Kouroussa	165	185	234	290	340	7380	410	13.0	.27	18000
	Siguiri	750	810	943	1200	1340	29700	424	13.5	.20	70000
	Koulikoro *	1060	1200	1520	1800	2000	47900	399	12.7	.24	120000
	Kirango	1100	1200	1396	1600	1700	44000	321	10.2	.15	137000
	Tilembeya	700	780	954	1100	1210	30000	208	6.6	.20	144000
	Mopti *	925	1000	1149	1300	1400	36200	128	4.1	.14	281600
	Dire *	870	950	1160	1320	1450	36600	108	3.4	.19	340000
	Tossaye	840	910	1125	1290	1400	35500	100	3.2	.19	355000
	Ansongo	825	870	1020	1150	1215	32200	71	2.2	.14	455000
	Niamey *	700	800	1050	1180	1260	33100	47	1.5	.20	700000
	Gaya	900	1000	1200	1380	1500	37800	38	1.2	.17	1000000
Gorauol	Alconqui *	3.5	4.3	6.4	8.5	10	202	4.5	0.14	.38	44850

(I) 1952-1975 for tributaries in Niger

cont'd overleaf

Table 4-6 Annual Streamflow Senegal Basin 1903-1974

River	Station	discharge ($m^3 s^{-1}$) return period (years) dry 10	5	Mean	5	wet 10	Volume Mm^3	Mean runoff mm	Sp. runoff $l\ s^{-1}\ Km^{-2}$	Coeff. of var. CV	area Km^2
Bafing	Dakka Saidou	190	220	272	340	375	8580	546	17.3	.22	15700
	Dibia	270	320	414	510	560	13100	397	12.5	.25	33000
Bakoye	Toukoto	50	60	87	120	135	2740	166	5.4	.33	16500
	Oualia	75	100	162	220	245	5110	60	1.9	.37	85600
Falémé	Fadougou	65	80	113	150	175	3560	383	12.1	.31	9300
	Gourbassi	80	100	160	200	225	5050	337	10.7	.30	15000
	Kidira	100	130	192	250	290	6050	209	6.6	.34	28900
Sénégal	Galongo *	370	440	593	760	860	18700	147	4.7	.29	126900
	Kayes	360	440	613	780	870	19300	123	3.9	.30	157400
	Bakel *	430	540	754	985	1100	23800	109	3.5	.33	218000
	Matam	425	540	763	1000	1120	24100	105	3.3	.33	230000
	Dagana	460	540	684	820	890	21600	81	2.6	.23	268000

Table 4-7 Annual Streamflow Gambia Basin 1903-1974

Gambia	Goulombo	165	210	300	400	450	9460	225	7.1	.34	42000

* IHD (International Hydrologic Decade) Stations

water-balance equation, since in most cases this equation cannot improve the accuracy of the water resource data for the project area. The error involved in estimating river basin rainfall will usually be greater than the total runoff. This error also exists in calculating the actual evapotranspiration loss.

It is possible that a water balance equation could be utilized to estimate the actual evapotranspiration of a large area. On an annual basis and in the majority of the watersheds in this area, groundwater flow is negligible with respect to the magnitude of the other terms of the water-balance equation. Consequently, estimates of actual evapotranspiration losses will always be more realistic than estimates based on soil-moisture extraction models.

It should be noted that differences in rainfall and runoff shown on Map 4-3 will indicate only approximate estimates of the annual evapotranspiration since the reference periods used for runoff differ from those related to rainfall, and areal rainfall can only be estimated by inspection.

4.3.2 Monthly Streamflow

All streamflow regimes in the Savanna are characterized by very large variations of flow between the wet and the dry season. In many cases, the flow ceases altogether during several months. Even the largest rivers exhibit wide variations of flow as shown by the variability of monthly flows in Table 4-8.

For the purpose of uniformity, all flow data presented in the Appendix have been arranged so that the water year starts on the first of May. This choice is justified by the fact that the great majority of streams in the Savanna have minimum flows during the month of April. An important exception is shown by the flow data for the Niger River.

Because of the great length of the Niger River, peak flows take several months to travel from upstream to downstream. As a result, peak flows on the Niger may occur at Koulikoro in September (Fig. 4-4), at Dire in December and at Niamey late in January. Further downstream, at Gaya (Fig. 4-5), two peaks of similar magnitude are observed, the first in September and the second in February. The first peak results from runoff from nearby tributary watersheds, whereas the second peak originates 2,500 km. upstream.

Examples of the variability of monthly mean discharges are given in Figures 4-2 to 4-7. The flows for the selected probability levels (the 10, 25, 50, 75, and 90 percent chance of occurrence), were determined by fitting the log-normal frequency distribution to the monthly discharge series. As might be expected, the monthly flows show a very wide range, particularly during the wet months.

TABLE 4-8

MEAN MONTHLY DISCHARGES AT SELECTED STATIONS

		MAXIMUM MONTH		MINIMUM MONTH	
RIVER	STATION	$m^3 s^{-1}$	Month	$m^3 s^{-1}$	Month
CHARI	N'Djamena	3,090	OCT	73.0	MAY
LOGONE	Lai	1,805	SEP	58.0	APR
BLACK VOLTA	Bamboi	941	SEP	32.0	MAR
NIGER	Koulikoro	5,257	SEP	66.0	APR
NIGER	Niamey	1,761	JAN	106.0	JUN
SENEGAL	Bakel	3,329	SEP	8.9	MAY
GAMBIA	Goloumbo	1,208	SEP	5.0	MAR

4.3.3 Flood Flows

Among 340 stream-gauging stations examined for this report, about 120 stations provide flow data of suitable quality, continuity, and duration to permit a statistical evaluation of flood flows of the 10-year return period with a high degree of confidence. In certain cases the observation periods were long enough to obtain an estimate of the value of flood flows at the 100-year frequency level. However, the latter estimates must be treated with caution in the absence of very long-term historic data and information on channel changes in the reaches in which the gauging stations are situated.

The evaluation of extreme flood flows was not attempted but is usually based on the meteorologic analysis of great storms of record, leading to determinations of probable maximum precipitation, and resulting runoff from contributing drainage areas. The problem becomes extremely complex in very large drainage areas in tropical Savanna regions, where the maximum flood peak is a seasonal phenomenon resulting from the cumulative effect of many partial area storm, events and non-current tributary contributions. Channel and valley storage have a pronounced effect on seasonal hydrographs, modifying short-term contributions and increasing the duration of seasonal flooding. Searches for historic evidence of past great floods are an important part of such investigations.

The more common floods on the larger catchments and probably the extreme floods on the smaller catchments, result from squalls of limited breadth which travel from east to west across the Project Area. Often, these squalls do not lose their intensity as they travel west because water which has been precipitated is continuously renewed by moisture inflow. A study of high intensity showers (Mounis, 1975) revealed that the duration of these showers rarely attains one hour in West Africa (see data for Ouagadougou in Figure 4-8). The short duration of high intensity showers prevents these events from attaining

DEBITS MOYENS MENSUELS SELON LEURS FREQUENCES

FREQUENCY DISTRIBUTION OF MONTHLY FLOWS

CHARI BASIN — OUHAM AT BOZOUM — 8100 Km^2

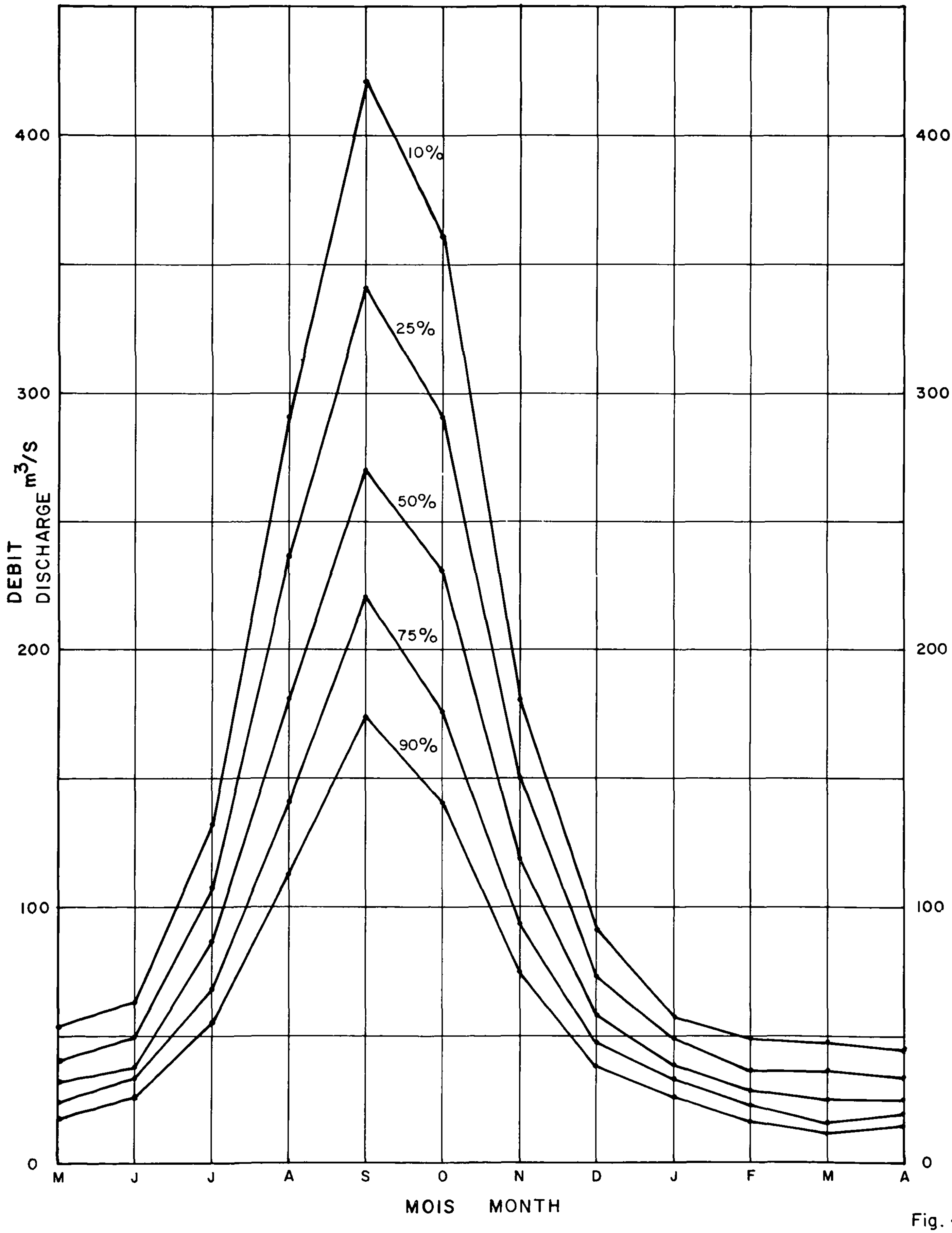


Fig. 4-2

DEBITS MOYENS MENSUELS SELON LEURS FREQUENCES
FREQUENCY DISTRIBUTION OF MONTHLY FLOWS

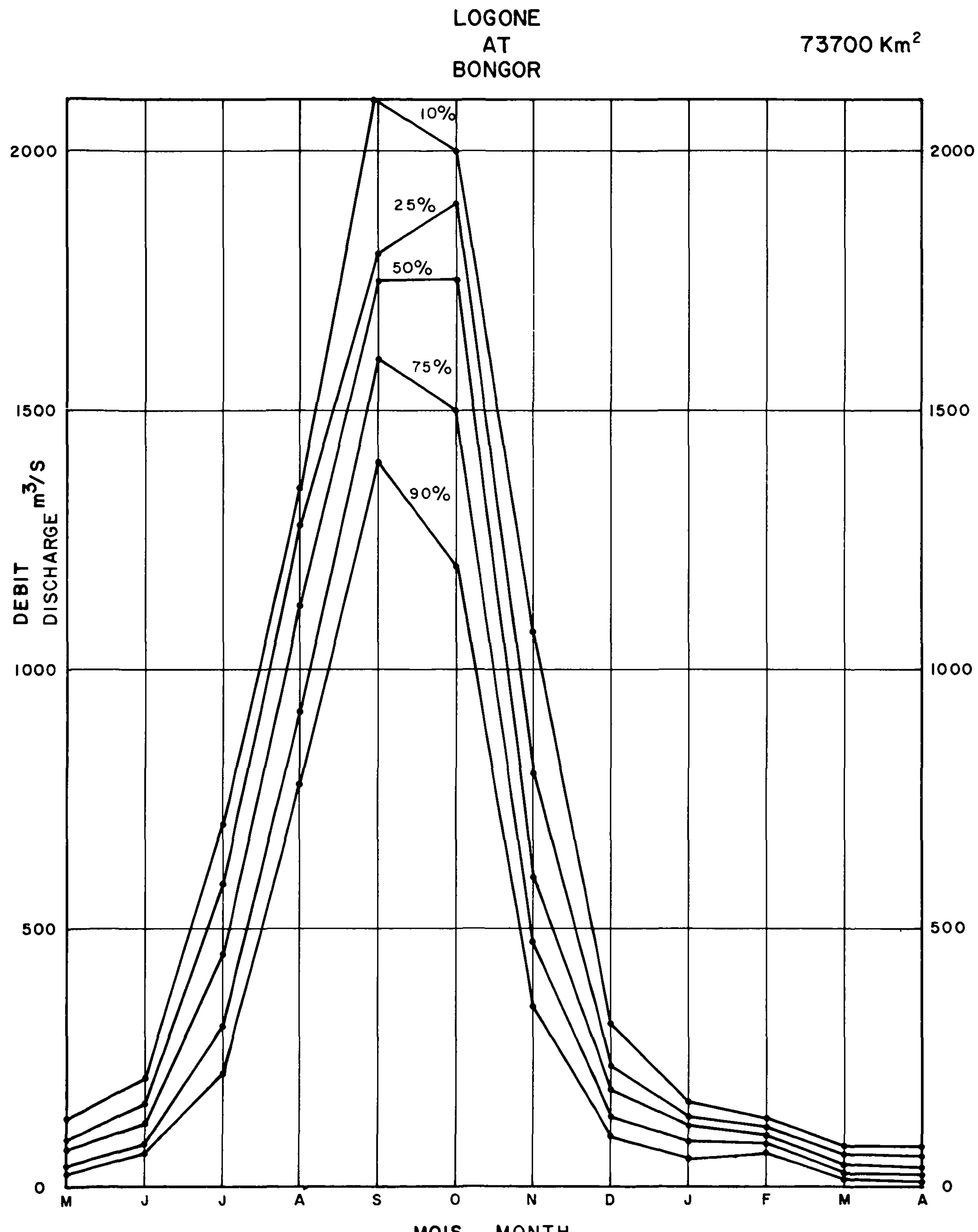


Fig. 4-3

DEBITS MOYENS MENSUELS SELON LEURS FREQUENCES
FREQUENCY DISTRIBUTION OF MONTHLY FLOWS

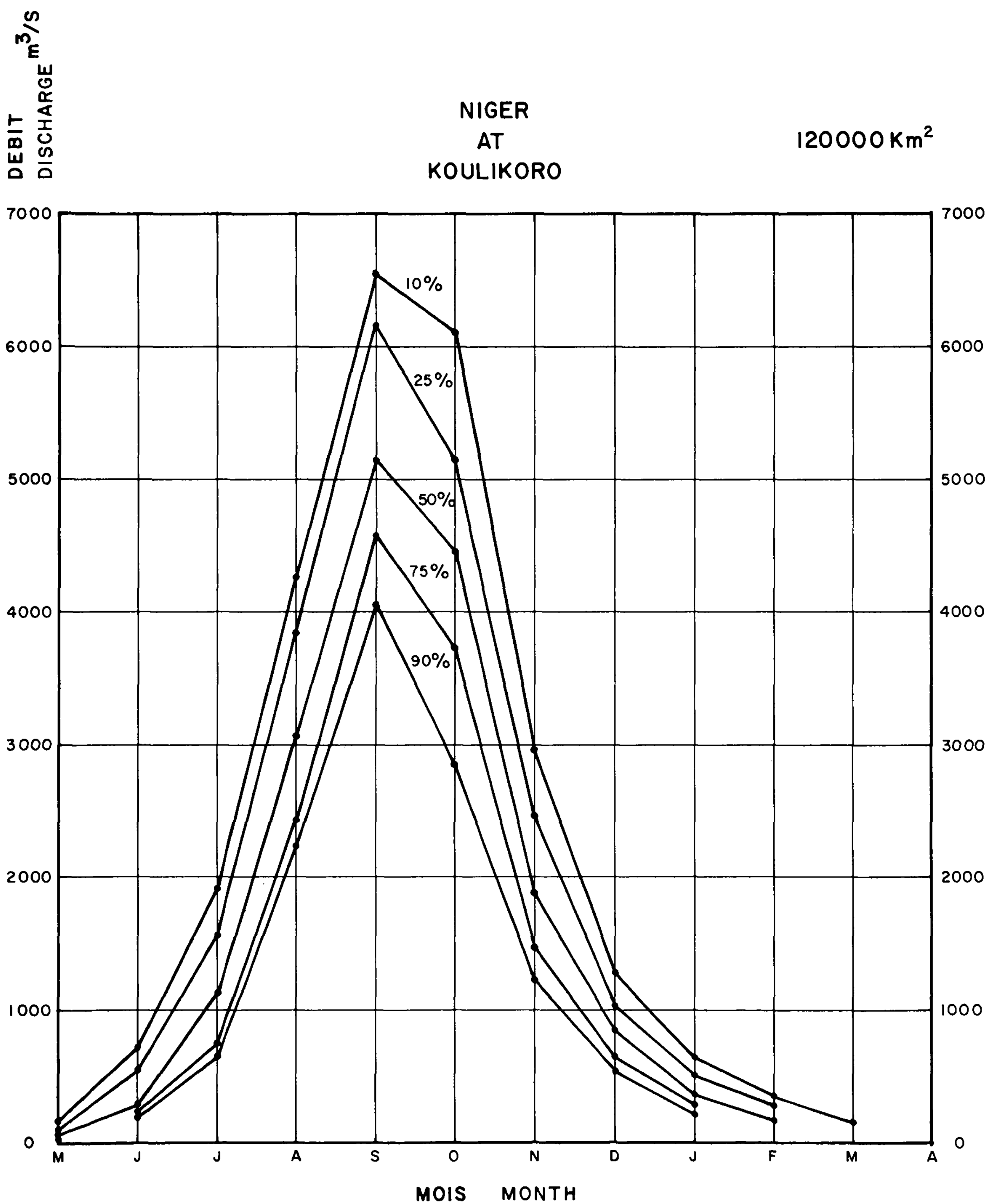
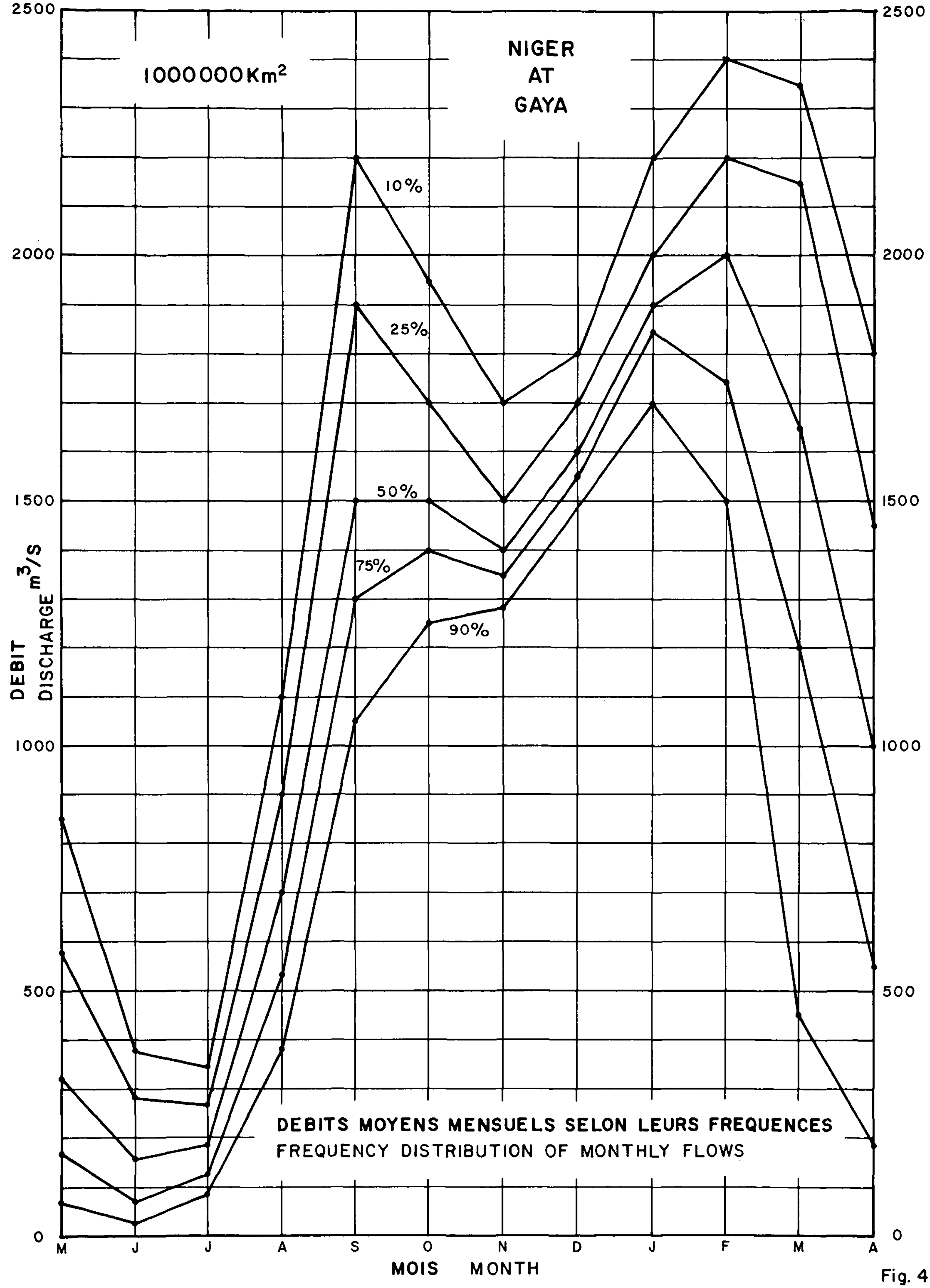


Fig. 4-4



NIGER
AT
GAYA
1000000 Km²
10%
25%
50%
75%
90%
DEBIT
DISCHARGE m³/S
2500
2000
1500
1000
500
0
M
J
J
A
S
O
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M
A
MOIS MONTH
DEBITS MOYENS MENSUELS SELON LEURS FREQUENCES
FREQUENCY DISTRIBUTION OF MONTHLY FLOWS

Fig. 4-5

DEBITS MOYENS MENSUELS SELON LEURS FREQUENCES
FREQUENCY DISTRIBUTION OF MONTHLY FLOWS

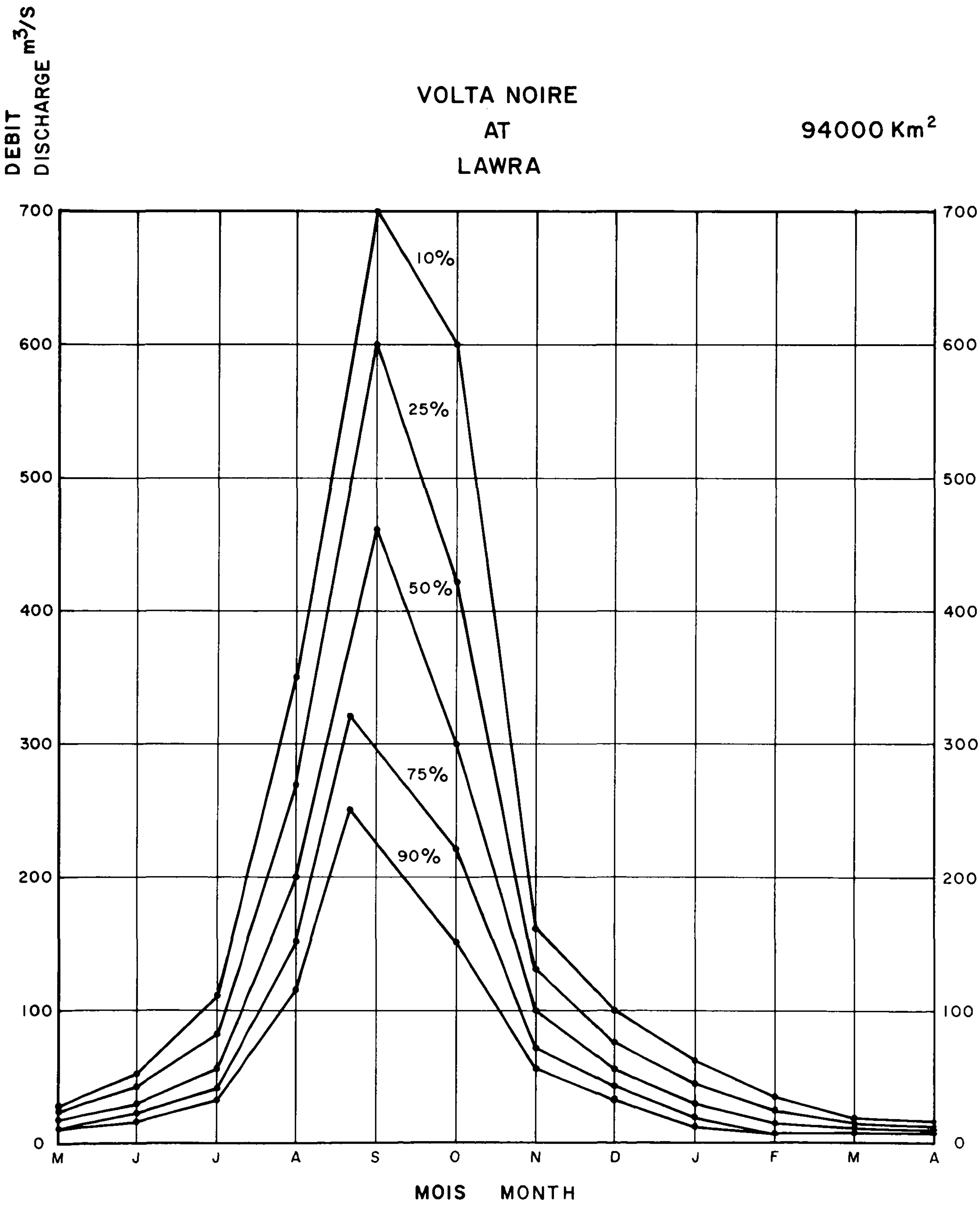


Fig. 4-6

DEBITS MOYENS MENSUELS SELON LEURS FREQUENCES
FREQUENCY DISTRIBUTION OF MONTHLY FLOWS

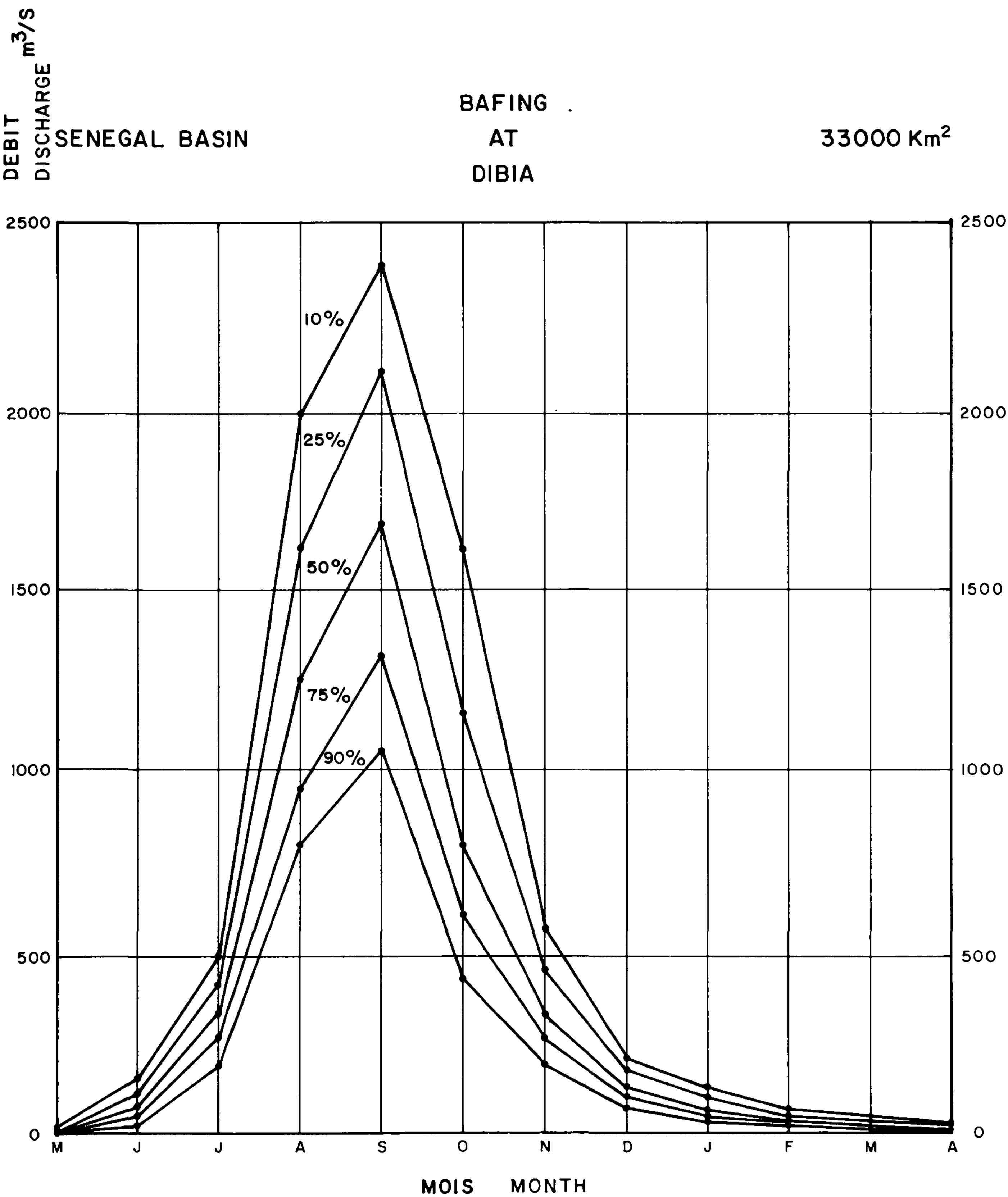
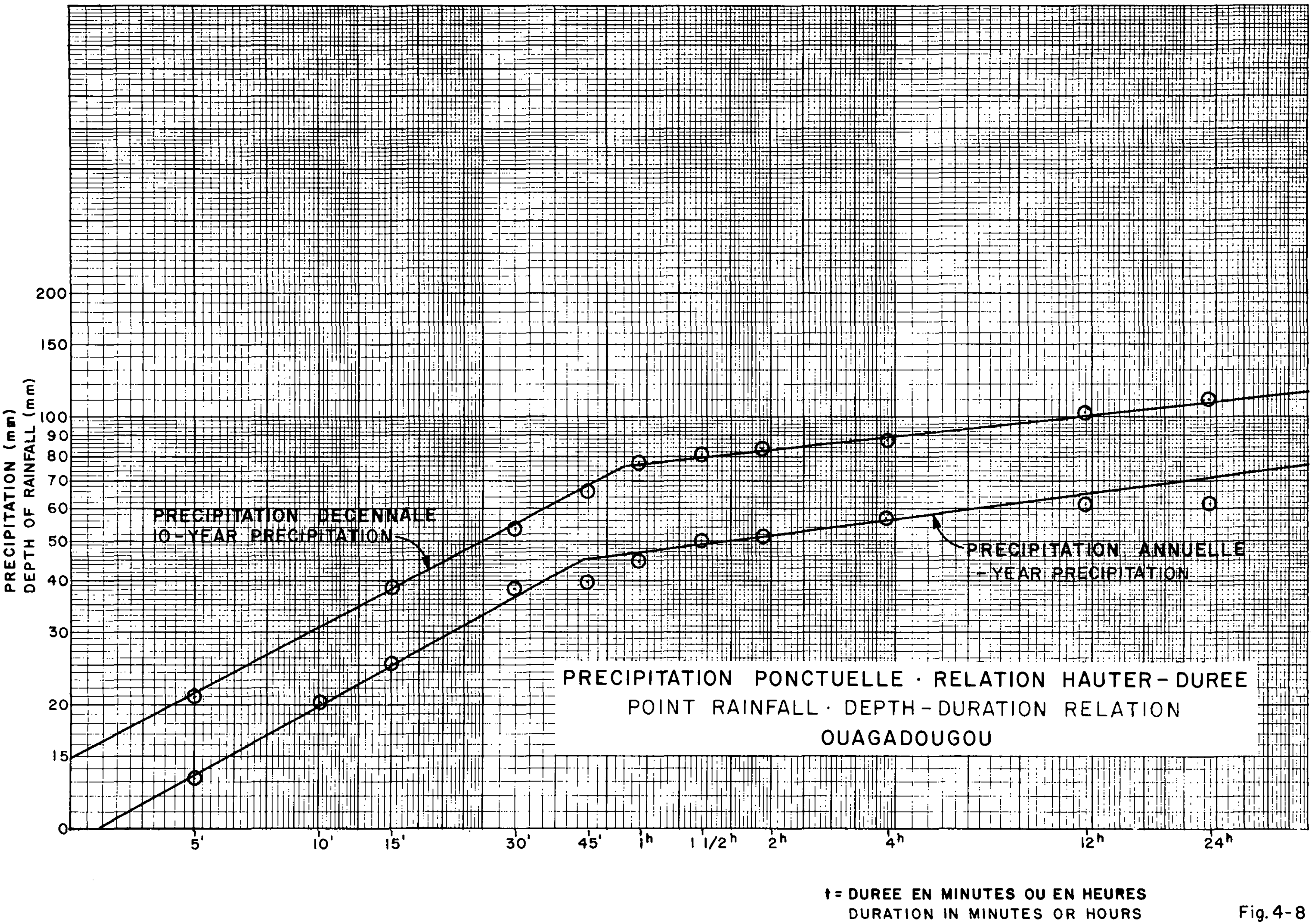


Fig. 4-7



PRECIPITATION (mm)
DEPTH OF RAINFALL (mm)
200
150
100
90
80
70
60
50
40
30
20
15
0
PRECIPITATION DECENNALE
10-YEAR PRECIPITATION
PRECIPITATION ANNUELLE
-YEAR PRECIPITATION
PRECIPITATION PONCTUELLE · RELATION HAUTER-DUREE
POINT RAINFALL · DEPTH-DURATION RELATION
OUAGADOUGOU
5'
10'
15'
30'
45'
1h
1 1/2h
2h
4h
12h
24h
t = DUREE EN MINUTES OU EN HEURES
DURATION IN MINUTES OR HOURS

Fig. 4-8

high total depths (see Map 4-4). Such rainfall incidents give rise to extreme floods on small watersheds but do not involve more than small fractions of the larger catchments at any one time. However, on rare occasions, it appears that the general movement of the monsoon air masses from east to west, accompanied by squalls of limited lateral extension, can be interrupted by the collapse of the Sahara High (ASECNA, 1966). If this occurs at a time when the Southern High encroaches on the African continent, abundant rainfall of several days duration may be observed over large areas giving rise to high flood flows on large watersheds.

As the extreme floods of large river basins may be generated by weather situations which are different from those which produce the more frequent smaller floods, statistical analyses which include only one or two large floods, cannot be relied upon to forecast design floods having return periods of one thousand years or more.

4.3.3.1 Evaluation of Flood Flows

Flood discharge-frequency relations were based on the annual maximum series compiled from the hydrologic records. In all cases, the peak discharge used was the daily mean discharge. This figure will differ from the instantaneous peak flow in the case of the smaller watersheds. Although mathematical methods suited to the derivation of frequency curves by computer are available (Chow, 1964) and, indeed, are presented in Appendix 4, the basic data were also plotted on probability paper and graphical mean curves were drawn. In this way, it was possible to indicate lack of fit of the higher floods to the theoretical relation.

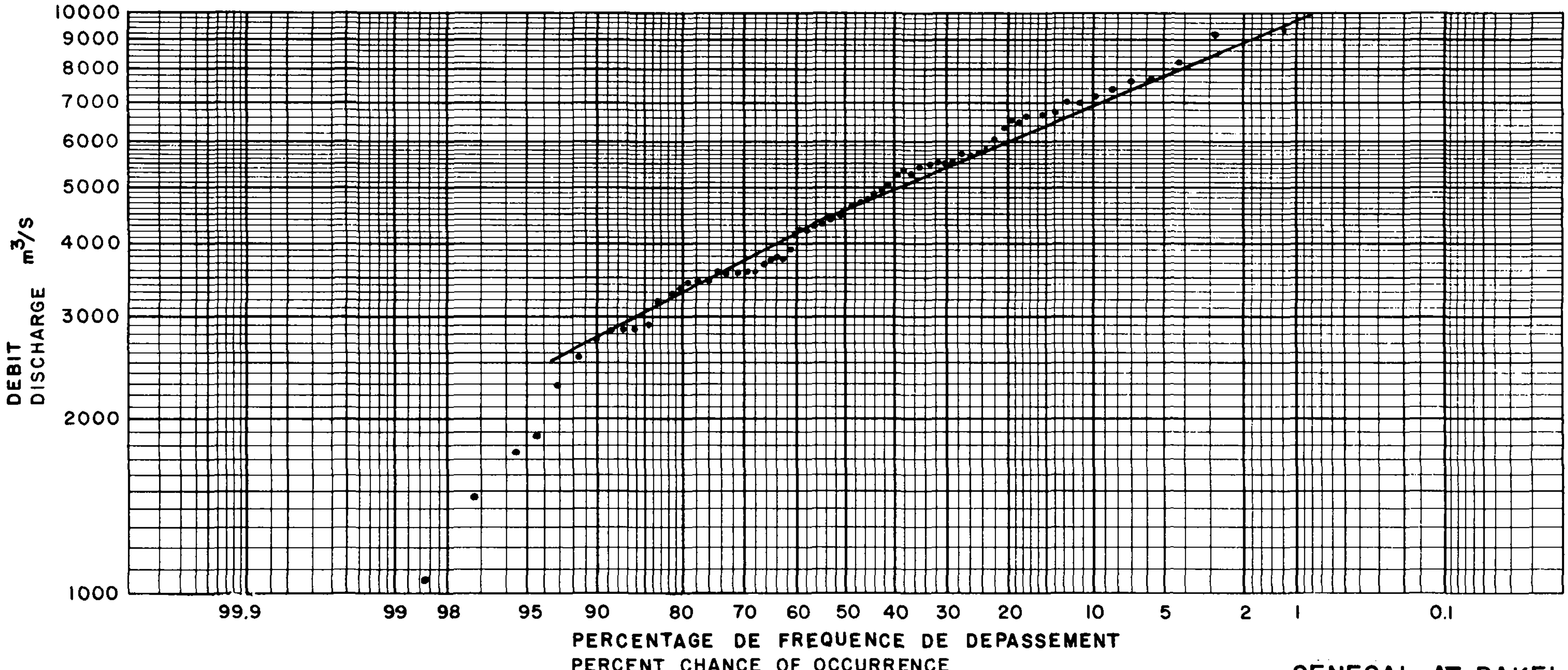
It should be pointed out that although a majority of the stations yield log-normally distributed annual maximum series, stations which present normally distributed samples are not rare in the project area. A few stations in zones of considerable over-bank flow have hypogaussian distributions of flood flows. One case was found where the most suitable frequency distribution appeared to be log-extremal, the "Malian" ("black") floods of the Niger River at Gaya near the entry to Nigeria.

Typical examples of different frequency distributions fitted to annual maximum flood series are shown on Figures 4-9 to 4-15.

4.3.3.2 Ten-Year Floods

Tables 4-9 through 4-14 present the best estimates of the 10-year floods considering both theoretical frequency relations and graphical interpretations of the plotted data. All the flood values contained in these tables are reproduced on Map 4-4 together with the values of the specific flows. The relation between the magnitude of the 10-year flood and the watershed area, (assumed here to be of the form $Q = AS^n$) has been determined for each basin by the method of least squares. These relations are indicated in Table 4-15 together with the correlation coefficient (r).

To locate the probable upper limit in the 10-year flood flows, envelope curves were drawn for each main basin as shown on Figure 4-16, together with the equations of the curves which were drawn parallel to the mean relations indicated in Table 4-15.

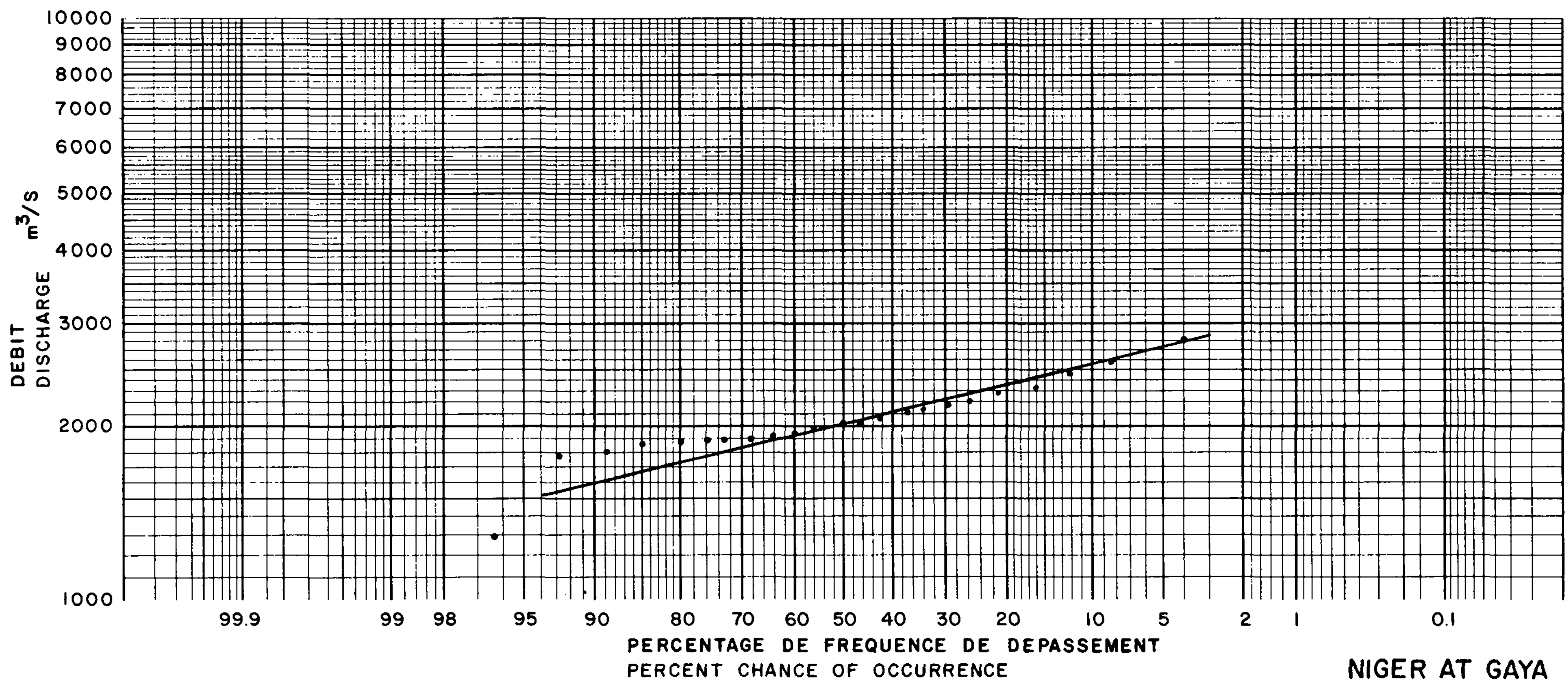


SENEGAL AT BAKEL

FREQUENCE DE CRUE

FLOOD FREQUENCY

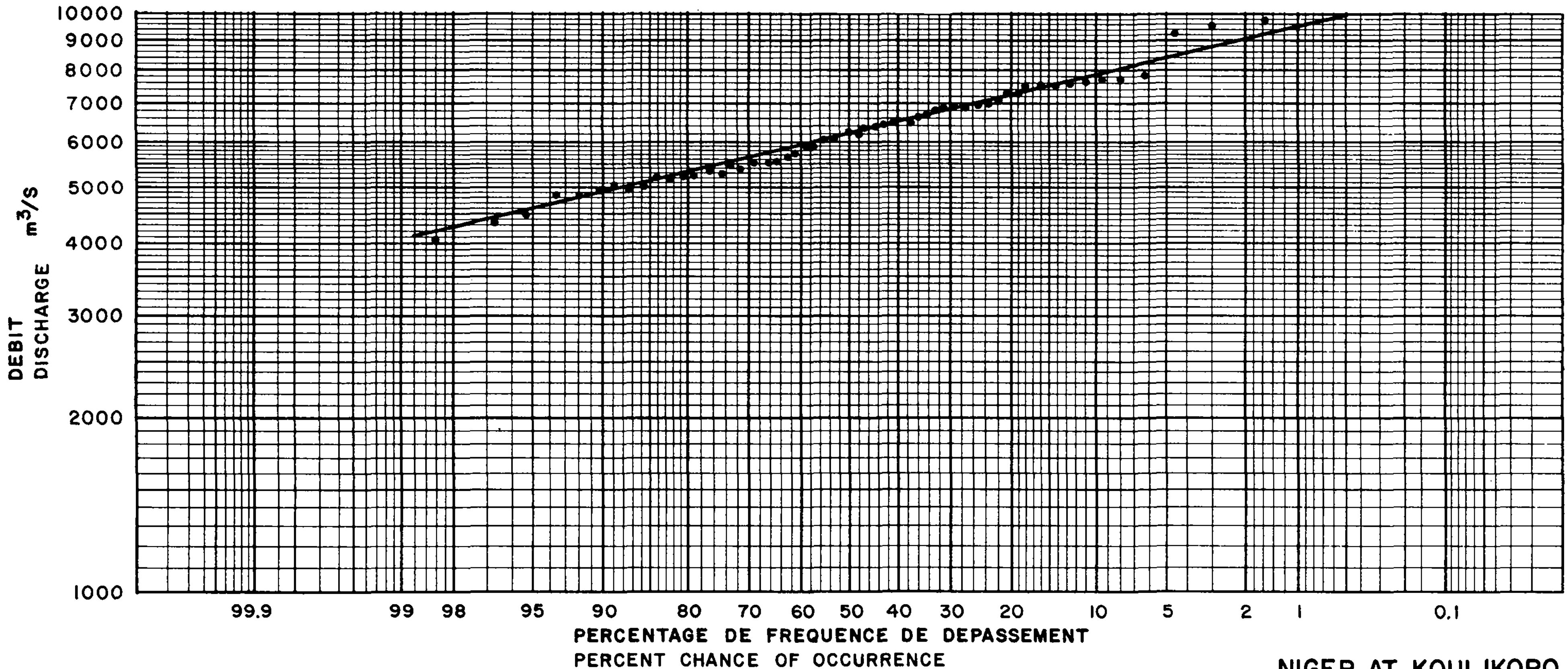
Fig. 4-9



NIGER AT GAYA
CRUE MALIENNE
MALIAN FLOOD

FREQUENCE DE CRUE
FLOOD FREQUENCY

Fig.4-10

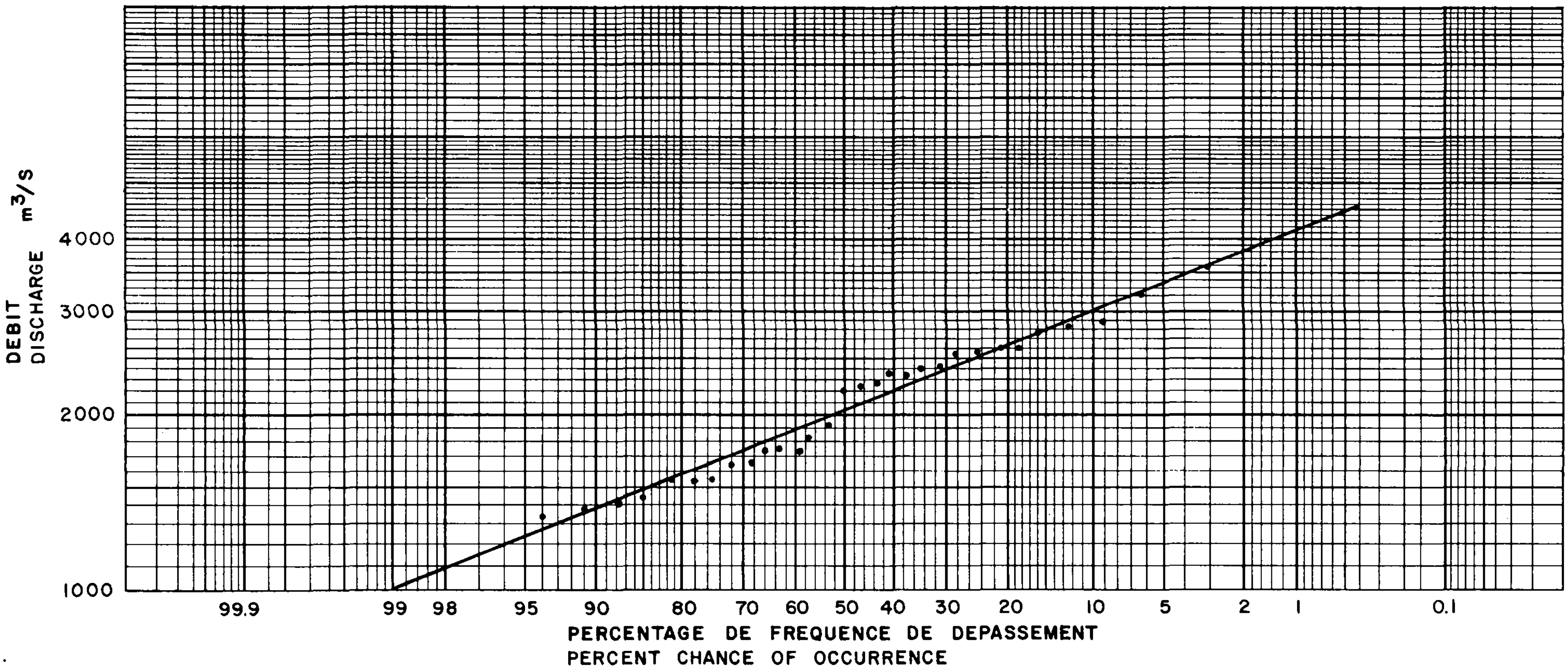


NIGER AT KOULIKORO

FREQUENCE DE CRUE

FLOOD FREQUENCY

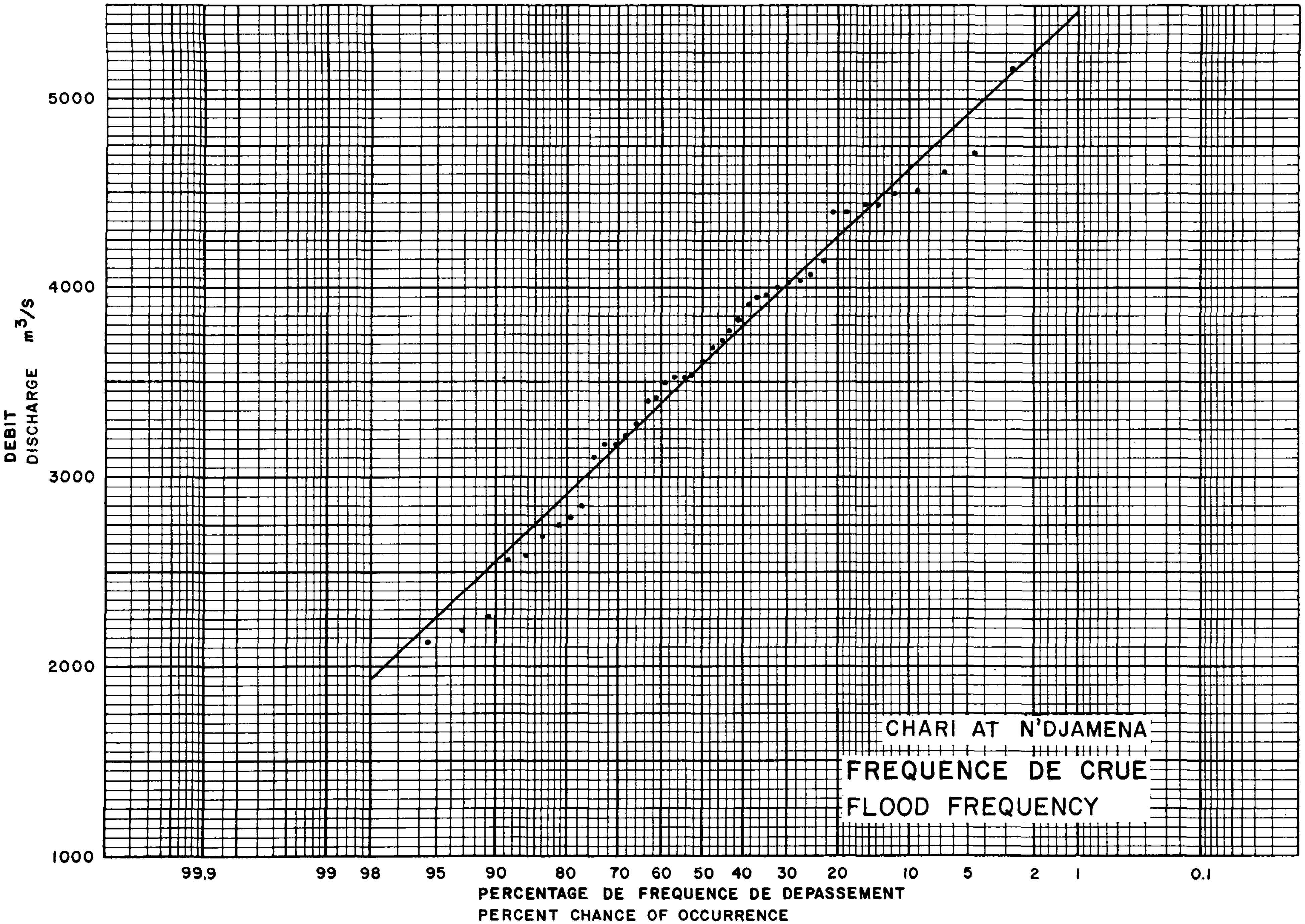
Fig. 4-11



LOGONE AT MOUNDOU

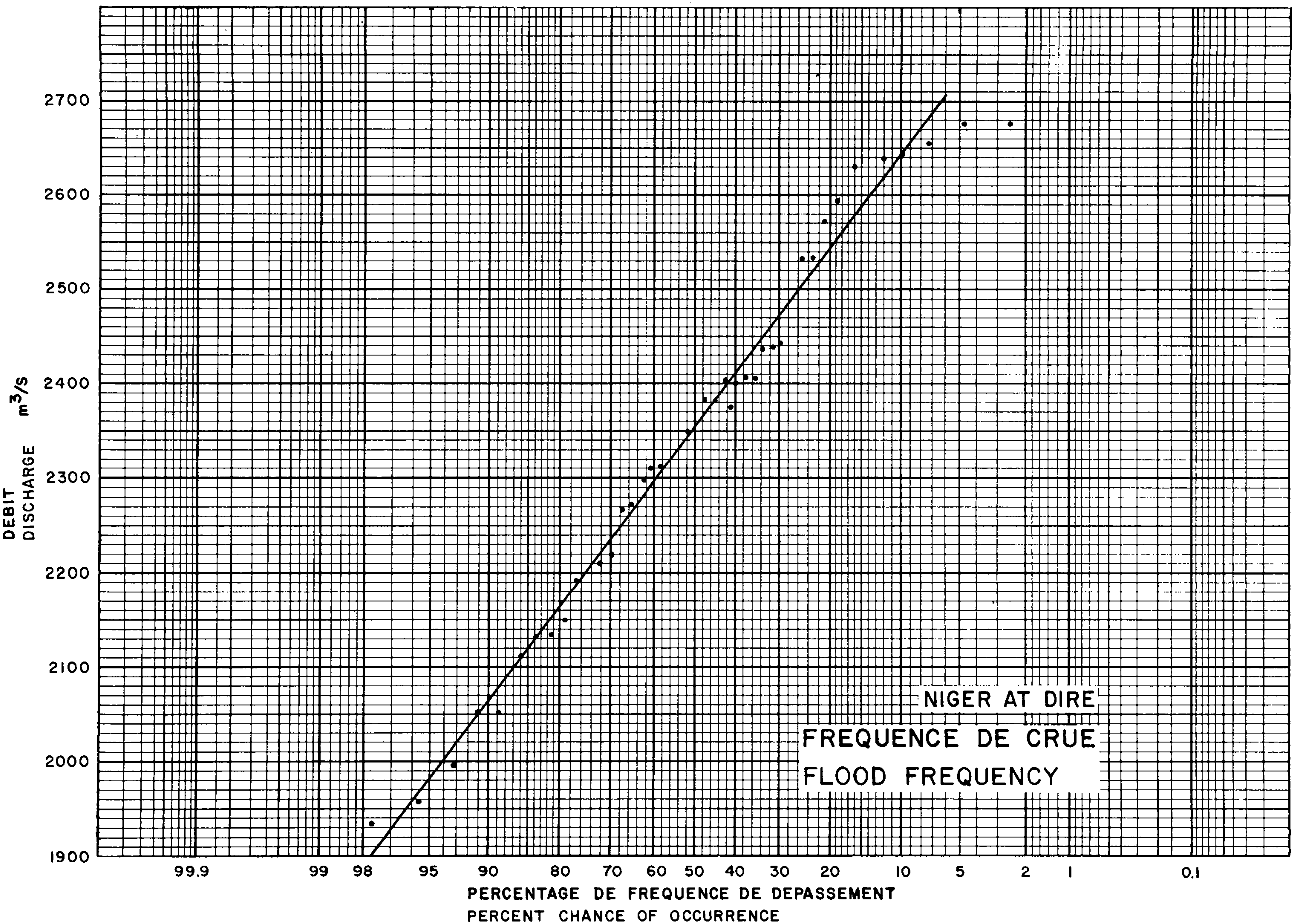
FREQUENCE DE CRUE
FLOOD FREQUENCY

Fig. 4-12



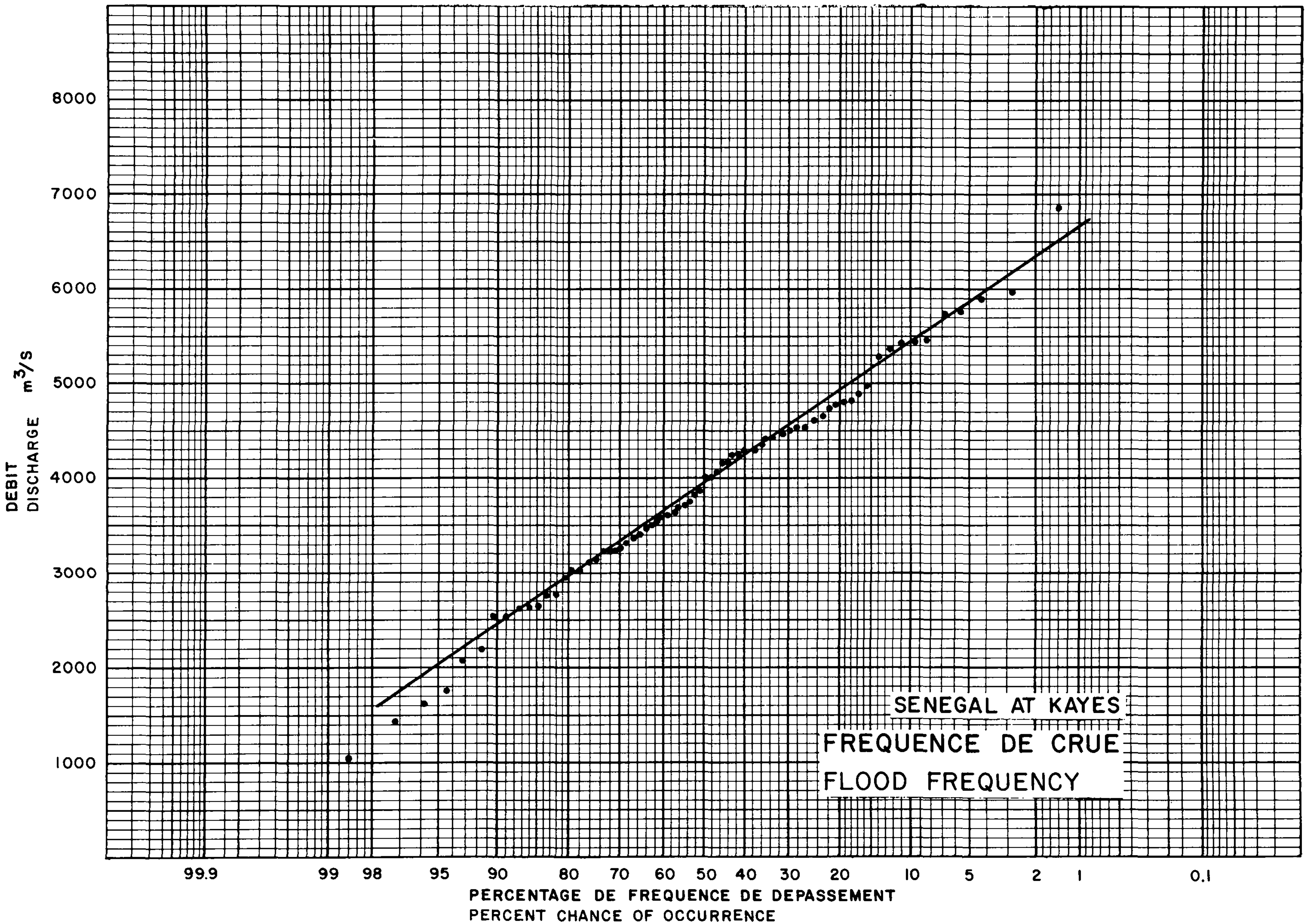
DEBIT
DISCHARGE m3/S
5000
4000
3000
2000
1000
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
PERCENTAGE DE FREQUENCE DE DEPASSEMENT
PERCENT CHANCE OF OCCURRENCE
CHARI AT N'DJAMENA
FREQUENCE DE CRUE
FLOOD FREQUENCY

Fig. 4-13



NIGER AT DIRE
FREQUENCE DE CRUE
FLOOD FREQUENCY
DEBIT
DISCHARGE m^3/s
2700
2600
2500
2400
2300
2200
2100
2000
1900
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
PERCENTAGE DE FREQUENCE DE DEPASSEMENT
PERCENT CHANCE OF OCCURRENCE

Fig.4-14



DEBIT
DISCHARGE m3/S
8000
7000
6000
5000
4000
3000
2000
1000
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
PERCENTAGE DE FREQUENCE DE DEPASSEMENT
PERCENT CHANCE OF OCCURRENCE
SENEGAL AT KAYES
FREQUENCE DE CRUE
FLOOD FREQUENCY

Fig. 4-15

Table 4-9 Ten-year flood flows in Chari Basin

River	Station	Area Km^2	Obs. years	Flow $m^3 s^{-I}$	Sp. Flow $l\ s^{-I}\ Km^{-2}$
Chari	Sarh	193 000	31	1670	8.6
	Bousso	450 000	25	3600	8.0
	Guelendeng	470 000	9	3640	7.7
	Mailao	500 000	22	3900	7.8
	N'Djamena	600 000	43	4550	7.6
Ouham	Bozoum	8 100	20	620	76
	Bossangoa	22 800	20	1640	72
Bahr Azoum	Am Timan	80 000	21	345	4.3
Bamingui	Bamingui	4 380	18	180	41
Bouca	Fafa	6 750	14	200	30
Gribingui	Crampel	5 680	12	133	23
Bahr Sara	Moissala	67 000	22	2830	42
	Manda	79 600	23	2950	37
Bahr Aouk	Golongosso	96 000	16	350	3.6

Table 4-10 Ten-year flood flows in Logone Basin

Logone	Moundou	33 970	31	3000	88
	Lai	56 700	22	3250	57
	Bongor	73 700	23	2500	34
	Logone G.	75 000	14	1090	14.5
	Baibokoum	21 360	12	4440	208 (doubtful)
Pendé	Begouladge	5 640	14	665	118
	Gore	12 020	12	840	70
	Doba C.	14 300	24	1000	70
M'béré	M'béré	7 430	14	1565	211
Tandile	Tchoa	5 870	16	160	27

Table 4-11 Ten-year flood flows in Niger Basin

River	Station	Area Km^2	Obs. years	Flow m^3s^{-1}	Sp. Flow $l\ s^{-1}Km^{-2}$	Source
Milo	Konsankoro	1000		300	300	ORSTOM
	Kankan	9900	17	1066	108	
Niandan	Baro	12600	11	1400	111	
Tinkisso	Tinkisso	6400		350	55	ORSTOM
Sankarani	Mandiana	21900		1250	57	ORSTOM
	Gouala	35300		1900	54	ORSTOM
Baoulé	Djirila	3970	8	460	116	
	Bougouni	15700		900	57	ORSTOM
	Dioila	32500		1270	39	ORSTOM
Bagoé	Guinguerini	1042	9	190	182	
	Tombougou	2580	14	400	155	
	Kouto	4740	14	430	91	
	Pankourou	31800	17	1820	57	
Niongoué	Ponondougou	709		39	55	ORSTOM
Bani	Douna	101600	31	3500	34	
	Bénény K.	116000		2550	22	ORSTOM
	Sofaya	129400		1620	12.5	ORSTOM
Niger	Kouroussa	118000	15	1585	88	
	Siguiri	70000		5000	71	ORSTOM
	Koulikoro	120000	57	7875	66	
	Kirango	137000	23	6900	50	
	Tilembeya	144000	24	3450	24	
	Mopti	281600	36	3050	10.9	
	Diré	340000	35	2640	7.8	
	Tossaye	355000	13	2310	6.6	
	Ansongo	455000	23	1970	4.4	
	Niamey	700000	41	2140	3.0	
	Gaya	1000000	23	2560	2.5	
Diaka	Kara	offtake	17	1750		

Cont'd.

Table 4-11 (cont'd) Ten-year flood flows in Niger Basin

River	Station	Area Km^2	Obs. years	Flow $m^3 s^{-1}$	Sp. Flow $l\ s^{-1} Km^{-2}$	Source
G. Maradi	Goundam	offtake		340		
Gorouol	Alcongui	44850	17	110	2.4	
	Dolbel	7500	15	116	15	
Dargol	Tera	2750	15	132	48	
	Kakassi	6940	18	123	18	
Sirba	Garbé	38750	17	522	13.5	
Diamangou	Tamou	4030	14	94	23	
Tapoa	W	5330	13	25	4.7	
Mékrou	Barou	10500	13	352	34	
Alibori	Banikoara	8150	18	570	70	
Sata	Couberi	13200	18	440	33	
Gouroubi	Diongéré	15350	8	107	7.0	

Table 4-12 Ten-year flood flows in Volta Basin

River	Station	Area Km^2	Obs. years	Flow $m^3 s^{-1}$	Sp. Flow $l\ s^{-1} Km^{-2}$
1. Volta Noire Basin					
Kou	Nasso	405	14	110	274
Volta Noire	Samendeni	4580	18	310	68
	Nwokuy	14800	15	240	16
	Kouri	20800	11	153	7.3
	Manimenso	32000	17	93	2.9
	Boromo	50000	19	168	3.4
	Dapola	78000	15	860	11
Black Volta	Lawra	94000	23	915	9.7
	Bui	125000	20	2300	18
	Bamboi	134200	20	2180	16
Tain	Tainso	3480	10	106	30
Pru	Pruso	1212	17	33	27
2. Red Volta Basin					
	Nangodi	11570	12	510	44
3. White Volta Basin					
Massili	Lumbila	2120	14	130	61
White Volta	Wayen	20800	12	210	10
	Yakala	33000	16	540	16
	Pwalagu	63350	22	1820	29
	Nawuni	92950	20	2170	23
	Daboya	96320	11	2500	30
	Yapei	102170	15	2740	27
Morago	Nakpandouri	1530	14	180	118
Sissili	Wiasi	9500	8	490	52
Kulpawn	Yagaba	10600	15	480	45
Nasia	Nasia	5175	11	450	87

Cont'd

Table 4-12 (cont'd) Ten-year flood flows in Volta Basin

River	Station	Area Km^2	Obs. years	Flow $m^3 s^{-1}$	Sp. Flow $l\ s^{-1} Km^{-2}$
Nabogo	Nabogo	1950	12	210	108
4. Oti Basin					
Penjari	Porga	22280	21	620	28
Magou	Tiele	836	13	75	90
Keran	Titira	3695	11	1050	284
Oti	Mandouri	29100	15	870	30
	Sansanne M.	35650	21	1680	47
	Saboba	50300	20	3185	63
	Sabari	59550	13	3800	64
Koumangou	Koumangou	6730	15	595	85
Kara	Lama Kara	1560	18	640	410
	Kpesside	2790	11	1030	368
Koimepouaba	Nagbeni	208	11	19	90
Sansorgou	Borgou	2240	14	174	78
5. Volta Basin					
Kama	Bassari	202	11	58	285
Gban Hou	Brouffou	320	8	72	224
Dayes	Hohoe	626	12	56	90
Daka	Yendi	1214	13	158	130
Volta	Yeji	260330	13	5600	21

Table 4-13 Ten-year flood flows in Senegal Basin

River	Station	Area Km^2	Obs. years	Flow $m^3 s^{-I}$	Sp. Flow $l\ s^{-I}\ Km^{-2}$
Bakoye	Toukouto	16500	18	1200	73
	Oualia	85600	20	2350	27
Bafing	Dakka S.	15700	21	2700	172
	Dibia	33000	21	4350	132
Falémé	Fadougou	9300	17	1800	194
	Gourbassi	15000	19	1900	127
	Kidira	28900	38	2700	93
Sénégal	Galougo	126900	41	5200	40
	Kayes	157400	73	5400	34
	Bakel	218000	72	7000	32
	Matam	230000	72	6000	26
	Dagana	268000	71	3250	12

Table 4-14 Ten-year flood flows in Gambia Basin

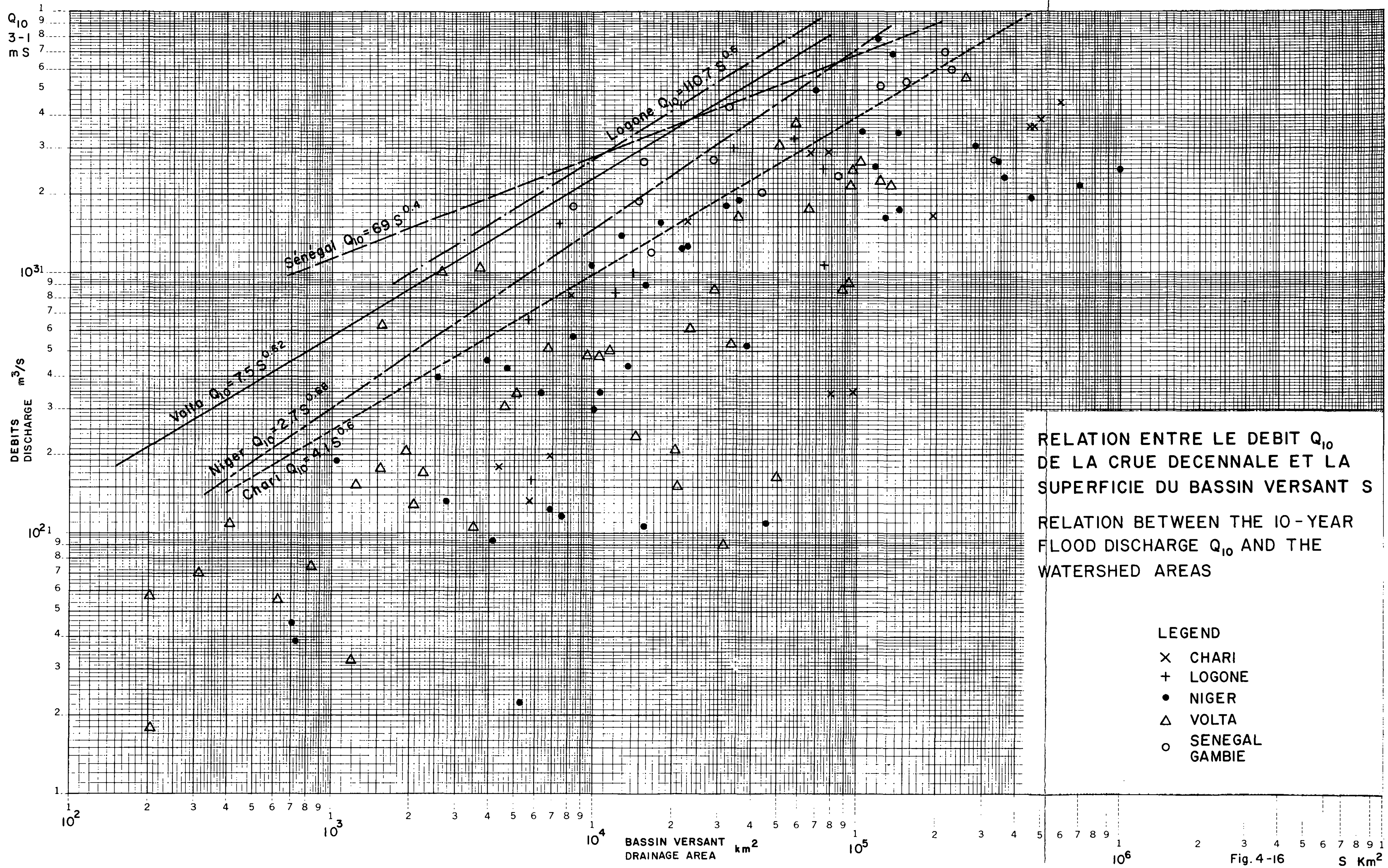
Gambia	Goulombo	42000	17	2040	49

TABLE 4-15

AVERAGE RELATION BETWEEN THE TEN-YEAR FLOOD FLOW

AND THE WATERSHED AREA

BASIN	REGRESSION EQUATION	r	NO. OF ITEMS
CHARI	$Q = 1.42\ S^{0.6}$	0.82	14
LOGONE	$Q = 3.2\ S^{0.6}$	0.63	10
NIGER	$Q = 1.64\ S^{0.68}$	0.95	18
VOLTA	$Q = 1.72\ S^{0.62}$	0.88	39
SENEGAL	$Q = 40.2\ S^{0.4}$	0.79	11



RELATION ENTRE LE DEBIT Q_{10} DE LA CRUE DECENNALE ET LA SUPERFICIE DU BASSIN VERSANT S

RELATION BETWEEN THE 10-YEAR FLOOD DISCHARGE Q_{10} AND THE WATERSHED AREAS

Fig. 4-16

In the case of the Niger River Basin, stations downstream of Koulikoro have been omitted from the calculation. Similarly, in the lower Senegal River Basin, calculations have been omitted because of inconsistent results.

4.3.3.3 100-Year Floods

Estimated 100-year flood flows together with the highest observed flood flows are listed in Table 4-16. The type of distribution used to determine the probable 100-year flood flow is also indicated. The complete annual maximum flood series may be found in Appendix 4.

The use of statistical extrapolations to complete flood series for which data are lacking is not advisable unless the resulting estimates are checked by graphical plots. In Table 4-17, the estimates derived from plots on suitable probability paper are compared with those obtained by mathematical adjustment of Galton and Pearson III frequency distributions.

TABLE 4-17

COMPARISON OF 100-YEAR FLOOD ESTIMATES (m^3 s-1)

RIVER	STATION	PLOT	GALTON	PEARSON III
Senegal	Bakel Kayes	9,500 6,600	11,500 8,170	8,760 5,970
Niger	Koulikoro Dire Gaya	9,500 2,700 3,300	9,710 2,920 3,240	9,760 2,890 3,080
Logone	Moundou	4,000	4,160	3,990
Chari	N'Djamena	5,900	6,250	4,970

TABLE 4-16

MAXIMUM OBSERVED AND ESTIMATED 100-YEAR FLOODS

RIVER	STATION	MAX. FLOW OBSERVED $m^3 s^{-1}$	100-YEAR FLOOD $m^3 s^{-1}$	OBS. YEARS	FREQUENCY DISTRIB.
CHARI BASIN					
Chari	Sahr	2,088	2,500	31	Pearson III
	Bousso	3,980	4,500	25	Galton
	N'Djamena	5,160	5,900	43	Galton
LOGONE BASIN					
Logone	Moundou	3,640	4,000	31	Gauss
NIGER BASIN					
Bani	Douna	3,840	4,100	31	Galton
Niger	Koulikoro	9,700	9,500	57	Galton
	Dire	2,677	2,700	35	Gauss
	Niamey	2,365	3,000(1)	41	
	Gaya	2,810	3,250(2)	23	Log-extreme
			3,300(3)	20	Galton
SENEGAL BASIN					
Paleme	Hidira	3,120	3,400	38	Gauss
Senegal	Galougo	6,880	6,200	41	Gauss
	Kayes	6,840	6,600	73	Gauss
	Bakel	9,340	9,500	72	Galton
	Matam	8,200	9,040	72	Galton
	Dagana	3,570	3,650	71	Gauss

(1) Possibly on account of interior delta evolution (Rouier, 1970), both the form and the magnitude of the flood hydrograph are undergoing significant changes.

(2) "Malian" flood, also subject to progressive modification.

(3) "Local" flood.

4.3.3.4 Conclusions Concerning Flood Flows

Because high intensity rainfalls are brief and limited in area, specific flood flows are very low compared with other climatic regions. None of the Project Area stations examined have had flows reaching 500 $l\ s^{-1}\ km^{-2}$ at the 10 percent probability level.

Considerable overbank flooding occurs in all of the basins studied. Also, several Savanna rivers flow through or into areas of very low rainfall. As a result, reductions of specific flows and actual flood discharges are frequently observed between successive gauging stations. This is particularly true in the following areas:

Black Volta in the Sourou region,
Niger in the Interior Delta,
Chari downstream of Sahr,
Logone downstream of Moundou, and
Senegal downstream of Kayes.

In view of the variety of frequency distributions which have been calculated for the Savanna, it is recommended that theoretical relations based on existing data not be used to calculate return periods greater than 10 years.

4.3.4 Low Flows and Drought

In spite of the fact that data concerning low flows are critical to the fishing industry, as well as river transport, measurements of low flows have not been given priority. Consequently, records of surface water resources frequently do not have any low-flow data, or cover a short series. Frequencies of daily low flows are presented in Table 4-18 for selected stations. Return periods are given for the 10-year dry, two- and 10-year wet periods. Due to the short length of record for most stations, the values observed during the recent

Table 4-18 DEBIT D'ETIAGE

LOW FLOWS ($m^3 sec^{-1}$)

PERIODE DE RETOUR (ANS)/RETURN PERIOD (YEARS)

BASSIN BASIN	STATION	10 ANS SEC 10-YEAR DRY	2 ANS HUMIDE 2-YEAR WET	10 ANS HUMIDE 10-YEAR WET
SENEGAL	TOUKOTO	0	0	1
	OUALIA	0	0	0
	DAKKA SAIDOU	6	10	19
	DIBIA	0	5	13
	GALOUGO	1	3	11
	KAYES	1	3	10
	FADOUGOU	0	1	3
	GOURBASSY	0	0	2
	KIDIRA	0	0	1
	BAKEL	0	2	10
	MATAM	0	2	10
GAMBIA	DONNEES INSUFFISANTES INSUFFICIENT DATA			
NIGER	BARO	8	17	35
	KANKAN	6	14	32
	KOULIKORO	21	35	70
	PANKOUROU	1	2	4
	DOUNA	11	20	36
	MOPTI	38	50	115
	DIRE	22	52	110
	TOSSAYE	45	100	190
	ALCONGUI	0	0	0
	KAKASSI	0	0	0
	GARBE	0	0	0

Cont'd

Table 4-18 (cont'd)

BASSIN BASIN	STATION	10 ANS SEC 10-YEAR DRY	2 ANS HUMIDE 2-YEAR WET	10 ANS HUMIDE 10-YEAR WET
	NIAMEY	6	33	155
	BAROU	0	0	0
	GAYA	15	100	240
VOLTA	SAMENDENI	1	2	3
	MANIMENSO	4	6	9
	BOROMO	4	7	9
	LAWRA	6	8	10
	BAMBOI	4	13	35
	NANGODI	0	0	0
	YAKALA	0	0	0
	DABOYA	1	2	4
	PORGA	0	0	0
	SANSANNE MANGO	0	0	1
	SABOBA	1	3	8
LOGONE	BAIBOKOUM	9	16	25
	MOUNDOU	12	23	40
	DOBA	1	3	8
	LAI	28	47	69
	TCHOA	0	1	3
	BONGOR	14	30	58
	LOGONE GANA	19	28	39
CHARI	BAMINGUI	0	1	4
	SAHR	19	24	68
	MOISSALA	19	39	88
	AM TIMAN	0	0	0
	BOUSSO	49	107	232
	MAILAO	44	92	193
	NDJAMENA	68	121	214

drought were the lowest recorded.

Usually, flows decrease from January to April. Depending upon the time of arrival of the rains, the absolute minimum may occur from the end of March to the end of May. The flows are regulated by discharge from the natural flood storage areas, alluvial river back flow, and hydro-geological formations.

Streams that do not depend upon groundwater recharge are not significantly affected by several years of below normal rainfall. Thus, in certain areas, especially small watersheds, the effect of the drought on stream flow was not always noticeable. The right bank streams flowing into the Niger River, such as the Dargal and Goroual, were examples of this phenomenon.

Streams that traverse vast areas of marsh or are fed by groundwater are more vulnerable to rainfall shortages and consequently, the effect of drought was much more marked in such streams. The Bahr Azoum in Chad recorded a 70 percent drop in annual flows in 1968 and 1972. The drought has shown that for an area as large as the Savanna, there will always be anomalies, i.e., stream flow above average for the small basins, in spite of below average rainfall for the region as a whole. This is particularly true for the Sahelian Zone where runoff is characteristically irregular from year to year.

In 1968, of the large rivers in the Savanna, only the Senegal River had significant below average annual flows which reached a deficit of 45 percent. In 1969, the annual flows for all major rivers were normal or above normal except for the Chari. In 1972, the Senegal, Chari, Logone and Black Volta Rivers had the lowest annual flows ever recorded. The deficit was 66 percent at Bakel (Senegal River), 56 percent at N'Djamena (Logone River), and 60 percent at Lawra (Black Volta). Similarly, the flood flows were some of the lowest on record for these rivers. At Bakel (Senegal River), in April, 1974, no flow was recorded for eight days; and at Niamey (Niger River), for the same year, in July, a low flow of 5 m^3/s was recorded compared to an average annual minimum flow of 75 m^3/s. In 1973, the drop in the Chari River flows caused Lake Chad to shrink to about one third its average volume and to divide into two parts.

The recent drought is not unique to the Savanna. Streamflows of comparatively low values have been recorded in 1913-14 and 1940-45. Historical maps of Lake Chad indicate that in 1908, its surface area was the same as reached in 1975. The drought which occurred around 1913 was apparently of equal magnitude to the recent drought, whereas the drought of 1940-45 was only slightly less intense.

4.3.4.1 Sequences of High and Low Flows

The recurrence of a series of dry years alternating with a series of wet years has led to studies of cycles (see Figure 4-1). Much has been written on this subject (Baris-Teynac, 1962, 1963) but it would be hazardous to extrapolate from them to the future because only two complete cycles (each one lasting thirty years) have been observed at gauging stations. Historic records and correlations with the Nile and other basins may make it possible to extend the data base and assist in the detection of other periodicities.

Specific evidence of the length of the wet or dry cycles is rare. During the course of a 67-year period of record of the Niger River at Koulikoro, at least two cycles were observed lasting 20 to 25 years in which flows were observed at levels above or below the median. It is desirable to verify that such sequences are present in series generated by mathematical methods if they are to be used in operational studies of water development projects.

4.3.5 Small Watershed Runoff

Small watersheds of less than 1,000 km^2 are seldom gauged but, nevertheless, deserve critical examination because of their use in supplying small dams and water spreading (bas-fonds) projects. Two publications, one for 10-year flood estimates (Rodier, 1965), and the other for annual runoff in the Sahelian Zone (Rodier, 1975) have summarized most of the data for small watersheds.

The geography of the Savanna zone has certain features that result in relatively low rates of runoff. These include the following:

- Storm systems that characteristically move in a westerly direction, and are relatively small in area;
- Gentle longitudinal slopes and flat valleys;
- Very high evapotranspiration rates; and
- Streams that generally run from south to north (humid to dry) with the exception of the Volta and lower Niger Rivers.

In his study on annual runoff, Rodier had difficulty in generalizing the hydrologic characteristics of small watersheds. Soil infiltration capacities, slopes, and particularly the annual range of rainfall in area and time (including the inherent inadequacy of rainfall measurements for this type of study), all contribute to the wide variability of runoff. Statistical distributions are strongly asymetric and require a long series of observations which are rare for small watersheds. Furthermore, Savanna rivers frequently decrease in volume of flow in their downstream sections.

Values extracted from Rodier's study give a general idea of annual runoff coefficients defined as the ratio of stream discharge to rainfall. For a median probability of occurrence, small watersheds of less than 40 km^2 average 20 percent with a range of two percent to 25 percent. Medium size watersheds, 40 to 1,000 km^2 average seven percent with a range of one percent to 18 percent. For watersheds of 1,000 to 10,000 km^2 the average is four percent and ranges from one percent to 14 percent.

Small basin annual runoff has not been compiled on a regional basis for the higher rainfall areas of the Savanna, but studies by ORSTOM are in progress. It is expected that less variability and somewhat lower runoff coefficients will be characteristic of the southern Savanna.

4.3.6 Sediment Transport

Sediment studies in the Savanna Zone are very limited. Sediment sampling over a period of more than a few years has only been undertaken in the Chad Basin. Also, studies to determine the effect of sediment transport and deposition on river development have only been conducted on the lower Niger River Basin. The upper sections of the Niger and the Volta have received little attention, while the lower Volta in Ghana reportedly has measurements of sediment discharge at selected stations. Studies of the Gambia River are in progress.

Savanna rivers do not discharge large amounts of sediment. As shown in Table 4-19, the values in grams per cubic meters for these rivers are low when compared with such rivers as the Hwang Ho, China (44,000); the Colorado, U.S.A. (11,200); the Nile, Egypt (1,920); the Rhone, France (1,500); and the Congo, Central Africa (400).

Plots of suspended sediment samples and water discharge display a characteristic loop rating curve for the Savanna Rivers. As expected, rising stages always transport greater concentrations of sediment than steady or falling stages. During the dry season, sun, wind, fire, cultivation and animal grazing leaves the top layer of the land susceptible to sheet erosion. This land is further eroded by winds such as the Harmattan.

Tables 4-19 and 20 present existing sedimentation data. Total transport and the subsequent deposition of sediment do not appear to endanger existing or proposed reservoirs. The average degradation over the total drainage area amounts to only about one to five millimeters per 100 years. Exceptions to this exist on small basins with moderate to steep slopes as, for example, streams flowing from the Jos Plateau in Nigeria. The sediment transported to the Niger River in this area changes from a dark color, known locally as the "black flood", to a light color or, "white flood".

For small watersheds, the U. S. Bureau of Reclamation (1968) found suspended sediment discharges as high as 1,348 tons/km^2/year on a basin of 7000 km^2 on the Challowa River in Nigeria for the years 1967-68. Without doubt, similar high values exist for other watersheds within the Savanna with steep slopes and inter-intensive activities of man and animals which promote soil erosion.

Separate studies by NEDECO and the U.S. Bureau of Reclamation in Nigeria have demonstrated that suspended sediment samples constitute most of the total sediment load. Bed load was estimated to be only 6.5 to 8 percent for the Niger River and from 13 to 15 percent for the Kano River. Sediment concentrations are relatively uniform in vertical profiles with a slight increase at the bottom. In spite of the relatively small percentage of total transport attributed to bed load, the behaviour of the alluvial river bed is completely dependent upon the bed load quantities and requires further study.

Sediment load measurements will become increasingly important as pressure on the land increases and more soil erosion inevitably occurs, in

Table 4-19 Annual quantities of suspended sediment

Basin	Stream	Station	Year	Solid Transport Thousand tons/ year	$(T/Km^2/year)$	Concentration Average Annual g/m^3
NIGER	Niger	Baro	56	6580		
			57	11640		
SENEGAL	Faleme	Gourbassi	68-69	600	(40)	
	Soukoutaly	Bafing	68-69	1400	(47)	
	Kayes	Senegal	68-69	2300	(14.6)	
	Bakel	Senegal	68-69	2900	(13.3)	
CHARI	Bahr Sara	Manda	68-69	844	(10.6)	62
		$(79,600km^2)$	69-70	132	(1.7)	51
			70-71	132	(1.7)	45
			71-72	326	(4.1)	20
			72-73	549	(6.9)	46
			73-74	478	(6.0)	36
			74-75	995	(12.5)	56
	Chari	Sarh	68-69	251	(1.3)	39
		$(193,000km^2)$	69-70	212	(1.1)	34
			70-71	212	(1.1)	31
			71-72	135	(0.7)	29
			72-73	135	(0.7)	33
			73-74	154	(0.8)	27
	Chari	Chagoua	69-70	1246	(2.4)	57
		$(515,000km^2)$	70-71	1346	(2.6)	52
			71-72	1000	(1.9)	49
		N'DJAMENA				
		upstream	72-73	819	(1.6)	62
		from	73-74	900	(1.7)	54
		N'Djamena	74-75	1135	(2.2)	51

Cont'd

Table 4-19 (cont'd)

Basin	Stream	Station	Year	Solid Transport Thousand tons/ year (T/Km^2/year)		Concentration Average Annual g/m^3
LOGONE	Logone	Moundou	69-70	2208	(65)	138
		(33,920km^2)	70-71	2208	(65)	163
			71-72	2106	(62)	135
			72-73	1665	(49)	143
			73-74	1529	(45)	122
			74-75	1665	(49)	120
	Pende	Doba	69-70	352	(24.6)	78
		(14,300km^2)	70-71	313	(26.1)	76
	Logone	Kousseri	69-70	1347	(15.8)	111
		(85,000km^2)	70-71	1238	(14.6)	105
		NEAR	71-72	1025	(12)	111
		N'DJAMENA	72-73	1575	(18.5)	174
			73-74	1210	(14.2)	144
			74-75	1180	(13.8)	140

Table 4-20 Annual quantities of suspended sediment transported to Lake Chad as measured near N'Djamena in thousands of tons.

YEAR	CHARI at Chagoua	LOGONE at Kousseri	TOTAL
69-70	1246	1347	2593
70-71	1346	1238	2584
71-72	1000	1025	2025
72-73	819	1575	2394
73-74	900	1210	2110
74-75	1135	1180	2315

spite of efforts being made in some countries to introduce soil conservation measures.

Although bed load appears to represent only a small percentage of the total sediment load, more measurements will be required in the foreseeable future to confirm this statement or indicate otherwise. The conventional method, using bed load samplers is both time-consuming and not very accurate. However, now that more and more dams are being built, it should be possible to measure the deposition of coarse sediment, that is, bed load at the top deltas either by echo sounder from a boat or by modern surveying methods after the water level has dropped.

4.3.7 Water Quality

Surface water quality has received little attention in the Savanna. In most cases, studies concerning water resources deal with water quality only as a short appended section that lists the results of a few samples. No long-term or systematic sampling of water quality has been found to exist. This is partially due to the fact that no serious water quality problems have been found to exist. Studies of the limiting effect of individual ions on specific agricultural crops has been undertaken in a few instances.

In 1972, Grove made a reconnaissance study of the chemical composition of the Senegal, Niger, Benue, and Chari Rivers. His analyses are reported upon in Table 4-21. In addition to his own measurements, Grove included data assembled from a number of scattered and unpublished sources.

In general, surface waters have been found to be low in hardness, alkalinity, and total dissolved solids. In certain locations, nitrate and ammonia levels have been found to be high, indicating possible pollution from organic sources.

Table 4-21 Analyses, in parts per million, of water from West African rivers (after A.T. Grove, 1972)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
River	Sample No.	Date 1969	Place	Distance Km	Field pH	Conductance at 25 C mho	Na	K	Ca	Mg	Cl	SiO_2	Hardness Ca + Mg ppm HCO_3
						St. Louis							
Senegal	1	10 Oct	Diama	29	7.2	52	4.0	1.6	4.1	2.2	3	12	22
Senegal	2	10 Oct	Debi	69	7.0	44	3.2	1.3	3.9	2.0	2	11	22
Senegal	3	11 Oct	Diaouar	90	7.0	45	1.8	1.6	3.8	1.9	<1	5	22
Senegal	4	12 Oct	Dagana	169	6.9	42	1.7	1.5	4.3	1.9	<1	11	22
Senegal	5	12 Oct	Podor	268	7.4	40	1.7	1.5	3.6	1.8	<1	7	21.5
Senegal	7	16 Oct	Guidala	367	7.4	37	1.7	1.5	3.7	1.8	<1	9	20.5
Senegal	8	16 Oct	Ouala	401	7.5	35	1.7	1.1	3.6	1.5	<1	10	19.5
Senegal	9	17 Oct	Vinding	492	7.5	36	1.3	1.1	3.4	1.8	<1	8	19.0
Senegal	11	18 Oct	Tiguéré	610	7.6	33	1.7	1.2	3.5	1.6	<1	11	19.0
Senegal	13	19 Oct	Waoundé	715	7.6	34	1.7	0.9	0.9	1.6	<1	7	18.5
Falémé	15	20 Oct	Confluence	823	7.5	42	1.7	1.2	4.1	1.9	<1	9	21.0
Senegal	16	20 Oct	Senegal	835	7.6	34	1.3	0.8	3.0	1.6	<1	9	18.5
						Koulikoro							
Niger	17	28 Oct	Segu	180	7.2	26	1.4	1.5	2.4	1.0	<1	10	12.9
Bani	18	29 Oct	Mopti	502	6.8	38	1.6	1.4	3.1	1.4	<1	5	17.8

Cont'd

Table 4-21 (cont'd) Analyses, in parts per million, of water from West African rivers (after A.T. Grove, 1972)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
River	Sample No.	Date 1969	Place	Distance Km	Field pH	Conductance at 25 C mho	Na	K	Ca	Mg	CI	SiO_2	Hardness Ca + Mg ppm HCO_3
Niger	19	30 Oct	Doua	700	7.2	32	1.4	1.4	2.8	1.3	<1	10	16.7
Niger	20	4 Nov	Gao	1308	7.1	38	1.8	1.8	3.3	1.9	<1	7	18.0
Niger	21	7 Nov	Tillabery	1570	7.1	38	1.9	2.0	3.4	1.8	<1	9	19.0
Niger	22	10 Nov	Lafagu	2370	7.2	49	4.9	2.0	3.7	2.05	<1	10	24.2
Niger	23	12 Nov	below Kainji	2620	7.2	56	4.6	3.8	4.1	2.0	<1	10	24.8
Kaduna	24	14 Nov	confluence	2850	7.3	55	3.8	2.4	5.2	1.7	<1	14	26.0
Gurare	25	14 Nov	confluence	2900	7.4	50	4.3	2.0	4.4	1.6	<1	15	24.7
Niger	26	14 Nov	Koton Karifi	2920	7.4	54	4.1	2.5	5.0	1.8	<1	12	26.2
						Lokoja							
Benue	27	15 Nov	above Lokoja	25	7.4	53			5.8	1.8	3.8		29.5
Benue	28	15 Nov	below Makurdi	200	7.3	35	3.4	1.4	3.5	1.9	<1	14	18.5
Katsina Ala	29	16 Nov	confluence	250	7.1	26					<1		14.9
Benue	30	16 Nov	Ibi	350	7.2	39					<1		19.8
Donga	31	16 Nov	confluence	390	7.1	30					<1		15.6
Gongola	32	16 Nov	confluence	670	7.6	83					<1		40.0
Faro	33	17 Nov	confluence	790	8.0	74					<1		38.0

Cont'd

Table 4-21 (cont'd) Analyses, in parts per million, of water from West African rivers (after A.T. Grove, 1972)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
River	Sample No.	Date 1969	Place	Distance Km	Field pH	Conductance at 25 C mho	Na	K	Ca	Mg	Cl	SiO_2	Hardness Ca + Mg ppm HCO_3
Benue	34	17 Nov	Garoua	870	7.6	83	4.6	1.8	8.8	3.1	<1	15	46.5
From Chad													
Logone	35	29 Nov	Yagoua	370	7.5	55					<1		28.2
Logone	36	29 Nov	Logone Gana	200	7.4	72	5.0	2.1	6.5	2.5	<1	17	33.5
Shari	37	29 Nov	Chagoua	130	7.2	54	3.4	1.6	5.0	2.0	<1	14	26.0

Summarizing, surface water quality appears to be satisfactory for agriculture and stock, although it should be noted that general knowledge of the presence of such elements as a) boron, iron and manganese and b) sulfate and nitrate ions is for all purposes non-existent. Likewise, as far as potable supplies are concerned, more information is required on the presence or otherwise of ammonia, lead, fluorine, nitrites and nitrates. However they are unlikely to be present in significant amounts, except perhaps on reaches below towns and and cities. Such places would not be considered for intakes for water supplies; nevertheless the effect of potential pollution on fisheries would have to be considered.

Water supplies have been taken from rivers such as the Niger and its tributaries in Nigeria for many years using conventional and often elementary treatment without adverse effects on the local population. The same can be said for supplies in Ghana.

4.4 SUMMARY

There are considerable surface water resources in the Savanna; although they are poorly distributed in time and space, much consideration has been given to the construction of large dams to regulate water distribution. Such dams undoubtedly offer a vast potential for controlling a resource which critically limits the development possibilities of the area. However, careful technical, environmental, and socio-economic evaluation of proposed dams is necessary to avoid inadequate, premature and excessively costly projects. The results obtained from large scale irrigation projects have, in a number of instances, been quite disappointing. Farmers experienced in irrigation are few in West Africa, therefore intensive irrigated agriculture similar to that practiced along the Nile is difficult to visualize in the near future in the Savanna.

It should be realized that for a long time to come, the great majority of the rural population will be compelled to practice rainfed cropping and raise livestock and will continue to provide the largest part of agricultural production by such means. Large scale irrigation projects will only reach a small proportion of the population and will be difficult to implement and operate. It is, therefore, recommended that special attention be given to simple schemes of small to medium scale irrigation, and water spreading. There exist already numerous small earthen dams throughout the Savanna that could potentially be directed to the irrigation of small plots, with a proper extension service providing assistance. Also, irrigation from groundwater should not be overlooked. Irrigation systems based on groundwater are relatively easy to finance, implement, and operate.

Finally, it is important to institute more precise plans of national and basin development with due regard for all sectors of water users including urban and rural populations, agriculture, livestock, and industry. While the full implementation of these programs represents a considerable amount of work over some decades, its urgency demands that work be initiated as soon as possible.

CHAPTER 5

GROUNDWATER RESOURCES

5.1 INTRODUCTION

This Chapter, which is designed to serve as a base document for regional planning, was prepared with the consultant assistance of two firms having long time experience in the Savanna Region. BRGM (Bureau de Recherches Géologiques et Minières) the French Geological Survey and BURGEAP (Bureau d'Etudes de Géologie Appliquée) a French firm of consulting hydrogeologists prepared, under subcontract, preliminary hydrogeologic maps conceived by the TAMS/CIEH* hydrogeologist. These maps and accompanying information constituted the working basis for the preparation of this Chapter.

The TAMS/CIEH hydrogeologist visited the project area and discussed the groundwater situation with governmental authorities in order to derive a first-hand overall understanding and specific knowledge of the groundwater conditions and problems in Western and Central Africa. Also, basic data were collected and analyzed, and examinations as well as general and detailed inquiries were made, while relevant documents and reports from CIEH's Documentation Center and other sources were studied. No additional investigations such as well inventories, pumping tests, water quality analyses, geophysical surveys or exploratory drilling were made. This chapter is based entirely on existing data and documents, the preliminary maps prepared by subcontractors, and information from discussions with numerous hydrogeologists practicing in Western and Central Africa. Some areas, however, are not well covered due to the insufficiency of available information or the impossibility of obtaining it.

Although topography and climate constitute primary factors affecting the infiltration of water underground, geology is the paramount factor which determines the occurrence, distribution, movement and quality of groundwater. The geological nature and structure of the terrain, among other things, influence

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* Interafrican Committee for Hydraulic Studies

relief forms, which in turn have an important impact on the climate. Subsurface geology determines not only the location and boundaries of groundwater reservoirs but also their ability to store and transmit water as well as the quality of the water they bear. For these reasons, an overall description of the geology of Western and Central Africa is outlined below before presenting groundwater conditions in the region.

5.2 GEOLOGY

The geology of Western and Central Africa, a tectonically inactive region, is relatively simple, featuring structural regularity and lithostratigraphic uniformity, a characteristic of the rest of the continent. Africa consists of a very ancient basement, the African Shield, made up of massive igneous and metamorphic rocks which outcrop extensively, and of coastal and huge inland basins filled with marine and continental sediments. The project area is dominated by these features, resulting in little (but enough for rural water supply) groundwater in the basement, and extensive, variable-productivity aquifers in the sedimentary basins.

5.2.1 Geologic and Structural Setting

5.2.1.1 The Basement Complex

The African Shield, or Precambrian basement complex, originating from the consolidation of magma, has undergone large-scale fracturing movements from remote geologic times. This has resulted in the development of a series of immense uplifted fault blocks and extended, subsided basins (see Fig. 5-1). Both basement and basin rocks evidence virtually no folding; exceptions are the Mauritanides and Atacora mountains.

The huge Libero-Ivorian-Voltaic Shield and its continuation by the Nigerian Shield and the Central African Shield to the East occupies much of the project area, especially the southern part. To the North, the Tibesti, the Hoggar with Aïr and Adrar des Iforas and, to the West, the Reguibat Shield as well as the Mauritanides constitute limits to the sedimentary basins, but they are out of the project area. All to the good for some groundwater occurrence, the salient characteristics of these basement areas are intense fracturing and weathering, which resulted in a lateritic cover, a typical feature in tropical Africa.

5.2.1.2 The Sedimentary Basins

The sedimentary basins are located between these basement areas; only their southern parts however lie within the project area boundaries. From the West to the East, they include : (i) the Senegalo-Mauritanian Basin bounded by the coastal Guinea Basin and separated by the Mauritanides from (ii) the huge Taoudeni Basin which continues, through the Sudanese Strait between Adrar des Iforas and the Voltaic Shield, into (iii) the Niger Basin, continued in Nigeria with the Sokoto Basin and eastward through the Tegama plateau between Aïr and the Nigerian Shield with (iv) the large Chad Basin. To the Southeast, the Central African Shield separates that Basin from the immense Congo Basin, which is out of the project area. So are the small coastal basins of Ivory Coast and Sierra Leone. In Nigeria, the Benue Basin and Lower Niger Basin continue into the large coastal basin of Nigeria which terminates in Cameroon and Benin, Togo and Ghana. Due to their areal extent and the nature of their sedimentary fill, all of these basins are of great hydrogeological interest.

5.2.1.3 Historical Geology

Paleozoic transgressions resulted in covering the basins with marine deposits, now consolidated rocks, with generally poor water-bearing characteristics. The Taoudeni Basin was the first inland basin in which the seas advanced, the others being transgressed first in Jurassic time or later. The Hercynian orogeny, the only one which affected Western and Central Africa, produced such features as the Mauritanides (Cambro-Ordovician) and the Atacora Mountains, and contributed further to the faulting and fracturing of the basement.

During the Mesozoic, erosion continued to wear down the elevated areas of the region. At the same time, from the Jurassaic-early Cretaceous, thick strata of continental sediments, especially the "Continental Intercalaire", a well-known series and aquifer throughout Africa, were deposited all over the inland basins. The great transgression of the Cretaceous (except in the Chad Basin), which lasted until the Eocene, resulted in a system of marine sediments including the Maestrichtian and Paleocene series, famous aquifers of the Senegalo-Mauritanian Basin and coastal basins, and in hydrogeologically mediocre deposits (except in Nigeria) in the Taoudeni and Niger Basins.

Cenozoic time featured the general regression of the sea accompanied by the deposition of another widespread groundwater-bearing system, the "Continental Terminal", from the Eocene through the rest of the Tertiary and Quaternary. However, a transgression took place in the Miocene, especially in the coastal basins, resulting in sandy and clayey deposits, except in the Taoudeni and Niger basins which feature marly and clayey rocks and limestone. Important volcanic episodes took place in Africa during the late Tertiary and Quarternary (for example, Dakar area and central Nigeria). However, extrusive and intrusive rocks of recent or ancient age are a minor component in the project area.

5.2.2 Lithostratigraphy

A large variety of hard and soft rocks is exposed throughout Western and Central Africa and the project area (see Maps 5-1 and 5-2, Vol. 2). As shown in Fig. 5-1, prominent components are (i) the igneous and metamorphic rocks of the Precambrian basement complex, (ii) the Paleozoic sub-tabular formations made up of quartzite, schists, sandstone and dolomite, and (iii) the Mesozoic and Cenozoic sedimentary cover, featuring unconsolidated deposits, sandstone, and calcareous and clayey series. Most of the Mesozoic and Cenozoic sediments are of continental origin, with exceptions in the Senegalo-Mauritanian

Basin and other coastal basins. Uniformity and regularity characterize the lithostratigraphy of the region, with most of the main series spreading over hundreds of thousand of square kilometers without major change in character or thickness.

5.2.2.1 The Basement Complex

The basement complex, covering more than half the project area, is composed of (i) highly metamorphosed and somewhat folded Archeozoic granites and gneisses (for example, the Dahomeian) (ii) less metamorphosed and folded Pre-Cambrian granites, schists, quartzite and eruptive rocks such as the Atacorian, Birrimian and Tarkwaian, and (iii) Infra-Cambrian formations made up of granites, schists, sandstone and volcanic rocks, such as the Fale-mian in the Mauritanides. The Archeozoic is exposed over extended areas, while the Pre-Cambrian outcrops mostly in the Libero-Ivorian-Voltaic and Cen-tral African shields, and the Infra-Cambrian has much less significance. The lithologic nature of the basement is not conducive to good groundwater pros-pects but these negative features are enhanced by its fracturing and weathering.

5.2.2.2 The Sedimentary Basins

The extended sedimentary sub-tabular formations of Paleozoic and also Infra-Cambrian age mainly lie in the Taoudeni Basin and the relatively small Guinea Basin where they occupy large areas. They are several hundred meters in thickness, and sometimes more than 1,000 m. They include (a) a system of sandstone and quartzites with schists and calcareous series , and (b) an underlying system of schists including dolomite beds, some sandstone, quartzite and carbonates. The lithology of the Paleozoic and Infra-Cambrian formations is not favorable for the occurrence of groundwater, which however, happens to be improved by fracturing.

Mesozoic and Cenozoic sedimentary formations are areally extensive in the Niger and particularly in the Taoudeni and Chad basin parts of the project area; they are also the prominent formations of the Senegalo-Mauritanian Basin. They are thicker when of marine origin (over 3000 m) than when of continental origin (probably about 1000 m).

The thick, extended "Continental Intercalaire" series of late Jurassic to Cretaceous age is composed of sand, sandstone, clay and marl and occurs in all the above basins (and the Nigerian basins) except the coastal basins, including the Senegalo-Mauritanian basin; however, it is not well developed in the Taoudeni Basin. Maestrichtian (late Cretacous) sand and clay are a significant marine series of the coastal basins, especially the Senegalo-Mauritanian Basin, and so is the Paleocene (early Tertiary) limestone. Generally, marine Cretaceous and Paleocene (i.e. post-Continental Intercalaire) sediments are clayey and marly in the Taoudeni and Niger Basins, and sandy in Nigeria and the coastal basins. The "Continental Terminal" of Eocene to Quaternary age, although less thick (150-200 m and over 400 m in Chad) but areally more extensive than the "Continental Intercalaire", is a prominent series, especially in Chad, and mainly comprised of clay, sand and sandstone, sometimes overlain by or undifferentiated from Quaternary clastics. There is little alluvium in the project area.

In summary, many thick, porous and pervious strata occur in the sequence of Mesozoic and Cenozoic formations, which thus offer good groundwater prospects, except when these formations are clayey or marly.

The lithostratigraphy of the region may be summarized as follows in Table 5-1. The geology is presented in Map 5-1, including cross-sections.

5.3 THE AQUIFERS

Groundwater occurs nearly everywhere in Western and Central Africa, including in the basement complex, in sufficient quantity for rural water supply. Not surprisingly, a broad spectrum of water-bearing characteristics feature the diversified geologic components of the region, with best

TABLE 5-1 LITHOSTRATIGRAPHY OF WESTERN/CENTRAL AFRICA

Geologic Time		Age (million years) Cumulative	Absolute	Geologic Unit	Lithology (Rock type)	Thickness (meter)
	-Quaternary		0.7	Ad, Aa, A: Recent Sedimentary Cover	dunes alluvium fluviatile, lacustrine and marine deposits	20- 100 10- 50 ? 5- 150 (Chad)
CENOZOIC	-Tertiary	55		Bct Continental Terminal	Clayey sand and sandstone, sand, clay	50- 200 (over 400 in Chad)
	Pliocene		(6)			
	Miocene		(12)			
	Oligocene		(16)			
	Eocene		(20)	Be Eocene, (marine)	Clay, marl, clayey sand and sandstone, limestone and dolomite	70- 200 ?
	Paleocene			Bp Paleocene (marine)	limestone and dolomite, clay, marl	50- 150
MESOZOIC	- Cretaceous	190	(65)	Bm Maestrichtian (marine)	sand, clayey sand and sandstone, clay, marl	250- 500
	-Jurassic		(35)	Bci Continental Intercalaire	clayey sand and sandstone, sand, clay and marl	200- over 400 (more in Chad and Niger)
	-Triassic		(35)	B Undifferenciated Mesozoic deposits	clay and marl, clayey sand and sandstone, sand, sandstone, limestone and dolomite	over 1000 (3000 ?)
PALEOZOIC	- Permian	500+	(25)	Q Paleozoic and Infra- Cambrian sub-tabular formations	Pg sandstone; quartzite, limestone and dolomite, schists, pelites, argillite Pq quartzite; sandstone, limestone and dolomite, schists, pelites, argillite	Several 100; up to over 1000 (Guinea)
	- Carboniferous		(85)			
	- Devonian		(50)			
	- Silurian		(130)			
	-Ordovician			S Paleozoic and Infra-Cambrian sub-tabular formations	Ps, schists, sandstone, quartzite, limestone and dolomite Pd, dolomite; schists, pelites argillite, unconsolidated rocks	some 10 several 100; up to over 1000
	- Cambrian		(70)			

(Cont'd)

TABLE 5-1 (cont'd.) LITHOSTRATIGRAPHY OF WESTERN/CENTRAL AFRICA

Geologic Time	Age (million years) Cumulative Absolute	Geologic Unit	Lithology (Rock Type)	Thickness (meter)
Infra-Cambrian	1500 (1000)	ψ Cambrian and Infra-Cambrian (metamorphic)	schists, pelites, argillite, unconsolidated rocks; sandstone, quartzite, limestone and dolomite; basic extrusive and intrusive rocks	
Pre-Cambrian	} over 2000	ϵ Low-metamorphism rocks	schists, pelites, argillite; unconsolidated rocks; sandstone, quartzite, limestone and dolomite; basic extrusive and intrusive rocks	
Archeozoic		γ Granite and gneissic basement	granites and gneisses; unconsolidated rocks (weathering) lateritic hardpan	0 - 50 0 - 10
Various geologic times		β Basic extrusive and intrusive rocks	dolerite, basalt, dunite; lateritic hardpan	0 - 10

Source: adapted from BURGEAP Subcontract.

groundwater availability in the sedimentary basins.

As shown in Fig. 5-2, the basement is an areally extensive, poor aquifer, while Infra-Cambrian and Paleozoic hard rocks generally are mediocre to poor aquifers. The Continental Intercalaire is a good groundwater reservoir, frequently deep, and so are the marine formations of Maestrichtian and Paleocene age, while the other Cretaceous series are mediocre aquifers (except in Nigeria) due to their clayey-marly facies. The Continental Terminal and Quaternary clastics are fair to good groundwater reservoirs.

5.3.1 Classification

For classification and practical purposes, the French hydrogeologists have defined two fundamental types of aquifers in the region. Continuous aquifers ("Aquifères Généralisés") are those with either interstitial or fracture porosity, and a large areal extent; they are comprised of unconsolidated as well as consolidated sedimentary rocks of Mesozoic and Cenozoic age. Discontinuous aquifers ("Aquifères Discontinus") include impervious or poorly pervious rocks which are locally water-bearing due to secondary permeability from fracturing and/or weathering. Basement complex rocks, Paleozoic sedimentary hard rocks such as massive quartzite, sandstone, limestone and dolomite, and small alluvial formations belong to that category. This classification has its merits but is somewhat confusing and will not be used in this report. Suffice to say that the region features two broad types of groundwater reservoirs: 1) the igneous and metamorphic basement complex, a poor aquifer characterized by fractures and an irregular weathered zone; and 2) the sedimentary filling of the basins featuring hard-and soft-rock aquifers with generally good to fair, but sometimes mediocre or poor, water-bearing characteristics.

The aquifers in the project area are mapped in Fig. 5-2, with an explanation summarizing their main characteristics. Their thickness is presented in Table 5-1 (Geology section). Their approximate outcrop areas are summarized below in Table 5-2. Over half the project area is covered with

TABLE 5-2 AQUIFER OUTCROP AREAS IN THE PROJECT AREA (sq. km)

Country	Basement (poor aquifer) a	Sedimentary Basins: Paleozoic cover (poor-mediocre aquifer) b	Sedimentary Basins: Post-Paleozoic Cover (good-fair aquifers) c	Sedimentary Basins: Total, Sedimentary Basins d(b+c)	Total, Country e(a+b+c)	Percentage of total area underlain by good-fair aquifers
Benin	89 000		14 000	14 000	103 000	14
Cameroon	204 000		39 000	39 000	243 000	16
Central African Emp.	410 000		152 000	152 000	562 000	27
Chad	189 000		335 000	335 000	524 000	64
Gambia			10 000	10 000	10 000	100
Ghana	161 000		500	500	161 500	$\simeq 0$
Guinea	140 000	100 000		100 000	240 000	$\simeq 0$
Guinea Bissau		16 000	20 000	36 000	36 000	56
Ivory Coast	166 000				166 000	0
Mali	60 000	310 000	135 000	445 000	505 000	27
Mauritania	77 000	30 000	44 000	74 000	151 000	29
Niger	60 000		245 000	245 000	305 000	80
Nigeria	388 000		351 000	351 000	739 000	48
Senegal	32 000	45 000	117 000	162 000	194 000	55
Sierra Leone	30 000				30 000	0
Togo	54 000		2 000	2 000	56 000	14
Upper Volta	225 000	32 000	11 000	43 000	268 000	14
Total	2,546,000	553,000	1,457,500	2,010,500	4,556,500	32

basement rocks, a poor aquifer. Of the remaining area comprised of sedimentary basins, about one quarter is covered with the Paleozoic formations, poor-mediocre aquifers. Overall, only one third of the project area is made up of good-fair aquifers.

The hydrogeology of the project area is presented in Map 5-2, including characteristics of the geology, hydrogeology, aquifers, well types, depths and yields, groundwater quality and potential.

5.3.2 The Basement Complex

Igneous and metamorphic rocks are impervious and have nearly no porosity except in faulted, fractured and weathered zones. Weathering in tropical areas with humid climatic conditions starts generally at fissured parts of rocks, and results in a lateritic cover of variable thickness. In the Sahel area, lateritic covers do exist, having been developed in past geologic times when the climate was wet. The lateritic cover is irregular and sometimes not well developed, for instance in Togo.

5.3.2.1 Groundwater Occurrence

As shown in Fig. 5-3-A, weathering in granites and gneisses, has resulted in a 0-30 m thick weathered zone comprised, from top to bottom, of: (a) hardpan, a few meters thick, which may be missing; (b) kaolinic clay, up to some 10 m thick, sometimes absent; (c) residual coarse sand, a few meters thick; (d) basal coarse sand,boulders and fractured bedrock; and (e) bedrock more or less fractured generally down to 50-100 m, sometimes less or even more. In schists (Fig. 5-3-B), the following are the only existing horizons: (a) bauxite which may be missing; (b) the clayey horizon (lateritic clay) which may be up to 100 m in thickness; and horizon (d) made up in this case of fissured and fractured schists. In quartzite, sandstone and eruptive rocks, weathering horizons are non-existent or very limited. The residual coarse sand horizon (c) is groundwater - bearing and so is the basal horizon (d), and last but not the least the fractured horizon (e) when fracturing is significant; horizon (a), the hardpan, is sometimes an aquifer.

Groundwater occurrence, although homogeneous at regional scale, is much less so at local or well site scale (see Fig. 5-4). In fact, it is discontinuous and extremely variable, and a well may be relatively good in a weathered and/or fractured area and extremely poor if not dry a short distance away. This is due to the areal variations in weathering and fracturing. Highly weathered and fractured zones are generally coupled since weathering develops better from an already fractured zone. As a consequence, the thickest weathered zones are generally overlying fractured zones, all of which is favorable to the occurrence of groundwater. As a matter of fact, exploration in this type of hydrogeological environment consists in locating fractured zones by aerial photo-interpretation and geophysical measurements coupled with field inspection, which results in the best well yields either from the weathered horizon (residual sands and boulders) and/or better the underlying fractured zone down to, say, 80-100 m. Then, it is generally advisable to sink the well slightly apart from the fracture (or deepest part of the weathering trough), and not immediately above because clayey material generally occurs at that very point, and also because of dip considerations.

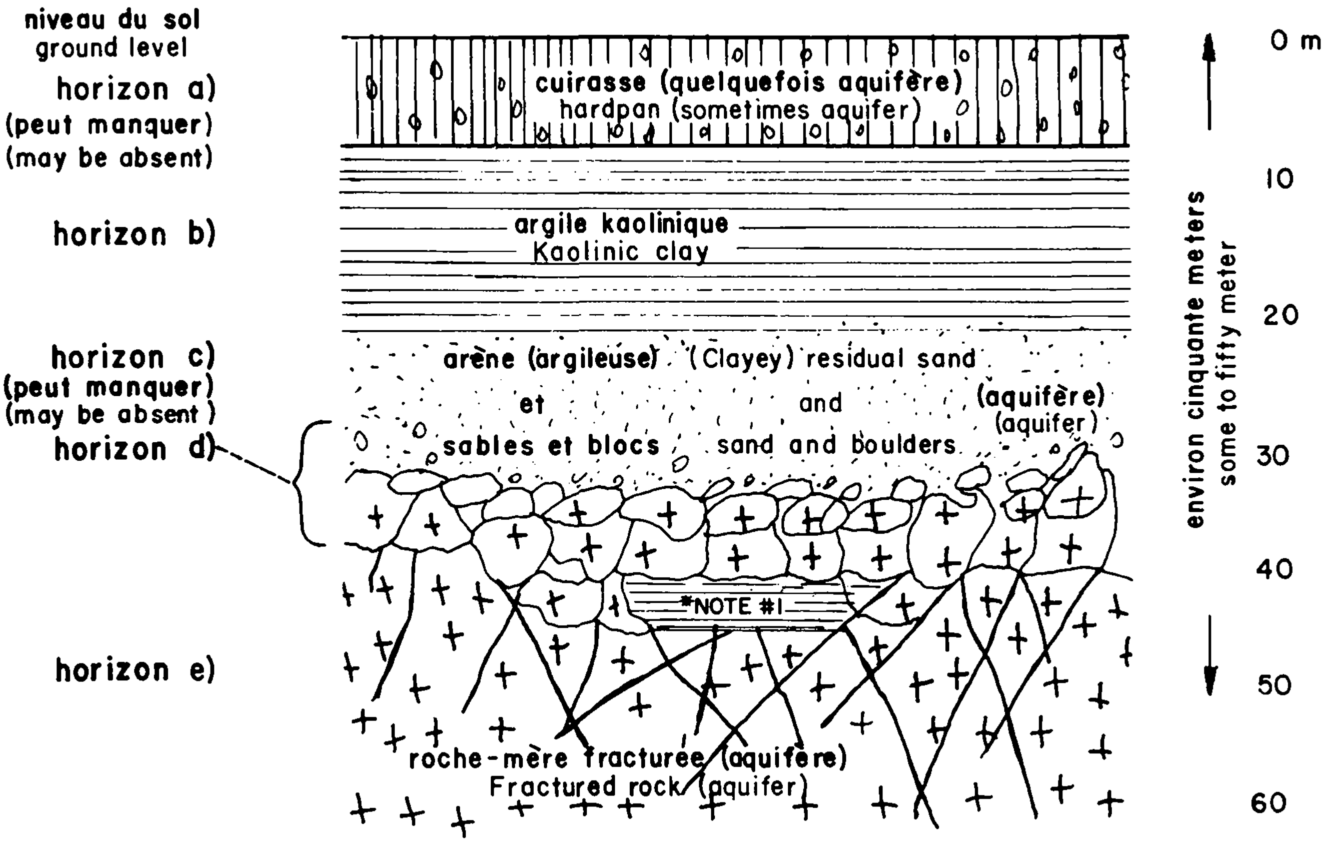
5.3.2.2 Well Yields and Depths

Well yields (see Map 5-3) range between 0 and exceptionally 50 m^3/h, for instance in the hardpan or in highly fractured schists. Generally, they are 0.5 to 8 m^3/h, the higher figures being typical of fractured zones in schists, and the lower ones of residual sand horizons in granites and gneisses. In basalt, good yields have been reported in Nigeria (Jos Plateau), with springs discharging 400 m^3/h and wells producing 10- 20 m^3/h. Aquifer transmissivities in the basement usually are in the 10^{-5} to 10^{-4} m^2/s range.

Well depths (see legend of Map 5-2) range from 5 to 70 m, being generally 15 - 40 m. Wells are deepest in schists and fractured zones of

COUPES SCHEMATIQUES DE L'ALTERATION ET DES HORIZONS AQUIFERES DANS LE SOCLE
SCHEMATIC SECTIONS OF WEATHERING AND GROUNDWATER OCCURRENCE IN THE BASEMENT

A/ Altération des Granites et Gneiss
Weathering in Granites and Gneisses



les meilleurs sites pour puits et forages sont de part et d'autre de l'argile d'altération qui occupe le centre de la zone altérée

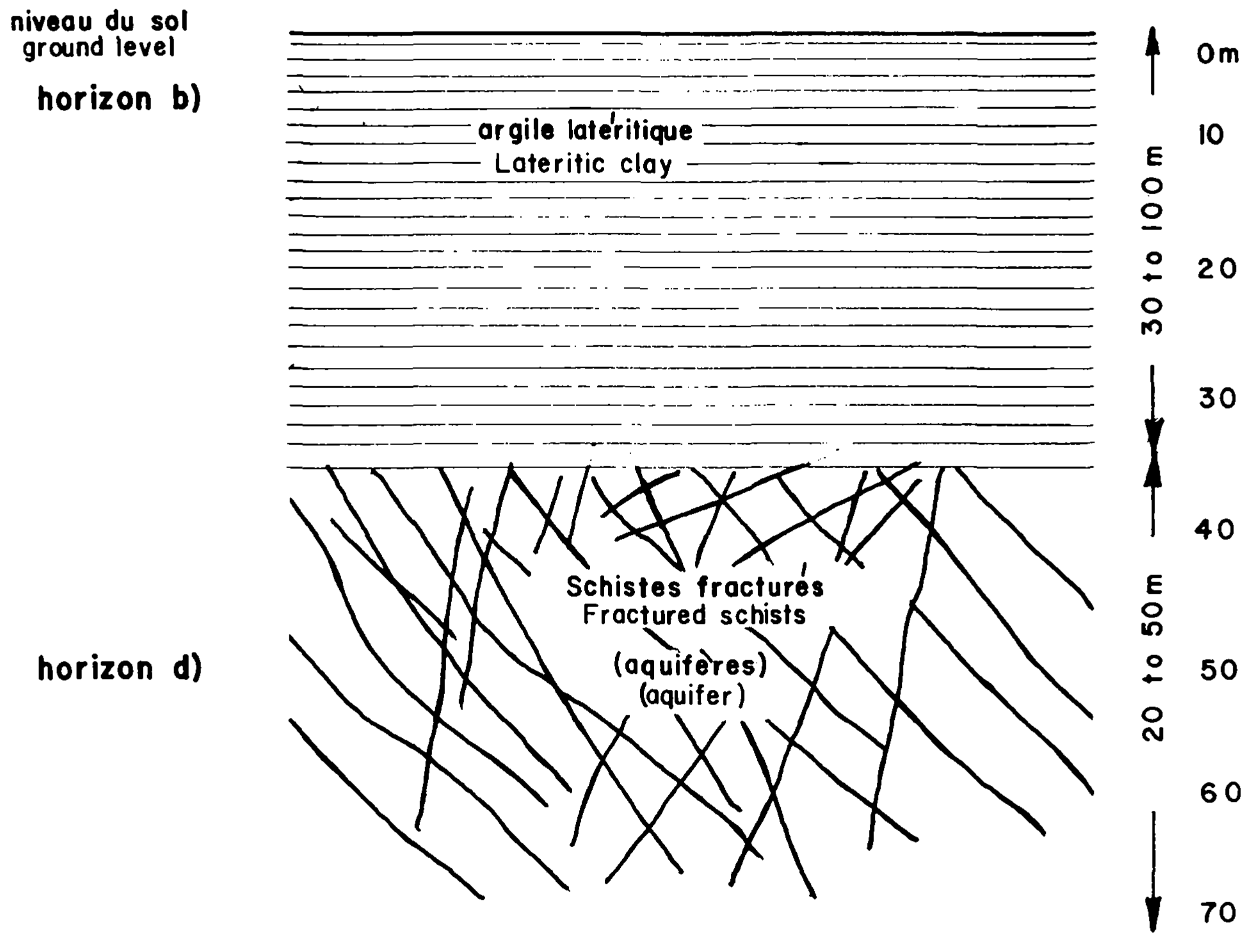
best location for wells is apart from the residual clay (center of alteration through)

NOTE # 1
argile d'altération
Residual clay

Fig. 5-3(A)

COUPES SCHEMATIQUES DE L'ALTERATION ET DES HORIZONS AQUIFERES DANS LE SOCLE
SCHEMATIC SECTIONS OF WEATHERING AND GROUNDWATER OCCURRENCE IN THE BASEMENT

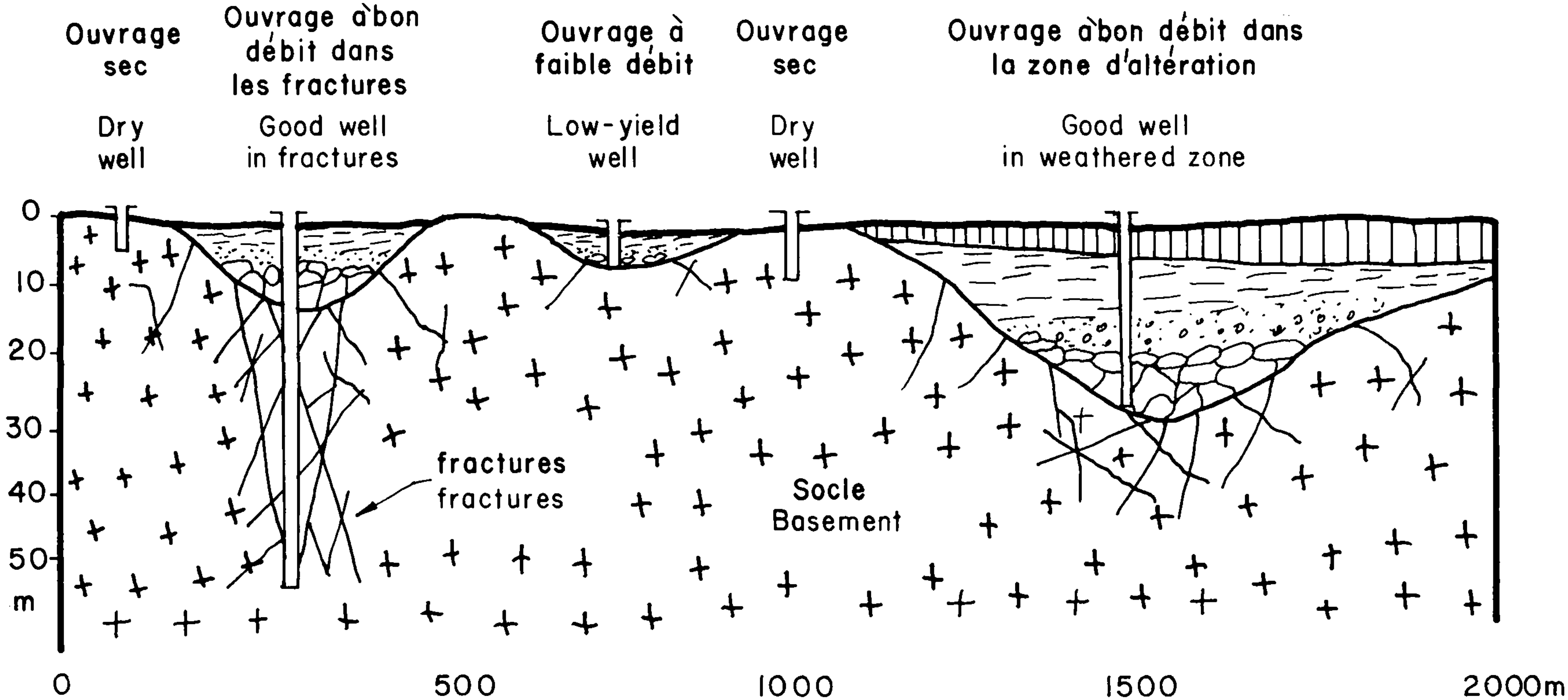
B/ Altération des Schistes
Weathering in Schists



les meilleurs sites pour puits et forages sont dans la zone fortement fracturée
best location for wells is where fracturing is dense

Fig.5-3(B)

COUPE TYPIQUE DES ZONES AQUIFERES DANS LE SOCLE
GROUNDWATER OCCURRENCE IN THE BASEMENT, TYPICAL CROSS-SECTION



Les zones aquifères sont les arènes et blocs de la zone d'altéraration, et les fractures
Groundwater occurs in basal sands and boulders of weathered zone and in fractures

Fig.5-4

igneous rocks, and commonly about 15-20 m deep in the weathered zones of granites and gneisses.

Typical well yields and depths are summarized in the following Table 5-3 (and in the legend of Map 5-2).

TABLE 5-3 WELL YIELDS AND DEPTHS IN THE BASEMENT

Rock Type	Well Yields (m^3/h)			Well Depths (m)	
	range	average	exceptional	range	average
-Cambrian and					
Infra-Cambrian schists	0-20	5		25-70	40
-Precambrian schists	0-20	8	40	25-70	40
-Granites, gneisses					
horizons a and c	0-5	0.2	10	5-30	15
horizons d and e	0-10	4	20	30-70	40
-Eruptive rocks	0-20	3	20	15-50	30

5.3.3 The Sedimentary Basins

The sedimentary basins cover nearly half of the project area featuring an extended, poor water-bearing Paleozoic cover in the Taoudeni Basin, and generally good Mesozoic and Cenozoic groundwater reservoirs, especially in the Chad, Niger, Senegal and Nigeria basins (see Fig. 5-2). Most sedimentary aquifers are made up of sand and sandstone, while calcareous aquifers are few and generally mediocre (except the Paleocene of Senegal and the Sokoto Basin in Nigeria). The characteristic weathering of the basement rocks affects exceptionally only the rocks of the sedimentary basins, for example the Paleozoic schists of Guinea. Well yields and depths are summarized in the legend of Map 5-2, and well yields in shallow and deep aquifers throughout the project area are shown in Map 5-3 (sheets 1 and 2, respectively). Depth to the top of deep aquifers is shown in Map 5-4, sheet 3 of 3.

5.3.3.1 Paleozoic Cover

The Paleozoic cover, several hundred meters in thickness and typical of the Taoudeni and most of the Guinea Basins and of Ghana, is a somewhat better aquifer than the basement complex. However, this fracture-porosity aquifer still is mediocre, if not poor, although sometimes fairly productive, for example the Aioun sandstone and Hodh pelite in Mauritania. Well yields range from 0 to 100 m^3/h, being generally 1 to 10 m^3/h. Dolomite and sometimes sandstone are the best water-bearing rocks, and schists are the poorest, while quartzite and sandstone generally yield 2-3 m^3/h per well. The Kou springs from sandstone in the Bobo-Dioulasso, Upper Volta area, discharging about 2-4 m^3/s, evidence the locally exceptionally good characteristics of the Paleozoic cover. Well depths are in the 5-70 m range, generally 25-40 m, the deepest wells being in quartzite and the shallowest in dolomite. Below are typical figures for well yields and depths (Table 5-4).

TABLE 5-4 WELL YIELDS AND DEPTHS IN PALEOZOIC ROCKS

Rock Type	Well yield (m^3/h)			Well Depth (m)	
	range	average	exceptional	range	average
-sandstone	1-5	3	25	10-50	30
-quartzite	0-5	2	15	25-70	40
-Schists	0-5	1	10	5-70	30
-dolomite	0-20	10	100	15-20	25

5.3.3.2 Continental Intercalaire

The Continental Intercalaire sand and sandstone, with variable clay content, is one of the best, thickest (200-over 400 m) and deepest (up to several hundred meters) aquifer systems in the region. This system occurs throughout Africa, being one of the greatest groundwater reservoirs in the world, very attractive in the Sahara, Egypt, Libya, Sudan, Zaire and southern Africa. In the project area, it occurs in the Niger Basin (Tegama sandstone), Sokoto, Benue and Lower Niger basins (Nigeria), and in the Central African Empire (Moukka-Ouadda and Carnot sandstone, good aquifers up to 200-300 m in thickness); it is not well developed in the Taoudeni Basin, and should be investigated in the Chad Basin. Groundwater may occur under either unconfined conditions in upstream parts of the aquifer or generally confined conditions elsewhere. Well yields range from 1 to 250 m^3/h (5 m^3/h in the average from relatively shallow traditional dug-wells, and 100 m^3/h and much more in the deep wells), with high yields in the Niger and Sokoto basins. Well depths are generally 10 to 100 m in the outcropping areas (dug wells) and up to several hundred meters elsewhere. Aquifer transmissivities usually are in the 10^{-3} m^2/s range and above.

5.3.3.3 Cretaceous

The Cretaceous marine deposits, up to a few hundred meters in thickness, include marly sandstone and limestone, clay, schists and so forth, especially in the Niger and Taoudeni basins. These rocks are mediocre or poor aquifers with typical well yields in the 0-20 m^3/h range. However, in the Nigeria and coastal basins (Benin, Togo, etc.), the Cretaceous deposits have a sandy facies and are good aquifers, especially in the Lower Benue, Lower Niger and Sokoto hasins where well yields are up to over 100-150 m^3/h (in the Upper Benue Basin, they are much lower, the aquifer being mediocre). Well depth is in the 50-150 m range and up, for instance in the Benue Basin. Aquifer transmissivities are good in Nigeria, being in the 10^{-3} - 10^{-2} m^2/s range in the Sokoto Basin.

5.3.3.4 Maestrichtian

The Maestrichtian sandy, generally confined aquifer, several hundred meters in maximum thickness, occurs in the Senegalo-Mauritanian Basin, especially in the Senegalese part, and in the coastal Togo-Benin-Nigeria Basin (see above Cretaceous aquifer). It is one of the most prolific aquifers of Western Africa, especially in Senegal, and also in the Gambia (and Guinea

Bissau). Well yields are up to 300 m^3/h, generally 100 m^3/h and more, and quite infrequently as low as 10-20 m^3/h. Yields decrease westward in Senegal and Mauritania due to the clayey nature of the sediments. Well depths are in the 100-500 m range, generally about 250 m. Aquifer transmissivities usually are in the 10^{-3} - 10^{-2} m^2/s range.

5.3.3.5 Paleocene (and Eocene)

The Paleocene (and Eocene) limestone and dolomite, a few tens to 100-200 m in thickness, are an interesting aquifer in Senegal where the Paleocene is karstic and in hydraulic continuity with the Maestrichtian, and also in the Upper Benue Basin in Nigeria. Elsewhere, facies are generally marly or clayey, and the aquifer is poor to mediocre (Sokoto, Lower Benue and coastal basins), while the above Cretaceous deposits are a dependable aquifer. Well yields, generally in the 0-15 m^3/h range (frequently 3 m^3/h) when facies are clayey, reach 100-300 m^3/h in Senegal and where the aquifer is calcareous and karstified. Well depths, 25-50 m where the aquifer is shallow, may be 150-200 m elsewhere.

5.3.3.6 Continental Terminal

The Continental Terminal sand, sandstone and clay, 50-200 m in thickness and much more in the Chad Basin (up to 1000 m and more ?), occur in all of the basins of the project area. It is the prominent aquifer system in the Chad Basin where it needs to be explored further. This system is frequently unconfined but also involves confined conditions, for instance in the Chad and Sokoto basins where it features two or three aquifers. Well yields are generally 5 m^3/h from dug wells and about 50 m^3/h from drilled wells, and up to 100-150 m^3/h. Well depths range from 10 to 150 m, being generally 40 m or more. However, they should be much deeper in many instances in order to take full advantage of that prolific, relatively shallow aquifer system. Aquifer transmissivities usually are in the 10^{-4} - 10^{-3} m^2/s range.

5.3.3.7 Plio-Quaternary and Quaternary

The Plio-Quaternary and Quaternary clastics, 5-100 m thick (and more in Chad), are exposed in all the basins of the project area. They are especially good aquifers in Nigeria, Niger, Senegal and above all in Chad. Well yields are in the 0-150 m^3/h range, generally a few to about 5-10 m^3/h, the best being from the sand dunes (Senegal) and fluviatile-lacustrine-marine deposits. Alluvium is not much developed in the region but forms noteworthy aquifers (associated with the Senegal river, for example). Buried valleys ("dallol" in Niger) such as the Azawak in Niger, the Tilemsi in Mali (North of Gao), the Bahr El Ghazal in Chad and others in Mauritania should be held as good prospects, and further investigated. Well depths, up to a few hundred meters (Chad Basin) generally are 5 to 20 m and need not be more than some tens of meters in most circumstances. Aquifer transmissivities are variable, in the 10^{-5} - 10^{-2} m^2/s range and are especially good in the Pliocene and in the Lake Chad area.

5.3.3.8 Summary

The sedimentary aquifers occur and may be rated as follows in the project area:

-Senegalo-Mauritanian Basin: alluvium and dune sand, fair to good, especially in Senegal; Continental Terminal, extended and fair to good, especially in Senegal, and the best aquifer of Mauritania; Eocene, poor to mediocre; Maestrichtian (and Paleocene), extended, good but relatively deep.

-Guinea Basin : Quaternary, limited; Tertiary, limited but may be fair to good; Paleozoic, poor.

-Taoudeni Basin : Niger alluvium, areally extensive but of no interest due to the occurrence of the Continental Terminal, extended and fair to good; Cretaceous, mediocre; Continental Intercalaire, relatively limited and good but somewhat deep; Paleozoic, extended but poor to mediocre, exceptional yields occasionally, for instance in Upper Volta.

-Niger Basin : Continental Terminal, extended and fair to good; Eocene, Paleocene, Cretaceous, poor to mediocre (Cretaceous good in Sokoto Basin); Continental Intercalaire, extended, good but deep.

-Chad Basin : Quaternary, extended, thick, good but irregular; Pliocene, relatively extended and thick, good; Continental Terminal, extended, thick and good; Continental Intercalaire (Central African Empire, probably good), to be investigated.

-Lower Niger and Benue Basins : Quaternary, fair; Continental Terminal, good; Paleocene, poor but good upstream; Cretaceous, mediocre but thick and good downstream; Continental Intercalaire : thick and good.

-Togo-Benin Basin : Quarternary, fair; Continental Terminal, good; Paleocene, poor to fair; Maestrichtian, good.

5.3.4 Conclusion

The basement complex which occupies over half of the project area, especially the southern part, is a poor, but useful aquifer, fit in particular for rural water supply through shallow wells 15-40 m in depth and 0.5-8 m^3/h in capacity. It covers nearly all of such countries as Ivory Coast, Sierra Leone, Ghana, Guinea, Togo, Upper Volta, Benin, Cameroon and the Central African Empire which generally do not have other aquifers. However, such countries as the Central African Empire (northern, eastern and southern parts) Cameroon (Lake Chad area), Benin (coastal and northeastern parts) Togo (coastal area) and Upper Volta (northern and southwestern parts) do include some valuable aquifers, while Mauritania, Senegal, Chad and above all Nigeria have important water-bearing basement areas.

The sedimentary basins, mainly restricted to the northern and Sahel parts of the project area, are good groundwater reservoirs. The Chad, Niger, Senegalo-Mauritanian, Nigeria and also Taoudeni basins are especially large and attractive, while the small coastal basins of Benin and Togo contain noteworthy and useful aquifers.

The Paleozoic formations, poor-mediocre aquifers, are much developed in Mali and present in the Guineas, Mauritania, Senegal and Upper Volta (as well as in Ghana and Togo where schists were classified as basement); wells, generally 25-40 in depth, usually yield 1-10 m^3/h, and up to 100 m^3/h. The Continental Intercalaire, Maestrichtian and Paleocene aquifers are thick and deep, generally 150-250 meters (and up for the Continental Intercalaire), with good capabilities, wells yielding usually 100-150 m^3/h. The Continental Terminal, Pliocene and Quaternary are less deep, generally 20-100 m, and good aquifers, especially the first one from which wells yield up to 150 m^3/h. All of these post-Paleozoic aquifers mainly occur in the Lake Chad area, Niger, Nigeria, Mali, Senegal, The Gambia, Guinea Bissau and Mauritania.

Countries especially well endowed with good aquifers are Nigeria, Chad, Niger and Senegal. Others like Mali, The Gambia, Guinea Bissau, Central African Empire and even Mauritania are fairly well provided, while the Cameroon, Benin, Togo, and Upper Volta, have some noteworthy sedimentary aquifers. Overall, countries with several good aquifers are Nigeria, Chad, Niger, Senegal, and even Mali. Countries with some good aquifers include The Gambia, Guinea Bissau (extended area), the Central African Empire, Mauritania, Cameroon, Benin, and Togo. Countries generally with poor aquifers are Upper Volta, Guinea, Ghana, Sierra Leone and Ivory Coast.

5.4 GEOHYDROLOGY

The basement complex is a relatively simple unconfined aquifer in spite of somewhat heterogeneous groundwater conditions. The sedimentary basin aquifers constitute a complex system involving several water-bearing strata under either unconfined or confined conditions, and a broad range of groundwater conditions. In addition to water-bearing properties and well yields described in the preceding pages, water depth, movement, storage and quality and the safe yield are the inter-related key-factors which characterize these aquifers and condition groundwater availability and suitability in the project area. Also, present groundwater development plays a significant role in groundwater resources evaluation due to its impact on the potential and planning for additional use.

5.4.1 Groundwater Depth

Groundwater depth depends upon topographic, geologic, geohydrologic and climatologic conditions. Depth to water in the shallow basement and sedimentary aquifers and in the deep unconfined or confined sedimentary aquifers is presented in Map 5-4 (sheet 1 and 2 of 3). Depth to the top of the deep aquifers is shown in Map 5-4 (sheet 3 of 3). Depth of wells and aquifer thickness are described in the preceding pages and in Map 5-2.

In the basement complex, the groundwater level occurs between a few meters and 20-30 m below ground surface, being generally about 10-15 m. In fact, dug wells generally are or should be 15-40 m deep, with preferably about 5 m of water depth below the dry season water level.

In the sedimentary basins, phreatic groundwater, i.e. water in the first water-table aquifer encountered when sinking a well, is generally 20-40 m below the ground level, and up to 80-90 m. Groundwater in valleys and alluvium is generally the most shallow, 5-20 m deep, and so is groundwater in continuity with surface water bodies (Senegal and Gambia rivers, Niger river area - especially in Mali - , Chari and Logone rivers, etc). In arid zones (Sahel region), groundwater is the deepest, generally 40-60 m and more. Groundwater level fluctuations involve generally 5-10 m and more (especially in arid zones) between the dry and rainy seasons. In the Sahel, the past sequence of drought years has resulted in a generalized water table drop of several meters which is seemingly taking years to recover.

In the deep, generally confined aquifers, some wells flow at land surface (wells in Chad and Sokoto basins, for instance), but ground water level occurs most often at 10 to 50 m below ground level. Depth to the top of aquifers ranges between 100 and 500-700 m being generally at 200-300 m below ground surface. The Continental Intercalaire generally is the deepest aquifer.

5.4.2 Groundwater Movement

Natural recharge to aquifers, a not well known parameter, is mainly from rainfall, however it is nearly nil where rainfall is less than 400 mm per year, i.e. in the Sahel, while it is relatively significant southward, most probably up to 10-20 percent and more of rainfall. Important seasonal changes of the water table, involving a rise of several meters with the rains, demonstrate the significance of infiltration, while the fall of the same magnitude during the dry season evidences the high intensity of evapotranspiration. In addition to being through evapotranspiration, main groundwater outlet discharge is also through some springs and into rivers and streams to which aquifers provide a fair amount of baseflow. In coastal basins discharge also takes place into the sea, and a reverse movement (sea water intrusion) may take place in case of groundwater overdevelopment; potential for such landward movement of salty groundwater does exist in Togo, Benin, Guinea, Guinea-Bissau, Gambia, Senegal and Mauritania. As for the Lake Chad area, it is the outlet of subregional groundwater flow. Deep aquifers are recharged mainly through leakage from the water table aquifers and also by some infiltration in their own outcropping areas, which however is generally limited. Discharge through upward leakage also takes place where the head in deep groundwater reservoirs is high, for instance the Chad Basin.

As sketched in Figure 5-5, upstream segments of streams and rivers generally drain the water table aquifers, especially in the basement. Downstream segments of streams and rivers frequently recharge those Quaternary and Continental Terminal aquifers with which they are in hydraulic continuity, for instance the Niger river in Mali, the Chari and Logone, and the Senegal River; this is especially true during the rainy season. The order of magnitude of groundwater discharge into streams and rivers (baseflow) is appreciable judging by the lowflow measurements at gauging stations (see Surface Water Chapter). It seems to be over ten billion cubic meters per year in the project area. Groundwater discharge in streams and rivers is especially high in the Chad and Niger basins (some billions of m^3/year each) and is several tens of millions m^3/year in the Senegal Basin. This gives an estimate of the size of actual recharge to aquifers to which, however, upward leakage (evapotranspiration) in high water table areas and downward leakage to deep aquifers shall be added in order to have an estimate of total infiltration; these leakages are of a higher order of magnitude than the above discharge into streams and rivers.

5.4.3 Safe Yield

The safe yield (or natural recharge) of the aquifers in the project area is difficult to calculate due to the complexity of groundwater conditions, the hugeness of the area and the relatively limited availability of basic data. However, an order of magnitude, which is of concern in this report, was estimated using two methods, one by BRGM, the other by BURGEAP. Also, it may be noted that (i) in the Sahel aquifers, the safe yield may amount to a few billions of cubic meters per year, assuming an infiltration coefficient of less than one percent of the rainfall, and that (ii) in the rest of the project area, it may amount to several tens of billions of cubic meters per year, given the larger rainfall and a much higher coefficient of infiltration. The results of the BRGM and BURGEAP methods described below involve even higher figures.

The BRGM method (method A) involves the calculation of the difference between measured monthly rainfall and computed monthly evapotranspiration (TURC method), i.e. the effective rainfall (or total runoff), one part of which flows into rivers and streams, and the other part infiltrates underground. The latter part was estimated to range between 5 percent (on granites) and 100 percent (on dune sands) of effective rainfall. This was done through a trial-and-error approach, taking into account lithology, topography, fracturing, vegetation, baseflow and water-table fluctuations. The BURGEAP method (method B) is somewhat similar except that surface runoff was measured in about 25 typical watersheds; measured rainfall minus surface runoff and computed evapotranspiration represents infiltration into groundwater reservoirs. The BURGEAP method frequently results in figures twice (or much more) as high as those from the BRGM method. The figures presented in this text and the following tables are from the most conservative of these two methods, i.e. the BRGM method. However, it should be borne in mind that the figures from the BURGEAP method are also reliable since they are founded on more measurements (and not assumptions) than those from the BRGM method.

Results from the BRGM method A in the project area are presented in Map 5-5 (sheet 1 of 2), which also shows contours of effective rainfall and those from the BURGEAP method B in Map 5-5 (sheet 2 of 2). These maps present the areal distribution of average natural recharge (safe yield) into shallow aquifers, part of which -in sedimentary basins- then leaks into the deep aquifers (while, throughout most of the project area, another part of which drains into streams and rivers). The estimated distribution of natural recharge shows the influence of geology and above all climate on infiltration. Recharge is generally in the ranges shown in the following Table 5-5.

TABLE 5-5 ESTIMATED NATURAL RECHARGE VERSUS ROCK OR AQUIFER TYPES

Rock or Aquifer	Range of Recharge*		
	millimeter/year		m^3/year/sq.km.
-Basement	range	average	average
. granite and gneisses	0-200	(50)	50,000
. schists	0-200	(50)	50,000
-Sedimentary Basins			
. Paleozoic cover			
sandstone and quartzite	0-200	(75)	75,000
dolomite and schists	0-100	(50)	50,000
. Continental Intercalaire, Cretaceous	0-200	(150)	150,000
. Continental Terminal and Quaternary	0-300	(150)	150,000

*These figures are much lower in the Sahel, generally less than 25 mm (25,000 m^3/yr/sq.km) and down to zero mm.

The following Table 5-6 presents tentative estimates of the safe yield in individual aquifers, countries and basins. These estimates, however, should not be taken literally, but considered as approximate orders of magnitude.

The order of magnitude of natural recharge (safe yield) in the project area is over 150 billion cubic meters per year, approximately equally shared between the basement (80 billion) and the sedimentary aquifers (85 billion). Clearly, there is an enormous renewable supply of groundwater to cope with any need. However, it should be borne in mind that groundwater may not be available at the right location, at a sufficient yield at the well head, or that the demand may be too high with respect to the aquifer's capability to transmit the groundwater to pumping wells at certain places.

This is especially true for the basement and for those aquifers in the sedimentary basins which are mediocre. Thus, although the above enormous quantities of groundwater do move through and are theoretically available from the aquifers of the project area, only a portion thereof is recoverable, actually that portion which wells are able to deliver(under economically acceptable conditions). This portion is especially high in good-permeability sedimentary aquifers and rather small in the basement and low-permeability aquifers (Paleozoic, etc.)

Summing up, aquifers and countries located in the southern part of the project area are generally endowed with a good safe yield due to high infiltration rates (humid climate areas), which is especially true when aquifers have good hydrodynamic properties. Those located northward and in the Sahel do not benefit from such favorable conditions, infiltration being very limited, if not nil, so that the safe yield is much less, however still quite encouraging in the case of high permeability aquifers.

The best sedimentary basins are (by order of decreasing importance) Chad (nearly half of the safe yield), Benue and Lower Niger (20 percent), Senegalo-Mauritanian (15 percent), Niger and Taoudeni; the coastal basins, however, are

TABLE 5-6 ESTIMATED SAFE YIELD PER AQUIFER, COUNTRY AND BASIN (Mm^3/yr)*

Basin	Country	Sedimentary Basins								Basement	Total
		Paleozoic	Continental Intercalaire (CI)	Cretaceous	Maestrichtian (M)	Paleocene-Eocene	Continental Terminal (CT)	Quaternary	Total (sedimentary)		
Senegalo-									12606	835	
Mauritanian	Mauritania	>60				0 ?	0 ?	36	96	15	111
	Senegal				incl. in CT	750	7460	260	8470	820	9290
	Gambia				dito		1040		1040		1040
	Guinea Bissau	1000			2000		Included in Maestrichtian	Included in Maestrichtian	3000		3000
										5500	
	Guinea	3000							3000	4000	7000
	Sierra Leone									1500	1500
Taoudeni									12548	5570	
	Mali	9380	0 ?				778	Included in	10158	1800	
	Upper Volta	1960					430	CT	2390	3770	6160
	Ivory Coast									6600	6600
Coastal									720	7900	
	Ghana			included in	30				30	3200	3230
	Togo			Maestrichtian	40	20	incl. in M.		60	1600	1660
	Benin				30	100	400	100	630	3100	
Niger									4311	21380	
	Mali (Sud Adrar)						53		53	1800	
	Niger		included in Cont. Term.				1628	included in CT	1628	180	
	Nigeria (Sokoto)		1200	300		100	500		2100	19400	
	Benin (")		500				30		530		
Lower Niger									16500		
and Benue	Nigeria		2700	10200		2000	100	200	15200		
	Cameroon		1300						1300		

(Cont'd.)

TABLE 5-6 (cont'd.) ESTIMATED SAFE YIELD PER AQUIFER, COUNTRY AND BASIN (Mm^3/yr)*

Basin	Country	Sedimentary Basins								Basement	Total
		Paleozoic	Continental Intercalaire (CI)	Cretaceous	Maestrichtian (M)	Paleocene-Eocene	Continental Terminal (CT)	Quaternary	Total (sedimentary)		
Chad									35990	33500	
	Chad		included in Cont. Term.				12800	4100	16900	2800	19700
	Niger (Koramas)							1890	1890		
	Nigeria							3700	3700		
	Cameroon							1000	1000	10200	
	Central African Emp.		6300				6200		12500	20500	33000
Total for 5 countries in 2 or more Basins	Mali	9380					831	0	10211	1800	12011
	Benin		500		30	100	430	100	1160	3100	4260
	Niger						1628	1890	3518	180	3698
	Nigeria		3900	10500		2100	600	3900	21000	19400	40400
	Cameroon		1300					1000	2300	10200	12500
TOTAL		15400	12000	10500	2100	2970	31419	17486	85675	79485	165060

*Source: From BRGM (subcontract) basic data.

also noteworthy and useful groundwater reservoirs. The best aquifers are the Continental Terminal (and Quaternary) -over half of the safe yield-, the Continental Intercalaire (15 percent), the Cretaceous (in Nigeria only) -12 percent- and the Maestrichtian (10 percent); Paleozoic groundwater, although present in large quantities, can be recovered only partially due to low aquifer permeability. Countries with the best recoverable safe yield are Nigeria (about 25 percent of the safe yield), Chad (20 percent), Senegal (10 percent), Niger, Mali, Cameroon, Central African Empire, Guinea Bissau, Gambia and even Benin. The other countries are rather poorly endowed especially Sierra Leone, Togo and Ghana, and those with Sahel territories such as Mauritania and Upper Volta.

5.4.4 Groundwater Storage

Groundwater storage represents the volume of water stored underground in aquifer pore space. It depends upon effective porosity, the saturated thickness and areal extent of the aquifers. Storage figures presented in this report, however, represent less than the total storage in the unconfined and confined aquifers in the project area. Owing to the method of computation, -BRGM method, a traditional one in the region and French-speaking countries- they represent orders of magnitude estimates of the volumes of groundwater which could be realistically mined from unconfined aquifers, and a part of groundwater under pressure in confined aquifers (that part which is extractable under a conservative approach).

For sedimentary unconfined aquifers, the BRGM method takes into account only one third of a 100-meter maximum saturated thickness, provided that that third is located at less than 100 m depth below ground level. For confined aquifers the method consists of using the storage coefficient (and not the effective porosity of the aquifers) in calculating the volume of groundwater which would be obtained without dewatering the aquifer and with a maximum permissible drawdown of 100 meters.

For the basement complex, an educated guesstimate was attempted by assuming that the fractured and weathered horizons (residual and basal sands and boulders, and fractured zones) range between 0 and 20 meters in thickness, i.e. an average of 10 meters, and have an average effective porosity of 0.5 percent to 1 percent. Incidentally, this average thickness corresponds nearly to the order of magnitude of the seasonal water table fluctuations. This results in a maximum storage of 50,000 to 100,000 m^3/sq.km, i.e. a total of 125 billion to 250 billion m^3 in the project area. The same maximum figure would be arrived at by considering 20 meters in thickness and 0.5 percent porosity, or 5 meters and 2 percent, respectively(or the reverse). Even more conservative estimates (10,000-25,000 m^3/sq. km.) would nevertheless result in several tens of billions m^3 of groundwater storage in the basement in the project area.

Storage estimates are presented in Map 5-6 which shows the range of groundwater storage per sq. km. throughout the project area. These data may be summarized as follows in Table 5-7:

TABLE 5-7 ESTIMATED GROUNDWATER STORAGE VERSUS ROCK OR AQUIFER TYPES

Rock or Aquifer	Storage (m^3/ sq. km.)
. Basement	50,000 (and under)
. Paleozoic cover	25,000
. Continental Intercalaire	over 1,000,000 (up to over 5 million)
. Cretaceous	50,000 to a few millions
. Maestrichtian	over 1,000,000 (up to over 5 million)
. Paleocene	over 1,000,000
. Continental Terminal, Quaternary	50,000 to 1,000,000 (up to 5 million)

The following Table 5-8 presents tentative estimates of groundwater storage per aquifer, country and basin. These figures, however, should not be taken too literally, and could, for example, as well be one third higher or lower.

TABLE 5-8 ESTIMATED GROUNDWATER STORAGE PER AQUIFER, COUNTRY AND BASIN (million m^3)*

Basin	Country	Sedimentary Basins: Paleozoic	Continental Intercalaire	Cretaceous	Maestrichtian	Paleocene-Eocene	Continental Terminal (CT)	Quaternary and/or Pliocene	Total (sedimentary)	Basement (total basement)	Total
Senegalo - Mauritanian									193 900		
	Mauritania	3 000				1 700	7 000	7000(dunes)	18 700	7 700	26 400
	Senegal				60 000	5 900	69 000	4600(")	139 500	3 200	142 700
	Gambia				4 100		9 600		13 700		13 700
	Guinea Bissau	2 000			20 000		included in	Maestrichtian	22 000		22 000
	Guinea	10 000							10 000	14 000	24 000
	Sierra Leone									3 000	3 000
Taoudeni									67 060		
	Mali	25 430	?				36 400	included in	61 830		
	Upper Volta	3 230					2 000	CT	5 230	22 500	27 730
	Ivory Coast									16 600	16 600
Coastal				(included					16 875		
	Ghana			in	750				750	16 100	16 850
	Togo			Maestrichtian)	750				750	5 400	6 150
	Benin				375		15 000		15 375		
Niger									376 775		
	Mali (Sud Adrar)						4 600		4 600		
	Niger		100 100				65 600	26 600	192 300		
	Nigeria (Sokoto)		101 000	41 000			7 500		149 500		
	Benin (")		30 000				375		30 375		
Lower Niger and Benue									350 750		
	Nigeria		120 000	166 250		10 500	750	750	298 250		
	Cameroon		52 500						52 500		
Chad									363 600		
	Chad		important				64 500	93 000	>157 500	18 900	>176 400
	Niger (Koramas)							2 600	2 600		
	Nigeria							47 000	47 000		
	Cameroon							16 000	16 000		
	Central African Emp.		112 000				28 500		140 500	41 000	181 500

Cont'd.

TABLE 5-8 (Cont'd) ESTIMATED GROUNDWATER STORAGE PER AQUIFER, COUNTRY AND BASIN (million m^3)*

Basin	Country	Sedimentary Basins								Basement	Total
		Paleozoic	Continental Intercalaire	Cretaceous	Maestrichtian	Paleocene-Eocene	Continental Terminal (CT)	Quaternary and/or Pliocene	Total (sedimentary)	(total basement)	
Total for	Mali	25 430	?				41 000		66 430	11 500	77 930
5 countries	Benin		30 000				15 375		45 750	8 900	54 650
in 2 or more	Niger		100 100				65 600	29 200	194 900	6 000	200 900
basins	Nigeria		221 000	207 250		10 500	8 250	47 750	494 750	38 800	533 550
	Cameroon		52 500				28 500	16 000	68 500	20 400	88 900
Total		43 660	>515 600	207 250	85 975	18 100	310 825	197 550	1 378 960	234 000	>1 612 960

*Source: From BRGM (subcontract) basic data.

The order of magnitude of total groundwater storage in the project area is about 1,500-2,000 billion cubic meters, with about 80 percent of it in the sedimentary basins and the rest in the basement. This is about ten times as much as the safe yield, the ratio of safe yield to storage being about 6 percent for the sedimentary basins and 34 percent for the basement (and the Paleozoic). This not surprisingly suggests that the time of residence of groundwater in the basement (and Paleozoic) is small compared to that of groundwater in the sedimentary basins, which indicates that basement (and Paleozoic) groundwater is relatively highly renewable while that in the basins is much less so inasmuch as the basins are generally located in areas with lesser infiltration rates and natural groundwater recharge. All of this is especially true northward and for the deepest aquifers, for which the above ratio is about 2 to 5 percent, and lower in Sahel areas.

The above enormous figures, although not to be taken at face value, are conservative and underestimated with respect to those which would be obtained by using American methods for groundwater storage calculation, especially in sedimentary basins. As a matter of fact, groundwater storage could well be twice as much in the basement, and probably, say, four or five times higher in the sedimentary basins if calculations were made using the total saturated thickness and the effective porosity of aquifers, instead of partial thickness and, in the case of confined aquifers, of the storage coefficient and a 100-meter maximum drawdown without dewatering the aquifer.

This suggests that the volumes of groundwater stored in the project area are undoubtedly very large, and the mineable part represents billions of cubic meters of water per year for hundreds of years. As already pointed out, there is generally no groundwater availability problem in the region, except at specific locations where well productivity is low and/or the demand excessive; for example the basement area, large cities in coastal basins or irrigation water demand that is too large for aquifer and well productivity.

Summing up, sedimentary basins, especially those composed primarily of unconsolidated rocks, have the bulk of groundwater in storage in the project area, while the basement contains only a minor and hardly recoverable part of it. The sedimentary basins containing the most groundwater in storage are (by order ofdecreasing importance) : Chad, Niger, Benue-and-Lower Niger (with each of them containing about 25 percent of the groundwater storage), then Senegalo-Mauritanian (about 20 percent), Taoudeni (about 5 percent) and last the coastal basins. The best storage aquifers are : the Continental Intercalaire (nearly half of groundwater storage), Continental Terminal (about 20 percent), Cretaceous (about 15 percent), and Quaternary (about 15 percent), while the Maestrichtian contains about 5 percent, and the Paleozoic and Paleocene-Eocene are negligible. The countries with the best recoverable groundwater storage are Nigeria (about one third of it) Niger (about 15 percent), Chad, Senegal and Central African Empire (about 10 percent each); Cameroon, Mali and Benin (about 5 percent each) are fairly well provided, while Guinea Bissau, Mauritania, and The Gambia have noteworthy amounts; Upper Volta, and above all Ghana and Togo, are poorly endowed, while Guinea, Ivory Coast and Sierra Leone have nearly nothing, which however is still several billion cubic meters of groundwater in storage.

5.4.5 Groundwater Quality

Groundwater quality is generally good throughout the region and even exceptionally good for such an arid and semi-arid environment. Map 5-7 shows groundwater quality in the project area in three classes : good-excellent, admissible-mediocre, and poor. These classes, designed for irrigation suitability, are those of the U.S. Salinity Laboratory, depending upon the sodium absorption ratio (SAR) and electrical conductivity of water. Overall, groundwater is usually suitable for irrigation in the Maestrichtian, Continental Terminal and Quaternary aquifers in the Senegalo-Mauritanian Basin, in the Continental Terminal aquifer in the Taoudeni Basin (Niger River area), in the Continental Intercalaire, Cretaceous, Continental Terminal and Quaternary aquifers of Niger, Nigeria and Chad (Lake Chad area, and Benue and Lower Niger basins).

In the basement, groundwater is especially fresh, frequently 250 mg/l and less in total dissolved solids (TDS), and exceptionally up to 1 or 1.5 mg/l. Groundwater from granite and gneisses is generally better than that from schists. Typical results of some analyses of basement groundwater are presented below in Table 5-9.

TABLE 5-9 GROUNDWATER QUALITY IN THE BASEMENT (mg/l)

Aquifer	Ca	Mg	Na	K	Cl	S04	HC03	TDS	pH
Basement, in Senegal	26.7	20.2	25.5	4.2	7.3	3.8	73	203	
Basement, in Nigeria	2-223	0.1-12.7	3.2-52.4	3.2-76	1.5-102		3.9-117.4	60-946	6.1-9.2
Basement, in Cameroon	3-184	1-66	8-77	10-40	1-40			76-821	6-76
Volcanic rocks,Nigeria	18-41	0-30	4-34	2-6	2-7		39.7-205	112-500	7.3-7.9

In the sedimentary basins, the quality is somewhat inferior, although usually good. TDS content ranges from a few hundred to a few thousand mg/l, being generally in the 500-1000 mg/l range. It is virtually constant in aquifers of marine origin, and much more variable in those of continental origin. Also, it usually increases with the clayey content and in the downstream parts of the aquifers. This is the case for instance in the Western part of the Senegalo-Mauritanian Basin in the Continental Terminal and in the Maestrichtian (which also presents a Fluoride problem), and around Lake Chad where groundwater quality is poor. Generally, sedimentary aquifer groundwater is corrosive. In the coastal basins, there are some sea water intrusion problems, potential or actual, due to inappropriate pumping patterns or intensive groundwater development.

In the Paleozoic aquifers, groundwater from sandstone and quartzite is very good and better than that from schists and dolomite. In the Mesozoic and Cenozoic aquifers, groundwater quality is more variable, being generally good in the Quaternary, and fair to good (although occasionally poor) in the other systems and series.

Typical results of analyses of groundwater from sedimentary aquifers are presented in the following Table 5-10. High nitrate contents generally suggests groundwater pollution. Iron problems do occur in several aquifers.

5.4.6 Conclusion

The basement offers an amount of groundwater (safe yield and storage) generally consistent with rural water supply needs. This groundwater lies at relatively shallow depth, usually about 15-40 meters below ground surface, and is of good to excellent quality. Nearly all the countries in the project area include basement terrain, which allows for satisfactory rural water supply. The safe yield from the basement may be estimated at 80 billion m^3 per year, and the groundwater storage at 200-250 billion m^3.

The sedimentary basins are especially wealthy in groundwater resources of generally satisfactory quality for most needs. The water level in shallow aquifers is usually 20-40 m below the ground surface and sometimes deeper (Sahel areas), and wells can generally supply rural, livestock, municipal, industrial and also agricultural needs. Deep aquifers, up to several hundred meters in depth, and generally 100 to 300 m deep, hold water under pressure, usually at 10 to 50 m below ground surface. Both shallow and deep sedimentary aquifers offer a total safe yield on the order of 85 billion m^3 per year, and a total groundwater storage of nearly 1,500 billion m^3. These figures are on the conservative side and could well be much higher, especially groundwater storage which could be several times as much if the total thickness of aquifers was taken into account.

TABLE 5-10 GROUNDWATER QUALITY IN SEDIMENTARY AQUIFERS (mg/l)

Aquifer	Ca	Mg	Na	K	Cl	SO4	HCO3	Nitrate	Iron	TDS	pH
-Phreatic, Eastern Senegal	43.7	20.3	40.4	4.95	42.9	18.2	95			388	
-Alluvium, Cameroon	34-149	15-39	2-272	3-55					0.3	298-902	
-Alluvium, Nigeria	0-17	0-3	3.1-19	0-16	1-40		12.2-41.2	0.01-8.8	0.04-3	134-184	5.8-8
-Quaternary, Lake Chad Basin	16-200	2.67-13.36	10.1-655	3.5-66	1.8-155	64.8-1860	92.7-361			85-3121	6.5-7.9
-Pliocene, dito in Nigeria	4-70	0-27.7	13.9-218	5-23.2	1-122		47.3-360	0.1-55	0-8	180-5970	6.1-9.2
-Lower Pliocene, dito	1-68.1	1.21-24.3	23.9-322	2.03-15.2	3.54-92	16.8-653	174-372		0.1-7	169-1375	6.6-8.1
-Continental Terminal, Lake Chad Basin	2-26	1.2-10.9	126.5-266	2.8-10.5	17.7-73.4	4.8-218	238-549			269-748	7-8.6
-Continental Terminal, Niger Basin (Sokoto)	4.1-136	0.4-55.8	2.4-98	0.2-22.8	2-15.3	3-588	3-246	0.3-99		61-1088	6.4-7.5
-Continental Terminal, Taoudeni Basin, Mali	8-130	0-99.7	0.84-274.8		3.44-75.76	4.93-607.4	36.6-488				
-Maestrichtian, Senegal	0.49-59.2	0.15-70.1	0.18-1060	0.05-28	0.11-1460	0.2-250	0.1-390	0.05-70	0.16-10.7	144-2882	6-8.2
-Cretaceous, Cameroon	2.5-63	1-22	12-39		1-19					61-315	5.8-7.6
-Cretaceous, Niger Basin (Sokoto)	0-137	0-12	2-200	7.2-38	1-37		3-167	1.5-110	0.04-3.2	151-628	4.9-7.6
-Cretaceous, Lower Niger Basin, Nigeria	7-44	0.4-7.1	0.7-9-4	0-20.2	1-12.7		3.1-172	0-3	0.06-12	31-217	5.6-7
-Cretaceous, Upper Benue Basin, Nigeria	2.6-76.5	2.8-54.6	4.4-184	1-56	2.7-16		14-413	0.1-13.2		240-3982	5.3-7.1

Cont'd.

Table 5-10 (cont'd) GROUNDWATER QUALITY IN SEDIMENTARY AQUIFERS (mg/l)

Aquifer	Ca	Mg	Na	K	Cl	S04	HC03	Nitrate	Iron	TDS	pPH
-Cretaceous, Lower Benue Basin, Nigeria	16-112	4-61	5.4-71	2-9.2	3-19		1.5-169	0.5-3.3	0.08-0.5	26-1438	4.9-7.3
-Continental Intercalaire, Lake Chad Basin	58	1	449	10	745		152			1339	7.3
-Paleozoic, Mali	14.03-334.66	0-370.9	5.3-253		6.9-96.4	3.3-761.2	42.7-2830				

The safe yield is not as good in the Sahel as southward. It is especially high for the Continental Terminal and Quaternary aquifers (nearly 50 billion m^3/year), the Continental Intercalaire (12 billion m^3/year), the Cretaceous in Nigeria (10 billion m^3/year) and the Maestrichtian aquifers (over 2 billion m^3/year). This is especially true in Nigeria, Chad, Senegal, Niger and Mali.

Groundwater storage is significant in the Continental Intercalaire (about 500 billion m^3), Continental Terminal (about 300 billion m^3), Cretaceous and Quaternary (about 200 billion m^3 each) and quite significant in the Maestrichtian (about 100 billion m^3). Countries with the best recoverable storage are Nigeria, Niger, Chad, and Senegal. The other countries are much less well endowed, especially those to the South of the project area.

5.5 CONCLUSIONS

The geology of the project area involves a basement complex, covering over half the area, especially the southern part, and sedimentary basins which occur in the interior sahel countries and also in coastal areas such as Guinea Bissau, Benin and Togo.

The basement is a poor groundwater reservoir, which however is very useful for rural water supply. The sedimentary basins are huge groundwater reservoirs capable of meeting many water needs, including irrigation, at many places.

The best aquifers in the sedimentary basins are in (1) Senegal, The Gambia, Guinea Bissau; (2) the Lake Chad area, (Niger, Nigeria, northern Cameroon, western and southern Chad; (3) Niger; (4) Nigeria (Niger and Benue river basins, northeastern and northwestern Nigeria); and (5) Mali (Niger river area). They include various geologic formations, mainly the Continental Intercalaire, the Cretaceous (in Nigeria), the Maestrichtian-Paleocene, and the Continental Terminal and Quaternary.

Countries such as the Central African Empire, Benin, Cameroon, Mauritania, and even Upper Volta have noteworthy groundwater resources. The other countries, i.e. Guinea, Ghana, Ivory Coast and especially Togo and Sierra Leone are poorly endowed. However, they are not completely lacking in groundwater and can meet at least any rural water supply need, and even municipal/industrial ones (Togo, Ghana, Ivory Coast and Guinea coastal areas).

Groundwater in the basement complex usually occurs at about 15-40 meters below ground surface but may first occur at up to 70-100 meters. It is of very good quality, but well yields are low, generally a few cubic meters per hour or less.

In the sedimentary basins, groundwater occurs in shallow unconfined aquifers, necessitating wells of 20 to 150 meters deep (usually 30-50 m), and in deep and thick confined aquifers up to 700-800 m in depth (generally 100-300 m). Water levels in those deep aquifers frequently are 5 to 50 meters below ground level and sometimes flow at the surface. Well yields may be up to 300 m^3/hour (and over ?) especially in the Maestrichtian-Paleocene, Continental Terminal and Intercalaire and Cretaceous aquifers. However, values of 50 to 100 or 200 m^3/hour are much more usual. In the shallow aquifers, they usually are 5-150 m^3/h, the best being from the Continental Terminal and the poorest from the Paleozoic rocks.

Water quality in the sedimentary aquifers is not as good as in the basement rocks. However, the total dissolved solids content is usually under 1 g/liter, which is surprisingly good in such a semi-arid environment.

The safe yield of the basement aquifers in the project area is estimated to be about 80 billion cubic meters per year. For the sedimentary basins, this estimate is about 85 billion cubic meters per year, being concentrated in the southern part and much less in the Sahel, especially north of the 400-500 millimeter rainfall isoline where infiltration is poor.

Groundwater storage in the basement is estimated to be about 250 billion cubic meters. In the sedimentary basins, it is nearly 1,500 billion cubic meters, the bulk of which is recoverable; an additional several thousand billion cubic meters is stored below this uppermost 1,500 billion cubic meters.

Presently, groundwater development in the project area is small (except mainly at Dakar, Lome and Cotonou, and in northern Nigeria) amounting to a total of a few hundred million cubic meters per year. Sea water intrusion problems may develop locally at these and other coastal areas but could be controlled with artificial groundwater recharge and other techniques.

Costs of well construction are excessive, and operation and maintenance of wells and pumps is costly and frequently poor. Water well contamination is widespread in most of the rural water supply dug wells due to the use of manual water lifting techniques. All of these problems should be resolved prior to the implementation of the badly needed groundwater development programs for rural, livestock, municipal and agricultural water supply, because these programs would involve, say at least 200 to 500 billion francs CFA (several hundred million to two billion dollars) during the next 10 or 20 years.

Potential for additional groundwater development in the project area is enormous. In areas underlain by the basement rocks, there is generally a sufficient quantity of drinkable groundwater for meeting any foreseeable rural water needs with a dependable and safe supply.

In the sedimentary basins, including the Sahel countries, there is generally no problem in providing a rural, livestock and/or municipal/industrial water supply of satisfactory quantity and quality. However, well and aquifer capabilities at certain locations may not be sufficient to match the water demand, especially if it is exceptionally high and concentrated in space and time.

Irrigation from groundwater seems promising and feasible on a large scale principally in countries such as Senegal, Chad, Niger, Nigeria, and Mali where a total of 500,000 to 1,000,000 sq. km. offer encouraging prospects for such a purpose. Probably, about half a million hectares and perhaps more could be irrigated from groundwater within the next twenty years, using small units of a few to 10-40 hectares each. This would harmoniously supplement irrigation through large surface water development and other schemes, and should be started as soon as possible inasmuch as such small projects are relatively easy to finance, construct, operate and maintain, and are socially and environmentally suitable.

Programs to better ascertain this irrigation potential and to study its feasibility for development (as well as sub-regional, national and local groundwater development feasibility) are still needed and should be started promptly and continued. In addition, modern approaches such as aquifer modeling (and related needs as observation well networks and data banks) and artificial groundwater recharge will be needed to achieve optimum groundwater utilization. Their applicability should be ascertained and programs should be launched as soon as possible, as needed and feasible. Also, programs should be continued and intensified for collecting and organizing hydrogeologic information in the countries of the region, and detailed general and regional groundwater studies and investigations should be carried out for an optimum development of the region's invaluable groundwater resources.

GLOSSARY

Alluvium	A general term for sediments deposited in recent geological time by a stream or other body of water.
Anticline	An upfold of layered rocks in the form of an arch and having the oldest strata in the center. The reverse of a syncline.
Aquiclude	A geologic formation, group of formations or part of formulations that does not have enough permeability to supply an appreciable quantity of water to a well or a spring.
Aquifer	A geologic formation, group of formations or part of formations that is capable of supplying water to well and springs in usable quantities. An aquifer is unconfined (water table conditions), or confined (artesian conditions) depending on whether the groundwater level is at atmospheric pressure, or greater than atmospheric pressure due to the presence of an overlying confining geologic formation (aquiclude).
Aquifer System	A group of inter-related aquifers.
Artesian Well	A well in which the water rises under artesian pressure above the top of the aquifer the well penetrates, but does not necessarily reach the land surface.
Baseflow	That part of surface water runoff that comes from groundwater discharge into streams and rivers; generally, low flows are baseflow.
Bedrock	Any solid rocks exposed at the surface or overlain by unconsolidated materials.

Carbonate Rock	A rock consisting chiefly of carbonate minerals, such as limestone, dolomite.
Clastic Rock	A consolidated sedimentary rock composed of broken fragments that are derived from pre-existing rocks, e.g. sandstone, conglomerate, or shale, etc.
Colluvium	Loose soil material and/or rock fragments deposited by the action of gravity, usually at the base of a slope or cliff.
Consolidated	A rock that is firm and rigid in nature due to the natural interlocking and/or cementation of its mineral grain components. The reverse is unconsolidated.
Dolomite	A sedimentary rock composed of calcium and magnesium carbonate.
Drawdown	The measured difference between static level and pumping level in a well, i.e. the drop in the water level due to pumping.
Effective Porosity (or Specific Yield	Refers to that quantity of water in a rock which can be extracted by pumpage or drainage; expressed as a percentage. See Porosity and Storage Coefficient.
Evapotranspiration	The two processes, evaporation and transpiration, by which water returns to the atmosphere; transpiration is the discharge of water vapor by plants.
Extrusive	Refers to igneous rocks which become solid after ejection upon the earth surface, either in land or below water.
Facies	Lithologic character of a stratum or formation.

Fault	A fracture or fracture zone along which there has been movement of two rock masses relative to one another parallel to the fracture. The movement may be a few inches or many miles, horizontal or vertical.
Flood Plain	The strip of relatively smooth land adjacent to a river channel and built of alluvium carried by the river during floods. The flood plain is covered by water when the river is in flood.
Fold	A bend in the rock strata.
Formation	An assemblage of rock masses grouped together into a unit that is convenient for description or mapping.
Fracture	Break in rocks.
Granite	A coarse-grained igneous rock consisting of quartz, feldspar, and other minerals.
Groundwater	Subterranean water located below the water table, i.e. in the zone of saturation.
Igneous Rocks	Rocks or minerals that solidified from molten rock (magma).
Impermeable (or Impervious)	Having a texture which does not allow movement of water through rock.
Intrusive	Refers to igneous rocks which have penetrated into or between older rocks while molten but have solidified before reaching the surface.
Joint	A fracture in rock along which no appreciable movement has occurred. Joints are generally perpendicular to bedding planes.

Karst	A terrain, generally underlain by limestone, in which the topography is chiefly formed by the dissolution of rock, and which is commonly characterized by closed depressions (sinkholes), subterranean drainage and caves.
Limestone	A sedimentary rock consisting predominately of calcium carbonate.
Lithology	The composition and structure of rock.
Metamorphic Rocks	Refers to any rock derived from pre-existing rocks in response to pronounced changes of temperature, pressure and chemical environment.
Percolation	Movement of water through the interstices of rocks or soils except movement through large openings such as solution channels.
Permeability	The ability of a rock or soil to transmit water.
Porosity	The property of a rock or soil of containing spaces or voids; the ratio of the void space to the total volume in a given sample of rock or soil, expressed as a percentage. Usually measured as the quantity of water in a rock.
Potentiometric Surface	The level to which groundwater rises in a well or an aquifer (in a water table or unconfined aquifer, it is the water table; in an artesian or confined aquifer, it is the piezometric surface, also called artesian head: water level above the top of the penetrated aquifer).
Pumping Level	Depth to water in a well when the well is being pumped.

Quartzite	A very hard but unmetamorphosed sandstone.
Recharge	The addition of water to an aquifer by natural infiltration or artificial means.
Regression	General receding of the sea from the land (the sea level falls).
Runoff	That part of precipitation that appears in streams; includes surface runoff, and groundwater flow that reaches streams (baseflow).
Safe Yield	The amount of water which can be withdrawn annually from an aquifer or a groundwater basin without producing an undesired result. Usually, it is the annual recharge to the aquifer or groundwater basin.
Sedimentary Rocks	Refers to rocks formed from the consolidation of layered sediments that have accumulated in water.
Sinkhole	A funnel-shaped depression in the land surface, usually in a limestone region, developed by dissolving action of water and usually connected with underlying solution channels or cavities.
Solution channels	Joints or fractures in carbonate rocks which have been enlarged by the dissolving action of water and which are capable of transmitting large quantities of water.
Slate	A metamorphic rock formed by the metamorphism of shale.
Static Level	Depth to water in a well when the well is not being pumped.

Storage Coefficient	Volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In a confined aquifer, it represents groundwater under pressure (and is much lesser than the actual volume - specific yield - releasable from the pore spaces of the aquifer if it were dewatered). In an unconfined aquifer, it is virtually equal to the specific yield or effective porosity.
Stratigraphy	The arrangement of rock strata.
Subsidence	A local mass movement that involves principally the gradual downward settling or sinking of the earth's surface.
Syncline	A fold in rock strata that is convex downward and has youngest rock in the center. The reverse of an anticline.
Terrace	A level or gently inclined surface bordering a stream which represents a former level of the stream. Terraces are composed of alluvium produced by renewed downcutting of the flood plain or valley floor by the stream.
Transgression	General advancing of the sea upon a land mass (the sea level rises).
Transmissivity	The ability of an aquifer (or a rock stratum) to transmit water. It is the product of the permeability of the aquifer by its thickness.
Water Table	The upper surface of the zone of rock or soil saturated with groundwater. The surface in water table aquifer at which the water level stands.

Water Well	An artificial excavation (pit, hole, tunnel) generally cylindrical in form and often walled in, sunk (drilled, dug, driven, bored, jetted) into the ground to such a depth as to penetrate water-yielding rock and to allow water to flow or to be pumped to the surface.
Zone of Saturation	That part of the earth's crust beneath the water table in which all voids are filled with water.

CHAPTER 6

LAND RESOURCES

6.1 INTRODUCTION

This chapter, and the soil capability map in Volume 2 (Map 6-1), aim at providing a convenient synthesis of existing information on soils of the West African Savanna and their relative capabilities to produce crops.

This chapter outlines the methods used to prepare the soil capability map, and discusses in particular:

a) the existing information available on West African Savanna zone soils, and
b) the interpretation of that existing basic information in order to arrive at a soil capability map.

It is thought that information on these topics will assist the reader to understand how the capability map was compiled, what its limitations are, and therefore both what it can and cannot be expected to show.

Two recently published soil maps at the 1:5 million scale already provide a convenient synthesis of the basic soils information available for West Africa. However, the information is classified differently on each map, one being classified according to the French classification system and the other according to the rather different FAO (United Nations Food and Agriculture Organization) mapping unit.

The basic soils information available requires careful interpretation if it is to provide information on soil capability which can be effectively integrated in natural resource planning and management. In a study geared primarily to the effective use of water resources, information on the water available has to be combined with a knowledge of the capability of the soils to produce crops. Effective water resource planning, which has the final planning goal of securing an increased, sustained production of crops from the land, must logically take into consideration the potential of that land, and this varies considerably from soil to soil as well as with climate.

In this interpretation of the basic soils data, emphasis has been placed on examining and assessing those soil characteristics which affect the production of crops, using current agriculture techniques. The soils are put into five capability classes. The map shows the capability of both the major soils in each association, and of the associated, less extensive soils.

6.2 METHODS USED AND MATERIAL STUDIED

6.2.1 The Basic Soils Data

The primary task of surveying and examining West African soils and of mapping them at various scales was begun in most countries after the Second World War and has proceeded since then, generally at an increasing rate, so that today there is a considerable amount of basic information. This information, however, is still very uneven in both distribution (coverage) and quality. Some areas have been surveyed in detail on a large scale and other areas hardly at all. Other inconsistencies are due to the different types of survey and different soil classification schemes used so that sometimes it is difficult to fit together maps of adjacent areas which have been mapped and classified in different ways. In West Africa there are marked differences between the classifications used in English and French speaking areas. There has been insufficient contact between the two groups of workers.

A first attempt to correlate and put together this soils information was made by the SPI (Service Pédologique Interafricain). This work culminated in a 1:5 million soil map published in 1964 (D'Hoore, 1964). More recently a great deal of work has been carried out by groups of soil scientists responsible for synthesizing the much increased amount of soils information available and for producing from it two separate maps of West African soils, both on the 1:5 million scale, but differing in the classification systems used.

The first of these maps, referred to hereafter in this report as the IFAN map (Institut Francais Afrique Noir) was published in 1971 in the International Atlas of West Africa (Atlas International de l'Ouest Africain) issued by OAU (Organisation of African Unity) and printed by IGN, Paris. This map covers West Africa as far as 24°N and 14°E, and maps the soils classified according to the ten soil orders of the French classification system (Aubert, 1965) subdividing them into 72 different soil units (Table 6-1) each shown by a different colored symbol on the map. Additional soils information is given in detailed tables published with the map which group the 72 soil units into 390 mapping units or associations, for each of which the associated soils are indicated (Volume 3 Appendix 6-1).

The second soils map at the 1:5 million scale is that published by FAO as part of their mapping of the soils of the world, in which Africa is covered by three sheets. The West African soils map sheet includes North Africa and extends about 10° further east than does the IFAN map. Collaboration between the FAO soil scientists and others resulted in the boundaries of individual mapping units being the same in almost all cases as those shown on the IFAN map, but the classification of the soils of the units, and the corresponding map legends, are different. The FAO soil map of the world uses a bicategorical mapping system, rather than a hierarchical classification, in which there are 26 mapping units (with symbols A-Z), all but

TABLE 6-1

SYNOPSIS OF THE FRENCH CLASSIFICATION OF WEST AFRICAN SOILS

The order follows that given in the IFAN International Atlas of West Africa (OAU, 1971).

1. RAW MINERAL SOILS

Climatic origin, desert soils, depositional		
	- over eolian sands of ablation	1A
	- over various rocks	1B
Non-climatic, lithosols	- over various rocks	1C
	- over ferruginous crusts	1D
	- undifferentiated	1E

2. IMMATURE SOILS

Immature desert soils, modal	- over various rocks	2A
	- over eolian sands	2B
Immature erosion soils, regosolic		
	- over gravels	2C
	- over pebbles	2D
	- over clayey sandstones and quartzites	2E
Immature depositional soils, modal		
	- over eolian sands hydromorphic	2F
	- coarse textured, over granite	2G
	- over sandy clay to loamy sand	2H
	- over loamy sand to sand alluvium saline or alkaline	2I
	- over marine or lake deposits	2J

3. ANDOSOLS

Andosols of hot climates, over basic igneous rocks	3A

TABLE 6-1 (Cont'd)

SYNOPSIS OF THE FRENCH CLASSIFICATION OF WEST AFRICAN SOILS

4. VERTISOLS

Topomorphic vertisols, grumusolic, modal		4A
non-grumusolic, modal		4B
hydromorphic		4C
alkaline		4D
Lithomorphic vertisols, non-grumusolic, modal		4E
alkaline		4F

5. ISOHUMIC SOILS, SATURATED

Brown subarid soils, modal	- over sands	5A
vertic	- over sandy clays	5B
	- over clay alluvium	5C
	- over clay from marls	5D
slightly alkaline	- over sandy clays	5E
Reddish brown soils, little differentiated		
	- on eolian sands	5F
modal	- on eolian sands	5G

6. MULL SOILS

Brown eutrophic soils, modal	- on clays, sometimes gravelly	6A
vertic	- on clays	6B
ferruginous		6C

7. SESQUIOXIDE RICH TROPICAL FERRUGINOUS SOILS

Slightly desaturated, little differentiated		
	- over eolian sands	7A
modal	- over oelian sands	7B

TABLE 6-1 (Cont'd)

SYNOPSIS OF THE FRENCH CLASSIFICATION OF WEST AFRICAN SOILS

7. SESQUIOXIDE RICH TROPICAL FERRUGINOUS SOILS (Cont'd)

hydromorphic	
- over sands	7C
Desaturated, modal	7D
concretionary	7E
reworked	7F
hydromorphic	7G
indurated	7H

8. FERRALITIC SOILS

Slightly desaturated, orthic, modal	8A
indurated	8B
impoverished, modal	8C
indurated	8D
reworked, modal	8E
indurated	8F
Moderately desaturated, orthic modal and yellow	8G
slightly rejuvenated	8H
slightly impoverished	8I
humic	8J
impoverished, modal	8K
yellow	8L
reworked, modal	8M
indurated	8N
rejuvenated	8O
little developed	8P
Highly desaturated, orthic, modal	8Q
yellow	8R
indurated	8S

TABLE 6-1 (Cont'd)

SYNOPSIS OF THE FRENCH CLASSIFICATION OF WEST AFRICAN SOILS

8. FERRALITIC SOILS (Cont'd)	
humic	8T
impoverished, leached	8U
reworked, modal and yellow	8V
slightly rejuvenated	8W
9. HYDROMORPHIC SOILS	
Humic, gleyed, acid	9A
Mineral, gleyed throughout	9B
gleyed at depth only	9C
with pseudogley, modal	9D
vertic	9E
10. HALOMORPHIC SOILS	
Non-degraded structure, saline, with crusts	10A
saline and acid	10B
With degraded structure, solonetz, columnar B	10C
prismatic or massive B	10D

three of which are further subdivided into subunits, of which about 55 appear on the West African map (Table 6-2).

Whereas the French classification used for the IFAN map is a detailed taxonomic, hierarchical classification based mainly on soil genesis as shown by profile morphology, the FAO map legend does not claim to be a system of classification as such but merely an attempt to fit on to a map soils already mapped and classified according to other systems, the nomenclature of which has often been retained. In practice the FAO mapping system appears to draw more heavily on some aspects of the United States soil taxonomy system as set out in the book "Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys," (USDA, 1975) than it does on the French system.

As a result of the elaboration of the FAO and US classification systems, we now have at least three distinct systems of soil classification in widespread use in West Africa, together with other systems associated with Charter (1957) and D'Hoore (1964) used more locally, in Ghana and Nigeria respectively. However, no suitable maps covering all West African soils have been published using the US system, while that of D'Hoore is now somewhat out of date, so that the present exercise in soil capability classification is therefore based on the soils information conveniently synthesized in the IFAN and the FAO soil maps published. In view of the great amount of careful work that has gone into the synthesis of these two maps, CIEH* feels that although it possesses sufficient basic material to make a new synthesis there would be little justification at this stage for duplicating the work already done. The major effort was therefore put into the interpretation of this basic data in terms of soil capability, though both the basic maps and the interpretations arrived at were tested by the use of additional material published at larger scales.

*Interafrican Committee for Hydraulic Studies

TABLE 6-2

SYNOPSIS OF THE FAO 1:5 million MAPPING

UNITS USED IN THE WEST AFRICAN

SAVANNA REGION

The mapping units are listed in alphabetical order of symbols. Mapping units thought to be absent in the zones are omitted.

A	ACRISOLS	f	ferric	L	LUVISOLS	c	chromic
		o	orthic			f	ferric
		p	plinthic			g	gleyic
B	CAMBISOLS	d	dystric			p	plinthic
		e	eutric	N	NITOSOLS	d	dystric
		f	ferralic			e	eutric
		g	gleyic			h	humic
		h	humic	O	HISTOSOLS	d	dystric
		k	clacic	Q	ARENOSOLS	c	cambic
F	FERRALSOLS	h	humic			f	ferralic
		o	orthic			l	luvic
		p	plinthic	R	REGOSOLS	c	calcaric
		r	rhodic			d	dystric
		x	xanthic			e	eutric
G	GLEYSOLS	c	calcaric	S	SOLONETZ	m	mollic
		d	dystric			g	gleyic
		e	eutric			o	orthic
		h	humic	T	ANDOSOLS	h	humic
		p	plinthic			m	mollic
H	PHAEOZEMS	h	haplic			v	vitric
I	LITHOSOLS	(not subdivided)		V	VERTISOLS	c	chromic
J	FLUVISOLS	c	calcaric			p	pellic
		d	dystric	W	PLANOSOLS	d	dystric
		e	eutric			e	eutric
		t	thionic			s	solodic

TABLE 6-2 (Cont'd)

SYNOPSIS OF THE FAO 1:5 million MAPPING

UNITS USED IN THE WEST AFRICAN

SAVANNA REGION

Y	YERMOSOLS	h	haplic	
		y	gypsic	
Z	SOLONCHAKS	g	gleyic	
		o	orthic	
		t	takyric	

6.2.2 Method of interpretation

During the preparation of the soil capability map CIEH carried out the following:

a) examination of current ideas on soil capability assessment and soil classification in general;

b) examination of existing basic soil data and soil maps for the Sahel and Savanna zones of West Africa and for individual countries and areas falling within those zones;

c) study of existing attempts and proposals to interpret the basic soils information available in terms of the agricultural potential of the soils, and to produce soil capability maps;

d) production of its own five-class classification of the capability of West African soils by assessing the profile characteristics of the soils mapped and interpreting them in relation to the capability of the soil to produce crops by current methods;

e) drafting of its own soil capability map of West Africa based on these new interpretations of the capability of the individual soils mapped, and then testing the map by comparing sections of it with other capability information available on larger scales.

In the above tasks, CIEH drew heavily on the facilities provided by its own documentation center, making use of the extensive collection of soil reports and maps it contains.

In its study of existing attempts to classify the soils of West Africa as regards their capability to produce crops, CIEH made use of the work of numerous soil scientists, but special mention must be made of the detailed studies of J. Riquier, now with FAO, Rome. Mr. Riquier has published several studies on parametric methods of soil classification (Riquier et al., 1970; Riquier, 1971, 1972 and 1974). CIEH was particularly indebted to his making available to it an unpublished study of the capability of the soils of the Sahel entitled "Carte des aptitudes et potentialités à la culture et au pâturage des sols du Sahel". Although the final classification system adopted by CIEH was different from that used by Riquier, CIEH would like to express its strong appreciation of the help given by a study of Mr. Riquier's unpublished researches into this field.

Obviously, however, any map synthesizing the knowledge available on the capability of West African soils must draw on the work of numerous pedologists and agronomists, both English and French speaking, far too numerous to list here. The exercise has given the compilers the opportunity of bringing together and comparing the work of these two groups of researchers, which is indeed one of the aims of the CIEH documentation center.

In particular, use was made, as detailed below, of 1:5 million soil maps published by FAO and by OAU. It was felt that a detailed study of both classification systems, followed by a careful comparison of the two maps based on them, would give more information on soil capability than would a study merely of one or the other system, even though the final map was based primarily on the 72 soil units of the French classification as mapped on the OAU/IFAN map.

For each of the 72 units an assessment of the following soil properties was made:

1. Base saturation
2. Salinity
3. Effective soil depth
4. Drainage and permeability
5. Presence of crusts
6. Topsoil and subsoil texture
7. Consistency
8. Presence of gravel and stones
9. Organic matter
10. Cation exchange capacity
11. Reserves of weatherable minerals
12. Topsoil structure

The overall capability of each soil unit was assessed paying particular attention to any unfavorable properties which might limit the ability of the soil to produce crops, but also giving due weight to favorable soil characteristics.

The method as outlined above was followed for the total area mapped except for the territories of Chad, the Cameroons and the Central African Republic. These territories are not covered by the OAU/IFAN map, or are only partly covered by this map, and for these areas the interpretation had to take as its starting point the FAO 1 : 5 million soils map. The procedure in the case of these territories was as follows:

(a) FAO mapping units, and the soils included in the mapping units, were listed for the three territories;

(b) The soils in the mapping units were converted as far as practicable to the corresponding French classification units (Table 6-3) using the knowledge gained by the study of the remaining

TABLE 6-3 CROSS KEY showing the correlation between the French soil orders and the major FAO soil mapping units in the West African Savanna region.

	1 RAW MINERAL SOILS	2 IMMATURE SOILS	3 ANDOSOLS	4 VERTISOLS	5 BROWN & REDDISH BROWN SOILS	6 BROWN EUTROPHIC SOILS	7 TROPICAL FERRUGINOUS SOILS	8 FERRALITIC SOILS	9 HYDROMORPHIC SOILS	10 HALOMORPHIC SOILS	
A ACRISOLS							x	x			(2)
B CAMBISOLS					x	x		x	x		(4)
F FERRALSOLS								x			(1)
G GLEYSOLS									x		(1)
H PHAEOZEMS			x								(1)
I LITHOSOLS	x										(1)
J FLUVISOLS		x					x		x	x	(4)
L LUVISOLS						x	x	x	x		(4)
N NITOSOLS								x			(1)
O HISTOSOLS									x		(1)
Q ARENOSOLS		x			x		x	x			(4)
R REGOSOLS		x									(1)
S SOLONETZ										x	(1)
T ANDOSOLS			x								(1)
V VERTISOLS				x							(1)
W PLANOSOLS									x		(1)
Y YERMOSOLS	x	x									(2)
Z SOLONCHAKS										x	(1)
	(2)	(4)	(2)	(1)	(2)	(2)	(4)	(6)	(6)	(3)	(32)

(b) (Cont.)

West African Savanna areas and by reference to publications on the soils of the three territories;

(c) The French classification units assessed as being the equivalent of the FAO soil map units were then given the soil capability classification ratings already assigned to them by the methods described above, and a two-symbol summary of the capability of each mapping unit was prepared.

The various mapping units shown on the FAO 1 : 5 million soils map for these three territories are listed in Volume 3 Appendix 6-2, which also gives the French classification units thought to be comparable, the capability ratings assigned to these units, and the overall one or two-figure summary of capability as indicated on the CIEH soil capability map.

6.2.3 Case Studies

The methods outlined above and the resulting 1:5 million soil capability map were tested as far as practicable by considering selected areas of the West African Savanna in more detail, in two case studies.

The first case study considered the soils information available for Upper Volta. The second case study considered two publications relevant to the interpretation of the soils of Nigeria: a detailed survey of part of northwestern Nigeria, and a detailed attempt to produce a quantitative numerical set of soil capability ratings for Nigerian soils as a whole.

The case studies serve to indicate some of the problems involved in making broad generalizations about soil capability at a scale of

1:5 million, and therefore some of the limitations of a map on that scale, as discussed further in subsequent sections.

The case studies themselves are included as Appendices 6-3 and 6-4 in Volume 3.

6.3 RESULTS

6.3.1 Map legend

Each of the 72 soil units of the IFAN map have been placed in one of five capability classes (See Table 6-4 on page 6-18). These five classes have been defined as follows:

Class 1: Generally good soils. These soils do not have any serious limitations, and are able to produce good yields of suitable, climatically adapted crops.

Class 2: Generally moderate to good soils which have slight to moderate limitations which may restrict their use. Yields of climatically adapted crops are moderately good

Class 3: Generally poor to moderate soils. These soils have one or more limitations of moderate intensity, are usually of fairly low natural fertility, and generally give low to moderate yields of climatically adapted crops under traditional systems of management.

Class 4: Generally poor soils. These soils have moderately severe to severe limitations and, under

Class 4 (Cont.)

traditional systems of management, give generally poor yields.

Class 5: Soils generally unsuited to cultivation, though sometimes locally suitable for rough grazing or other extensive uses. They suffer from limitations which are generally severe enough to exclude cultivation, such as shallow depth, steep slope or very unfavorable soil reaction (extreme acidity or salinity/alkalinity) virtually preventing crop growth unless improved.

It should be noted the definitions proposed:

a) refer to the capability of the soil at present, under traditional methods of cultivation, i.e. to the capability of the soil without major improvements, using traditional hand cultivation methods and with little or no use of imported fertilizer. The capability definitions refer to yields which range from poor (for class 4 soils) to good, but in the West African context the yields produced by traditional methods are generally somewhat low compared with yields that are obtained on agricultural stations using improved methods.

b) refer to a particular soil unit, but that most mapping units shown on the map consist of several soil units forming an association.

TABLE 6-4

SYNOPSIS OF THE CIEH SOIL CAPABILITY CLASSIFICATION OF THE 72 SOIL UNITS OF THE SOIL MAP OF THE WEST AFRICAN ATLAS (OAU, 1971)

SOIL UNIT (French Classif.) (See Table 6-2)	Capability classification and major limiting factors (limiting factors defined on Page 6-20)	SOIL UNIT (Fr. Class.)	Capability classification and major limiting factors
1A	5 t u	5B	3 h
1B	5 g	5C	3 h
1C	5 d	5D	3 h
1D	5 d	5E	2
1E	5 d	5F	5 t u
		5G	4 t
2A	5 t u		
2B	5 t u	6A	1
2C	4 d g	6B	2 w tt
2D	4 d u	6C	2
2E	4 d		
2F	4 t	7A	4 t u
2G	4	7B	4 t u
2H	3	7C	2
21	2	7D	3
2J	5 s	7E	3 g
3A	1	7F	3 g
4A	3 tt	7G	3
4B	4 tt h	7H	4 g
4C	4 w tt		
4D	4 w tt	8A	2
4E	4 tt h	8B	4 d
4F	4 tt h	8C	3
5A	2	8D	4 d

Cont'd.

TABLE 6-4 (Cont'd)

SYNOPSIS OF THE CIEH SOIL CAPABILITY CLASSIFICATION OF THE 72 SOIL UNITS OF THE SOIL MAP OF THE WEST AFRICAN ATLAS (OAU, 1971)

SOIL UNIT (French Classif.)	Capability classification and major limiting factors	SOIL UNIT (Fr. Class.)	Capability classification and major limiting factors
8E	3 g	9A	2 a w
8F	4 g d	9B	2 w d
8G	3	9C	1
8H	3	9D	1
8I	3	9E	2 h
8J	1		
8K	3	10A	5 s
8L	3	10B	5 a
8M	3 g	10C	5 s
8N	4 g	10D	5 s
8O	2 g		
8P	3		
8Q	3 a		
8R	3 a		
8S	4 a		
8T	2 a		
8U	4 a t		
8V	3 a g		
8W	3 a g		

c) have to be interpreted in relation to the fact that under traditional methods the productivity of many soils is restored by resting the land under natural fallow for various lengths of time after cropping. For this reason the productivity of a soil may vary considerably according to its cropping history, being relatively high after a long fallow and relatively low at the end of a long cropping period. This means that in practice there can be a range of productivity associated with soils put into the same capability class.

The yields which will be obtained from any soil will also be much influenced by the skill of the individual farmer and level of management.

The soil capability map should also be interpreted in relation to the climate, particularly local rainfall, though other factors such as insolation also affect yields.

6.3.2 Limiting factors

An attempt has been made to indicate what are thought to be the dominant limiting factors for each soil. These limiting factors, following usual practice, are indicated by a letter or letters placed as a subscript after the number indicating the capability class, e.g. 5s or 3g. In an attempt to give more precise information, however, than is often the case with soil capability classifications, a larger number than usual of subscripts have been used. These are as follows:

- a - acidity
- d - depth limiting
- g - gravelly, or gravelly and stony
- h - very heavy consistency
- s - salinity
- t - texture too light
- tt - texture too heavy
- u - unstable topsoil structure
- w - wetness, i.e. poorly drained

In practice some of these limiting factors are associated with each other and therefore often found together, e.g. t and u for sandy soils and w and tt for very heavy soils.

In many cases a soil suffers from a number of limiting factors to an approximately equal degree so that it is difficult to isolate just one or two of them. Additional limiting factors not enumerated here include locally steep gradients (often associated with d, depth limiting) and particularly low fertilities or water holding capacities (often associated with t, light texture, and d, depth limiting). In areas of similar climate local differences in water holding capacity can be very important. The hydromorphic soils of valley bottoms often give better and more varied crops because of their better water supply, due mainly to their topographic position rather than to the intrinsic qualities of the soil itself.

6.3.3 The mapping of major soils and associated soils.

The basic IFAN and FAO soil maps used show only the dominant soil unit in the association mapped. An association typically consists of several soils, however, often with one or more associated soils, each defined as occupying at least 20% of the mapping unit. Although the IFAN map indicates by the color symbol used only which one of the 72 soil units is dominant in the mapping unit, additional information on the 390 mapping units shown is given in separate tables, and in Appendix 6-1 capability ratings have been assigned for all the soils in each association, i.e. for the main soil and for associated soils.

On the soil capability map it is practicable to show, for each mapping unit, only two capability classes, i.e. the capability of the dominant soil and the overall capability of the other soils in the mapping unit.

The capability of the associated soils has been indicated, or summarized, by including a second symbol on the map, except in those cases where the capability class assigned the associated soils is the same as that assigned to the dominant soil, in which case only one capability class needs to be shown. The following examples show how the second symbol is used to summarize the capability of associated soils and inclusions.

Mapping unit	Capabilities of dominant soil/ associated soils.	Symbols shown on map
I 33	5, 3, 4	5 + 3
Vc 8	4, 4	4
Vc 10	4, 1	4 + 1
Ql 12	4, 4, 5, 3-4	4
Od 10	2, 2-4, 1-2	2
Lg 9	1, 1-2, 2-4, 4	1 + 2

A complete list is given in Appendix 6-1.

6.4 INTERPRETATION AND USE OF THE LAND CAPABILITY MAP

The production of the soil capability map is subject to a number of important constraints which limit its usefulness. The more obvious of these constraints and limitations include the following:

a) Unequal quality of the basic data

No capability interpretation can be better than basic soils data on which it is based, and this information, though conveniently summarized in the two soils maps discussed above, is essentially uneven in coverage and quality.

b) The basic soils maps employ taxonomic classifications

The IFAN soil map, used as the basis for the soil capability map, classifies soils according to French system. This complex system is a taxonomic system of classification which emphasizes those soil profile characteristics which are thought to reflect soil genesis. The classification is not designed to group soils according to their capability and therefore does not necessarily emphasize soil factors which affect practical agriculture. Although many of the criteria used in separating soil units do have some bearing on the agricultural value of the soil, it remains true that soils which are grouped together because of similar genesis often exhibit a wide range of characteristics of relevance to their productivity. Thus soils in the same soil unit may show a range of texture, gravel content, depth, water holding capacity, organic matter content and degree of erosion, all of which affect their capability to produce crops. Variations in these properties between soils grouped into a single soil unit may then result in a range of capabilities within that unit. The capability assigned that unit may then represent no more than an average for it, with individual soils in the unit varying considerably from average.

c) <u>General experience in interpreting soils data in West Africa is inadequate.</u>

Although there is a growing amount of soil analytical data available, there is a general lack of experience in correlating this information with crop performance in the field so that it is difficult to assess just what effects on yield such differences as soil reaction, cation exchange capacity and other properties might have.

d) <u>The small scale of the map results in loss of important detail.</u>

The small scale of the 1:5 million map imposes an obvious limitation on the amount of detail that can be shown. Although a small scale map has the advantage that it brings out the salient features of a large area, the disadvantage is that minor areas of soil cannot be shown, even though they may be locally important. Hydromorphic soils, for example, are present in almost every catena but very rarely are they in large enough areas to be shown on the 1:5 million map.

e) <u>Mapping units are usually associations of several soils.</u>

Even on most soil maps in West Africa produced on a larger scale than that used on the accompanying capability map, the usual mapping unit is not a single soil but a soil association or catena. A soil catena is a fairly regular sequence of soils related to relief. Soil catenas, first described in East Africa, are a very typical feature of African soils. A catena is often developed in two or more different local parent materials, with upper slope soils which are more or less sedentary, or at least reworked in situ, but with lower slope soils developed in local colluvium and valley bottom soils developed in alluvium. Some catenas are complicated due to the complex geomorphological history of the landscape. On the 1:5 million IFAN and FAO soil maps the soil unit shown is that of the dominant soil. The associated soils often belong to different soil units and may have differing capabilities. To some extent this has been indicated on the soil capability map by giving a second capability rating to the associated soils, as described above, but considerable simplification is sometimes necessary if the map is not to be overloaded with detail. The second capability rating, therefore, represents no more than an approximate summary of the capability of all the associated soils.

6.5 CONCLUSIONS

6.5.1 Extent of land capability classes

The map units as shown on Map 6-1 are put into one of twenty-five capability class combinations, as set out in Column 1, Table 6-5. Within each class combination the first number indicates the capability class of the dominant soil, and the second number the overall class assigned to the associated soil or soils.

TABLE 6-5

PERCENTAGES OF THE TOTAL SAVANNA AREA OCCUPIED BY EACH MAP UNIT, AND THE PERCENTAGES OCCUPIED IN TOTAL BY EACH OF THE SOIL CAPABILITY CLASSES 1, 2, 3, 4 AND 5

CLASS	%	Percentage of class divided between components				
		1	2	3	4	5
1	1.40	1.40				
1 + 2	0.85	0.55	0.30			
1 + 3	2.70	1.75		0.95		
1 + 4	1.84	1.20			0.64	
1 + 5	0.16	0.10				0.06
2	0.83		0.83			
2 + 1	0.05	0.02	0.03			
2 + 3	0.90		0.58	0.32		
2 + 4	0.53		0.34		0.19	
2 + 5	0.71		0.46			0.25
3	17.92			17.92		
3 + 1	3.89	1.36		2.53		
3 + 2	3.00		1.05	1.95		
3 + 4	9.24			6.01	3.23	
3 + 5	4.33			2.81		1.52
4	13.15				13.15	
4 + 1	1.84	0.64			1.20	
4 + 2	2.63		0.92		1.71	
4 + 3	10.23			3.58	6.65	
4 + 5	6.80				4.42	2.38
5	6.54					6.54
5 + 1	0.44	0.15				0.29
5 + 2	1.94		0.68			1.26
5 + 3	4.05			1.42		2.63
5 + 4	4.03				1.41	2.62
Totals	100%	7.17%	5.19%	37.49%	32.60%	17.55%

Table 6-6 indicates that the dominant capability classes in the savanna region in terms of area are classes 3 and 4, which together form the dominant soil in 73% of the area mapped, with class 2 soils being the least extensive (dominant in only 3% of the area mapped). Area in which class 1 soils are dominant cover about 7% of the area, whereas those areas dominated by class 5, soils of little or no productivity, total 17% of the savanna region.

TABLE 6-6

RELATIVE AREAS OF MAP UNITS DOMINATED BY SOILS OF EACH OF THE FIVE CAPABILITY CLASSES

Dominant Capability Class		Percentage of savanna area
Good	1	7.0
Moderate to good	2	3.0
Poor to moderate	3	38.4
Poor	4	34.6
Unsuited	5	17.0

The areas shown in Table 6-6 are simply the areas of map units in which soils of each capability class are dominant. However, if the dominant soil in a map unit in which two capability classes are shown is assumed to occupy 65% of the area of that unit, and the associated soil or soils 35%, then an estimate can be made of the actual area occupied by soils of each of the capability classes 1 - 5, irrespective of the combination in which they occur, as set out in full in Table 6-5. Calculated in this way, actual areas occupied by each of the capability classes are as given in Table 6-7

TABLE 6-7 EXTENT OF CAPABILITY CLASSES

Capability Class		Percentage of Savanna area	Extent (Km^2)
Good	1	7.2	327,135
Moderate to good	2	5.2	236,796
Poor to moderate	3	37.5	1,710,499
Poor	4	32.6	1,487,390
Unsuited	5	17.5	800,727
Total		100.0	4,562,547

6.5.2 Area and distribution of soils in each capability class.

Class 1 Soils

Areas mapped as class 1 soils alone total 1.4% of the savanna area, with a further 5.77% occurring mapped in combination with soils of lower capability classes, as set out in Table 6-5. These percentages correspond to actual areas of 63,876 and 263,259 km^2, equal to about 33 million hectares.

The soils of capability class 1 are mainly, in terms of the French classification system, Hydromorphic soils, particularly the mineral hydromorphic soils gleyed at depth only, or with pseudogley. In terms of the FAO mapping system, soils of this capability class are mainly Gleysols (humic, eutric and undifferentiated), Fluvisols (eutric and undifferentiated, gleyic Luvisols and gleyic Cambisols.

Areas mapped as class 1 soils occur mainly along the major rivers. In the west, they are to be found along the Senegal River, in minor areas to the south of Dakar, and along the river Gambia. There are large areas of class 1 soils in the area of the Niger river between Segou and Timbuktu, and in the area of the Bani River and its tributaries to the south. Further east, in Nigeria, soils of the same class are mapped along the Niger, with further extensive areas along its major tributary, the Benue, to the east. These areas extend eastwards to the Cameroon and the Central African Republic, while in the north-east of Nigeria further areas of class 1 soils are mapped north-east of Kano along rivers, such as the Komadugu Yobe and the Komadugu Gana, draining to Lake Chad. In the Central African Republic there are large areas of class 1 soils mapped along the Chari River, south-east of Lake Chad, to Sahr, and also north-east of Sahr along tributaries of the Chari River.

However, many minor patches of class 1 soils, including those developed in small areas of alluvium, are of necessity not shown by a map on this scale. Only the larger areas are indicated where class 1 soils are locally extensive enough to form either the dominant soil in the mapping unit or the major associated soil. In practice, most West African soil catenas include at least minor areas of soils developed in local alluvium, many of which would qualify as class 1 soils. Although individually of generally small extent, the total area of these minor, unmapped patches could be quite considerable. If it were assumed, for example, that in the remaining mapping units mapped as having dominant and associated soils of lower capability classes, merely 1% of the total area consisted of these minor areas of class 1 soils, then this would add about .9% of the area mapped, equivalent to some 40,000 km^2.

Class 2 Soils

Class 2 soils mapped alone total only 0.83% of the area mapped, with a further 4.36% of the area occupied by class 2 soils in association with soils of other capability classes. Class 2 soils therefore total 5.19% of the sahel-savanna areas mapped, equivalent to about 24 million hectares.

Soils placed in class 2 include those hydromorphic soils excluded from class 1, i.e. acid humic and vertic hydromorphic soils, and those gleyed throughout, as well as some immature soils over sandy alluvium, some hydromorphic ferruginous soils over sands and some brown subarid soils.

Class 2 soils are mapped mainly in the extreme north and north-east of Nigeria (including areas along the Komadugu River draining to Lake Chad, in south-east Nigeria (south of the Benue River), in areas in eastern Chad (along the Bahr Bala and Bahr Keita Rivers) and in the south of the Central African Republic (north of the Oubangui and M'Bomou Rivers). Minor areas of class 2 soils are mapped in coastal areas of Senegal and the Gambia, in interior areas of the Republic of Guinea, in Upper Volta and in nearby areas of Niger.

Class 3 Soils

Areas mapped as class 3 soils alone total 17.92% of the area mapped, with a further 19.57% found in association with soils of other capability classes (Table 6-5). In total, therefore, 37.49% of the area is mapped as class 3, which is defined as consisting of generally poor to moderate soils, usually of fairly low natural fertility, giving generally low to moderate yields of climatically adapted crops under traditional systems of management. In terms of area, these soils cover about 171 millions hectares, and form the most extensive of the five capability classes mapped.

Soils mapped in capability class 3 are mainly desaturated Tropical

Ferruginous Soils (equivalent to plinthic and ferric Luvisols in the FAO terminology) and slightly desaturated and desaturated Ferallitic Soils (ferric and orthic Acrisols, with some Nitosols). Minor areas of class 3 soils include some vertic Brown Subarid Soils (vertic Cambisols), Vertisols and Immature Soils. The Tropical Ferruginous Soils may be regarded as the modal soils of the moderately dry savanna areas of West Africa, with the slightly desaturated Ferrallitic soils being found in the wetter savanna areas (as well as in the forest areas to the south).

Class 3 soils are dominant throughout the southern half of the area mapped. They are also important in parts of the northern half, but are there subordinate in extent to class 4 soils.

Class 4 Soils

Areas mapped as class 4 soils alone cover 13.15% of the map, with a further 19.45% of class 4 soils found in association with soils of other capability classes, so that soils of this class total 32,60%, equivalent to about 149 million hectares.

Soils mapped in capability class 4 fall mainly into two broad groups of contrasting texture. The first group consists of generally very light textured, sandy soils, often showing little profile development, classified mainly as Immature Soils, Reddish Brown Subarid Soils, and Tropical Ferruginous Soils over eolian sands in the French classification system. These correspond mainly to Regosols and to luvic, cambic and ferralic Arenosols in the FAO legend. This group of soils is very extensive in the northern areas mapped, particularly in areas of Quaternary sands. The second broad group of soils in capability class 4 consists of soils of very heavy texture, the Vertisols. These are less extensive than the light-textured soils but are found in significant areas of Chad, and less extensively in areas of north-east Nigeria and south-east Upper-Volta.

In general it may be said that soils of capability class 4, mainly light textured, dominate large areas in the more northern, drier areas mapped.

Class 5 Soils

Areas mapped as class 5 alone cover 6.54% of the area, with an additional 11.01% of class 5 soils in association with soils of higher capability classes, giving a total of 17.55% or about 80 million hectares.

Soils mapped in capability class 5 fall mainly in three distinct groups -- loose, shifting dune sands, shallow lithosols and saline soils.

The loose sands of the ergs are found in Senegal, southern Mauritania and northern Mali, with minor areas in northern Upper Volta and elsewhere.

Areas of shallow lithosols over rock or ironstone occur in central Senegal, in south and south-east Mauritania and northern Mali, in an area of north-west Guinea which extends into south-west Mali, in eastern Mali and in central Nigeria.

Saline soils occur in northern Upper Volta, and in the Republic of Chad, both to the south and east of Lake Chad itself, and, more extensively, in the north-eastern area of the country, near Abeche.

CHAPTER 7

HUMAN RESOURCES

7.1 INTRODUCTION

The primary goal of the Savanna Regional Water Resources and Land Use Project is the planning of rational water resource development for the Savanna area. Attainment of this objective requires identification of the location, quality and quantity of existing water resources and assessment of present and future water requirements. The latter task necessitates an analysis of population distribution, density and projected growth rate.

The purpose of this chapter is to present a summary of what is currently known about the populations who inhabit the Savanna: who they are, how many there are, where they are located and the rate at which they are expected to grow.

The Savanna, as defined by average annual rainfall, is a semi-arid region which cuts across complex and frequently conflicting political, economic and social boundaries. Politically, it is an area in which national borders have been drawn only in the last two decades and political alliances are still heavily influenced by colonial heritages. Economically, it is an area in which international interdependence is not uncommon. (For example, the landlocked countries, e.g., Upper Volta, gain access to international markets via the more developed transportation facilities of coastal states, e.g., Ivory Coast). Socially, the Savanna is rich in ethnic groups. (Cameroon is reported to have 200 tribes speaking 24 major African languages). These groups are joined by familial, religious, and cultural ties which extend beyond national boundaries and frequently divide countries internally (witness the recent civil war in Nigeria).

Notwithstanding all the political, social and economic differences that exist among countries comprising the Savanna, all are united by the same basic dilemma: A critical limiting factor to development is the lack of predictable, reliable water supplies. The principal source of water in the Savanna, as in the Sahel, is rainfall, and like the Sahelian countries, the Savanna countries have recently been tragically reminded of the precariousness of this water source.

The populations inhabiting West Africa and the Middle African countries of Cameroon, Chad and the Central African Empire share certain demographic features. In general, the Savanna populations are primarily rural and agrarian and have high fertility and mortality rates. They are also very mobile, with a significant percentage of the people participating in frequent migrations.

7.2 METHODS AND MATERIALS STUDIED

7.2.1 Selection of Data Sources

The principal difficulty in preparing a demographic report for the Savanna is the shortage, or total lack, of reliable census data. Mauritania, Senegal, Mali, Upper Volta, Ivory Coast, Benin (Dahomey), Niger, Chad and Cameroon scheduled their first census for 1974-75. Unfortunately, the census figures from these surveys are not available at the time of this writing (1977). Although other project countries (i.e., Gambia, Guinea, Guinea Bissau, Sierra Leone, Togo, Nigeria, Central African Empire) have had a census taken, the data gathered is incomplete. Only the demographic data reported by Ghana is considered complete.

Several factors contribute to the deficiencies in existing data. One problem is that of enumeration. Frequently, informants do not report family size accurately. Usually, this results from a genuine confusion over peoples' ages, numbers of births and numbers of deaths. Sometimes, however, there is a deliberate reporting of inaccurate data due to personal considerations such as an unwillingness to report infant mortality, or fear of being taxed (Mali had a head tax for many years). Political considerations also affect the reliability of demographic figures. Certain West African countries have been noted for inflating their total population size to qualify for more international donor funds. Others have reinterpreted data that is considered unfavorable to the current government.

The limitations of existing West African demographic data became apparent during the recent Sahelian drought. Assessments of the demographic consequences of the drought vary significantly. U.S. Public Health Services experts calculated that at least 100,000 deaths had occurred in 1973 alone. In addition, a Special Report of the Carnegie Endowment for International Studies [Sheets and Morris, 1974] stated:

> "On a proportional basis, it was as if more than a million Americans had been struck down by a natural disaster."

John Caldwell [1975] an eminent West African demographer disputes this claim. He concluded that:

> "The drought was immensely distressing: it caused pain and sickness; it broke up households and herds; and it forced many to sell treasured articles. But it did not cause massive erosion of human numbers and it did not halt population growth...the major demographic response to the drought has not been death but migration."

In summary, the demograhic data available for the Savanna can be described as a jigsaw puzzle with many missing pieces. Although some additional data is being gathered by national and international organizations, it will be a while before an accurate picture is available. In the meantime, some of the missing data can be estimated by careful extrapolation from existing vital statistics and case studies. This, in fact, is what is currently being done by several prominent international groups such as the United Nations, the United States Agency for International Development, the International Statistical Programs Center of the U. S. Bureau of the Census, and the World Bank.

The figures presented in this Chapter are drawn from the United Nations, the International Statistical Program Center, the Population Reference Bureau and the World Bank. The figures prepared by these organizations are based on official statistics published by each country, which are adjusted or augmented using such methods as quasi-stable population models, Coale-Demeny life tables and Brass techniques.

The United Nations annually sends questionnaires to governments to obtain the latest available demographic statistics. The information so received is published unless analysis by the UN Population Division reveals significant internal inconsistencies in the data. If inconsistencies exist, adjustments are made using quasi-stable population models [UN 1968]. For each country and region, the UN presents basic demographic data on the total population. The UN also prepares three possible population growth projections - "low," "medium" and "high." These are based on an assumption of slow, moderate or rapid population growth. The medium variant is the one presented in this chapter. [UN 1975].

The International Statistical Programs Center (ISPC) gathers current information on vital rates, social and economic development and the activities of family planning and public health programs. Also considered are estimates and projections prepared by demographers and statisticians in national, regional, and international organizations. [U. S. Bureau of Census, ISPC, 1976].

The Population Reference Bureau figures are based on Government, UN, and ISPC estimates, although they are often adjusted and differ from those sources, Growth rates have been calculated based on the rate officially reported for 1972-73 or 1973-74, or by using the growth rate from the 1975 UN population projections (medium variant) for the 1970-75 period.

By reporting the estimates of the above organizations, it is possible to present a range of statistics for a given population characteristic rather than a single number. This approach is preferable because given the limitations of the data base, a range is likely to be less misleading for planning purposes than a single number. Also these organizations have had years of experience in working with incomplete and unreliable demographic data. However, use of such data does impose a constraint on the analysis in this report. These sources all report their findings on a nation-wide basis. Consequently, for those countries which do not fall entirely within the Savanna project area, it is not possible to separate the demographic characteristics of those individuals residing within the Savanna from those residing without.

7.2.2 <u>Demographic Indicators</u>

For the purposes of this discussion, the following demographic indicators were selected for analysis:

1. birth rate
2. death rate
3. percentage of population under 15 years old (dependent children)
4. life expectancy
5. population growth rate
6. urban population
7. population density

Birth and death rates are calculated per 1,000 of the total population regardless of age or sex. These crude rates can be used to calculate the natural increase of a population, i.e., the difference between the birth rate and the death rate per 1,000 population. Population growth rates are calculated by adjusting the natural increase of a population to reflect the effects of migration.

In developing countries, life expectancy (the average number of years of life for males and females at birth) is a useful indication of the health risks a population is exposed to. The leading causes of death in developing countries are infectious, parasitic, and respiratory diseases and digestive complications. Of interest to this project is the fact that many of the fatal or debilitating illnesses occurring in West Africa are water-borne.

Estimates of the percentage of children under 15 can be used as a measure of future population growth potential. Also, since most persons under 15 do not work, or work less efficiently relative to their consumptive needs than working adults, these figures are frequently used to estimate what percentage of the population in each country is economically dependent.

Census definitions of "urban" and "rural" populations vary widely among countries. Most countries define as "urban" those localities which, given typical national conditions, appear to function as urban centers. What may be classified as "urban" in one country may not be reported as such in another. The data sources cited in this chapter use the varied concepts "urban" population as defined by each nation.

Population density, calculated by dividing total population of a region by total land area, is a rough measure which ignores the fact that some land areas are inhospitable and do not invite dense habitation. This is particularly true in an area such as the Savanna. Nonetheless, population density is useful for comparing regions, particularly if considered in conjunction with population distribution.

7.3 RESULTS

7.3.1 General Social Profile of the Savanna

Among the numerous ethnic groups of the Savanna Region the largest tribes are the Hausa, Fulani (Peule), Yoruba and Voltaic. The three predominant religions are Animism, Islam and Christianity. In most of the project area French is the official language, in Gambia, Nigeria, Sierra Leone and Ghana the official language is English, and in Guinea Bissau it is Portuguese. Most of the population is engaged in subsistence production, primarily in agriculture and nomadic pastoralism.

To a large extent, rural population distribution and density in the Savanna are affected by environmental factors such as the presence or absence of adequate grazing lands, fertile soils, disease vectors and water. Urban centers found within the Savanna have grown largely for political and economic reasons. Map No. 7 shows the rural population distribution and density of the Savanna and the urban centers found in the Savanna today.

For the most part, the population is clustered along the periphery of the Savanna area which is closer to the coast. One can distinguish a coastal belt of more densely settled area. Starting in the West it includes coastal areas of Senegal and Sierra Leone; southern parts of the Ivory Coast, Ghana, Togo, Benin, Nigeria; and extends to parts of the Cameroons.

Of interest is the existence of several more densely populated nodes in the interior and northern areas of the Savanna. These include an area near Sego and Bamako in Mali, a center near Ouagadougou in Upper Volta, and a larger area in Northern Nigeria.

Between the coastal population centers and the northern population nodes, and to the east of these areas in Chad and the central African Empire, exists a very sparsely populated area, often with densities under 10 persons per square kilometer. The existence of this empty belt is due to a number of factors including disease vectors (the tsetse fly and the black fly) and the unavailability of permanent sources of water.

Historically, conflict, coupled with the practice of capturing members of other tribes for slavery, encouraged the clustering of tribal groups. Frequently, tribal leaders concentrated the economic and political powers of their empires, kingdoms or chiefdoms in one area. The colonial period reduced tribal clashes and there was some integration of members of different tribes, but, centers of tribal concentration still exist today, as illustrated by the Mossi in Upper Volta, the Yoruba and Bani in Nigeria and the Wolof in Senegal.

For the purposes of this study, the ethnic affiliations of the Savanna inhabitants are not as critical as the type of economic activity they engage in. In this regard, two principal groups are dominant in the Savanna, the sedentary farmers and the migratory herdsmen.

Most of the agriculture practiced in the Savanna is traditional and is dependent upon a rotation system based on rainfall and river flood waters, normally referred to by the French term "décrue". The sedentary farmers typically grow millet and sorghum in the north, and yams, cassava and manioc in the south. With the construction of irrigation projects some diversification in these basic crops has been introduced, especially rice and vegetables.

John Caldwell [1975] estimates that West Africa has well over 2.5 million nomads or migratory herdsmen. Cattle are considered the most important and valuable of the animals tended by the nomads, although their herds also include sheep, goats, camels and donkeys. Historically, the northern boundary of the nomads' range was set by rainfall; whereas, the southern boundary was set by the tsetse fly (south of 14°N, there is sufficient moisture to support this insect). Although little is known about the demographic characteristics of nomads as contrasted with sedentary farmers, recent studies have suggested certain differences. Ganon believed that the birth rate for nomads may be somewhat lower than that for sedentary populations (Ganon, 1975]. Also, Caldwell has speculated that mortality rates among nomads may be somewhat higher than those among sedentary farmers:

> "The only real case for suggesting relatively high mortality for the nomads is the harshness of their environment, the lack of medical or other services available to them, and the higher rate of malnutrition among their children shown by health surveys (admittedly, mostly taken during the drought)." [Caldwell, 1975].

Traditionally, a symbiotic relationship existed between the nomads and sedentary farmers. The nomads provided animal products such as milk, meat and skins to the farmers, who in turn provided grains and household necessities to the nomads. Moreover, the nomads utilized lands which were unsuited for farming. Recently, particularly in the aftermath of the drought, there has been increasing tension between the nomads and farmers. The historical rights nomads had to pasturage in the south and the river flood plains, are being challenged by farmers. The spread of irrigated farming, an increase in sedentary farmers owning their own herds, and the loss of pasturage during the drought has reduced the amount of pasturage available to the nomads and has increased the numbers of clashes between the two groups. Efforts at developing water resources in the project area will have to take into consideration the needs of both the sedentary farmers and the nomads.

7.3.2 Demographic Profile

Table 7-1 presents selected demographic estimates and projections for each of the Savanna countries. The figures are drawn from the United Nations (1975], the Bureau of Census International Statistical Programs [1976] and the Population Reference Bureau (1975, 86].

For the 17 countries, the average birth rate (45-50 per 1,000) is estimated to be roughly double the estimated average death rate (20.8-25.6).

TABLE 7-1 - SELECTED DEMOGRAPHIC INDICATORS OF THE SAVANNA COUNTRIES

COUNTRY	Percent National Land Area within Savanna (Approx.)	Total Population 1975 1/	Birth Rate 2/	Death Rate 2/	Growth Rate 3/	Projected Population 2,000 4/	Percent Population Under 15	Percent Urban Population	1975 Population Density (per sq. Km.)	Life Expectancy
Benin	100%	3.07 - 3.10	48-54	20.8-29	1.9-3.10	5.92	45	13.0-18.0	27	41-43.5
Gambia	100%	0.509 - 0.516	38-43	20.0-25	1.3-2.10	.85	41	12.8-14.0	49	40-41.0
Guinea Bissau	100%	0.522 - 0.525	37-40.8	23.2-25	1.0-1.76	.84	37	20.0-23.0	15	38-41.0
Togo	100%	2.23 - 2.25	49-56	21.0-25	2.4-3.40	4.64	46	13.5-15.0	40	41-43.5
Upper Volta	100%	5.96 - 6.03	48-54	24.8-29	1.9-2.60	10.97	43	7.0- 8.3	22	38-39.0
Senegal	90%	4.38 - 4.42	46-49	20.0-24	2.4-2.60	8.17	43	28.3-30.0	23	40-41.0
Nigeria	90%	62.93 -63.022	48-50	20.0-24	2.4-3.00	134.92	45	16.0-18.1	68	41-43.5
Guinea	90%	4.38 - 4.40	46-51	20.7-24	2.2-2.80	8.46	43	19.5-29.0	18	41-43.5
Ghana	70%	9.87 -10.00	47-51	17.0-22	2.7-3.40	21.16	47	29.0-32.4	41	44-46.0
Cameroon	55%	6.40 - 6.49	40-43	19.0-23	1.8-2.40	11.58	40	20.0-23.8	14	41-43.5
Ivory Coast	55%	4.38 - 6.67	45-52	18.7-25	2.0-3.10	9.62	43	20.0-28.0	13-20	44-46.0
Sierra Leone	55%	2.98 - 3.04	42-45	18.0-21	2.3-2.60	5.72	43	13.0-15.0	42	44-46.0
Mali	45%	5.63 - 5.70	51-55	25.0-28	2.3-3.00	11.25	44	12.0-13.4	5	38-40.0
Central African Empire	40%	1.70 - 1.80	43-48	20.0-28	1.6-2.60	3.36	42	27.0-35.9	3	41-43.5
Chad	40%	4.18 - 4.03	44-52	22.8-31	1.4-2.70	6.91	41	12.0-13.9	3	38-40.0
Niger	20%	4.55 - 4.59	49-55	20.0-25	2.4-3.00	9.57	46	8.0- 9.4	4	38-40.0
Mauritania	10%	1.24 - 1.32	43-47	23.0-27	1.4-2.20	2.28	42	10.0-11.1	1	38-40.0

1/ in millions
2/ per 1000 inhabitants
3/ percent of total population
4/ U.N. medium variant (U.N. 1975)

References:

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Taking into account population change due to migration, there results an average 1.96 - 2.7 growth rate per year. At this growth rate, which is among the highest in the world, the total population would more than double by the turn of the century. This will bring the population of the 17 countries from an estimated 126 million in 1975 to about 256 million in the year 2000. Prospects for reversing this trend seem dim. With the continual expansion of health services in the Savanna, it is expected that mortality rates will decline. Birth rates, however, are unlikely to be reduced. A review of existing and proposed family planning programs reveals that serious obstacles to family planning remain in Africa.

> "African culture is strongly pronatalist ... At the 1973 Seminar on Population Policy in Nairobi, it was concluded that 'fertility is highly regarded in some African societies ... Fertility is very important to the value of a married woman ...' In this cultural framework, many rural women worry much more about subfecundity than about overfertility." [Population Reference Bureau, 1975].

Given the reluctance of their citizens to practice family planning, most of the Savanna governments do not give high priority to population programs. Improved health care, education, increased employment are considered more important.

An average of approximately 45% of the population is under 15. This figure is frequently used in industrialized countries to calculate the "burden of dependency" index, where BD expresses the relationship between the number of dependents and the number of productive persons

$$BD = \frac{\text{fraction of population under 15 and over 60}}{\text{fraction of population between 15 and 60}}$$

However, in a subsistence economy, such as is found in the Savanna, many analysts suggest that children do not constitute a burden.

> "Economically and socially, the child...only represents a small expenditure, quickly reimbursed; it is even a good bargain: poorly fed and clothed, hardly or not at all educated, he engages very early in work productive of goods and services" [Afana, 1966].

On the other hand, Etienne Van de Walle has suggested that:

> "The evidence from budgetary surveys and agricultural inquiries on the economic contribution of children is not conclusive...there is plenty of evidence that children participate actively in field and housework. They gain in efficiency between 6 and 15 years of age, but it is difficult to say at what age they produce more than they consume." [Van de Walle, 1975].

Despite the apparent contradictions in the data, Van de Walle concludes that a reduction in fertility would immediately reduce the burden of dependency which in turn would reduce the investment required to employ and equip the labor force.

The vast majority of the Savanna population live in rural areas; only an average of 16.5-19.9% are classified as urban residents. However, there has been a dramatic increase in urbanization in recent years. The number of residents living in urban areas has roughly doubled since 1950, when it was estimated that only 9.6% of the population lived in urban centers. A common demographic assumption is that urban fertility is lower than rural fertility. On the basis of this assumption one could conclude that increased urbanization would reduce fertility rates. In West Africa, however, three distinct patterns have been observed concerning urbanization and fertility. Cohen has found that the Congo, Gabon, and to a lesser degree, Upper Volta have higher urban than rural fertility; Chad and Senegal have roughly comparable urban and rural fertility; Mali, Guinea and Togo have lower urban than rural fertility rates [Cohen, 1976]. Therefore, assessment of the impact of increased urbanization on fertility would require a country-by-country study.

7.3.3 Migration

Perhaps the least understood, and one of the most important factors affecting population distribution is migration. Large numbers of the Savanna population participate in seasonal or permanent migrations. Three types of migration in the Savanna are distinguished on Map No. 7. One is pastoral transhumance, which consists of regular seasonal movement of pasturalists shifting grazing lands for herds.

A second is labor migration which consists of young men leaving more traditional areas to seek jobs in mines, commercial agriculture and coastal urban centers. Most of these men maintain their ties to traditional areas of origin. The typical migratory routes are from north to south and from the interior to coastal areas. Examples include movement from Mauritania to Mali and Senegal; from Mali to Senegal and the Ivory Coast; from Niger to Nigeria; from Upper Volta to Ghana and the Ivory Coast. While much migration is seasonal or temporary, there is a net flow of population from North to South.

A third type of migration is religious. The movement of Moslem pilgrims has always been significant in West Africa. It has been estimated that pilgrimages involve tens of thousands of people per year (Mabogunje, 1975). It is assumed that these pilgrimages do not change population patterns, but the length of time involved in this undertaking and the reduction in work force that it entails, should not be overlooked.

Several other types of migration exist in the Savanna. Very important, but difficult to trace due to their irregularity, are migrations due to environmental conditions. Typically farmers move in search of cultivable land (Lobi of Ivory Coast), and pasturalists move in search of grazing lands and water, and in avoidance of disease vectors such as the tsetse fly. Recently, political conflicts have increased the number of migrants by creating political refugees.

Although there is very little data on the frequency and duration of migrations, it has been estimated that nearly 80 percent of the migrants stay at their destination for less than one year. Occupation of the migrants seems to be a determinant in their destination as well as the length of their stay. Trading groups such as the Fulani, Hausa, Yoruba and Zerma tend to travel to cities and frequently stay less than six months. In contrast, agricultural laborers such as the Senoufo and Kotaki travel to rural areas and stay longer than a year [Mabogunje, 1975]. Young men who travel to cities or Europe in search of work usually stay longer than a year [Caldwell, 1975].

As a result of the drought, the movement of Savanna inhabitants for environmental and economic reasons was intensified. Cities such as Bamaco and Mopti in Mali, Ouagadougou in Upper Volta, Zinder and Niamey in Niger, Kano in Nigeria and N'Djamena in Chad experienced considerable increases in population. The pressures created by large influxes of migrants led to clashes such as occurred between migrants and residents in eastern Chad [Caldwell, 1975].

7.4 CONCLUSIONS

The populations of the Savanna are predominantly rural. More than half of the surface area of the Savanna has densities of only 2-10 inhabitants per square kilometer (Km^2) and roughly 20-25 percent has densities of 10-20 inhabitants Km^2 (see Map 7). In general, the heaviest population centers in West Africa are outside of the Savanna and are located along the southern coast, in particular in Nigeria. An exception to this is the urban center which has been developing around Ouagadougou, Upper Volta (see Map 7). Notwithstanding the fact that population densities are low, serious population problems exist in the Savanna. The carrying capacity of the land is, on the whole, low and the anticipated population growth for the area is very high.

The high fertility and mortality rates characteristic of the Savanna populations pose significant problems for resource planners. In essence, efforts at reducing mortality rates, through improved health care programs and socioeconomic growth, have been more successful than efforts at reducing fertility rates through family planning. As a result, the average annual population growth rate for West Africa is increasing. The United Nations'

Population Division [1975] estimates that the West African annual growth rate increased from 2.37% in 1965 to 2.75% in 1975, and a rate of 2.92 is projected for 1995. The Middle African countries of Chad, Cameroon and Central African Empire are also believe to have an increasing growth rate. In 1965, the mean growth rate for these three countries was estimated at 1.96. In 1975 it was 2.15, and by 1995 it is expected to reach 2.44 [United Nations, Population Division, 1975]. Attitudes and efforts toward curbing population growth range from the government-supported, internationnally assisted population control programs of Ghana to the pronatalist views of Mauritania, Cameroon, and Central African Empire [AID, 1975].

The projected increase in annual population will result in greater population pressures on the land. Indicators of excessive population pressure on the Savanna are already beginning to appear. As identified by Hance [1970] in Population, Migration and Urbanization in Africa, indicators of excessive population pressure include:

1. Soil deterioration, degradation, or outright destruction.
2. Use of marginal lands.
3. Declining crop yields.
4. Changing crop emphasis, especially to soil-tolerant crops.
5. Reduction in the fallow period and lengthening of the cropping period without measures to retain soil fertility.
6. Breakdown of the indigenous farming system.
7. Food shortages, hunger, and malnutrition.
8. Land fragmentation, disputes over land, landlessness.
9. Rural indebtedness.

All of these problems are already visible in the Savanna Region and can be expected to intensify with the anticipated growth in population, unless measures are taken to increase the carrying capacity of the land.

The long-term demographic implications of the population redistributions which occurred during and after the drought are not yet known. However, one lesson from the drought is clear: A reduction in the carrying capacity of the land led to increased population pressure on the land, which in turn resulted in soil exhaustion, overgrazing, malnutrition and, in certain cases, violence. With a projected growth rate of 1.96-2.7, the Savanna will face population pressures which may exceed those experienced during the drought. If so, the drought will have presaged future crises.

As programs for water resources and other types of development are formulated in the Savanna, further analyses of the demographic characteristics of the specific localities concerned must be undertaken. Results of current research, being done by West African government and international agencies mentioned in this report, will be available soon and should facilitate such analyses. The success of any program will depend to a great extent on how well population patterns and growth are understood and taken into consideration.

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II. ANNUAIRES HYDROLOGIQUES/HYDROLOGICAL YEARBOOKS

Indiqués selon le pays et l'année/Listed by country and year

1949	ORSTOM. Annuaire hydrologique de la France d'Outre-Mer. Paris, 1951.
1950	ORSTOM. Annuaire hydrologique de la France d'Outre-Mer. Paris, 1952.
1951	ORSTOM. Annuaire hydrologique de la France d'Outre-Mer. Paris, 1953.
1952	ORSTOM. Annuaire hydrologique de la France d'Outre-Mer. Paris, 1954.
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1954	ORSTOM. Annuaire hydrologique de la France d'Outre-Mer. Paris, 1956.
1955	ORSTOM. Annuaire hydrologique de la France d'Outre-Mer. Paris, 1957.
1956	ORSTOM. Annuaire hydrologique de la France d'Outre-Mer. Paris, 1958.
1957	ORSTOM. Annuaire hydrologique de la France d'Outre-Mer. Paris, 1959.
1958	ORSTOM. Annuaire hydrologique des états d'outre-mer de la Communauté, des territoires et départements d'outre-mer, du Cameroun, et du Togo. Paris, 1961.
1959	ORSTOM. Annuaire hydrologique de l'Office de la Recherche Scientifique et Technique Outre-Mer. Paris, 1963.
1960	ORSTOM. Annuaire hydrologique de l'Office de la Recherche Scientifique et Technique Outre-Mer. Paris, 1966.
1961	ORSTOM. Annuaire hydrologique de l'Office de la Recherche Scientifique et Technique Outre-Mer. Paris, 1967
1962/1963	ORSTOM. Annuaire hydrologique de l'Office de la Recherche Scientifique et Technique Outre-Mer. Paris, 1967.
1964/1965	ORSTOM. Annales hydrologiques de l'Office de la Recherche Scientifique et Technique Outre-Mer. Paris, 1969.
1966/1967	ORSTOM. Annales hydrologiques de l'Office de la Recherche Scientifique et Technique Outre-Mer. Paris, 1972.
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1961	ORSTOM. Annuaire hydrologique du Dahomey. Cotonou, 1963.
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1962	ORSTOM. Annuaire hydrologique du Cameroun. Yaoundé, Institut de Recherches Scientifiques du Cameroun, 1964.
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1964	ORSTOM. Annuaire hydrologique du Cameroun. Yaoundé, Institut de Recherches Scientifiques du Cameroun, 1965.
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1965/1966/ 1967	ORSTOM. Mesures de débits. Adiopodoumé, 1969.
1968	ORSTOM. Mesures de débits. Adiopodoumé, 1969.
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1971/1972/ 1973	ORSTOM. Mesures de débits. Adiopodoumé, 1974.
1966	ORSTOM. Annuaire 1966, hauteurs d'eau journalières aux stations hydrométriques principales de Côte d'Ivoire. Adiopodoumé, 1967.
1967	ORSTOM. Annuaire 1967, hauteurs et débits journalières aux principales stations hydrométriques de Côte d'Ivoire. Adiopodoumé, 1968.
1969	ORSTOM. Annuaire hydrologique de Côte d'Ivoire. Adiopodoumé, 1970.
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GHANA

Origin to Feb. 1961	Ghana. Hydrological Services. The Volta River Basin hydrological data book. Accra, 1966.
1961-62	Ghana. Hydrological Services. River basins of Ghana, water year book. Accra, 1966.
1962-63	Ghana. Hydrological Services. River basins of Ghana, water year book. Accra, 1966.
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HAUTE-VOLTA

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1966	ORSTOM. Annuaire hydrologique de Haute-Volta. Ouagadougou, 1969.
1967	ORSTOM. Annuaire hydrologique de Haute-Volta. Ouagadougou, 1969.
1968/1969	ORSTOM. Annuaire hydrologique de Haute-Volta. Ouagadougou, 1970.
1970	ORSTOM. Annuaire hydrologique de Haute-Volta. Ouagadougou, 1971.
1971	ORSTOM. Annuaire hydrologique de Haute-Volta. Ouagadougou, 1972.
1972	Haute-Volta. Direction de l'Hydraulique et de l'Equipement Rural. Annuaire hydrologique de Haute-Volta. Ouagadougou, 1973.
1973	Haute-Volta. Direction de l'Hydraulique et de l'Amenagement de l'Espace Rural. Annuaire hydrologique de Haute-Volta. Ouagadougou, 1974.
1974/1975	ORSTOM. Annuaire hydrologique de Haute-Volta. Ouagadougou, 1977.

MALI

1968-69	Mali. Direction de l'Hydraulique et de l'Energie. Annuaire hydrologique. Bamako, 1969.
1969-70	Mali. Direction de l'Hydraulique et de l'Energie. Annuaire hydrologique. Bamako, 1973.
1970-71	Mali. Direction Générale de l'Hydraulique et de l'Energie. Annuaire hydrologique. Bamako, 1977.

NIGER

1966	ORSTOM. Annuaire hydrologique du Niger. Niamey, 1967.
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1972	ORSTOM. Annuaire hydrologique du Niger (le réseau Est-Nigerien). Niamey, 1973.
1972-73	Niger. Service du Génie Rural. Section Hydrologique. Rapport Niger-Moyen. Niamey, 1973.
1973	ORSTOM. Annuaire hydrologique du Niger (le réseau Est-Nigerien). Niamey, 1974.
1973-74	Niger. Service du Génie Rural. Section hydrologique. Rapport Niger-Moyen. Niamey, 1974.

1974-75	Niger. Service du Génie Rural. Section Hydrologie. Rapport Niger-Moyen. Niamey, 1975.
1975-76	Niger. Service du Génie Rural. Section Hydrologie. Rapport Niger-Moyen. Niamey, 1976.

NIGERIA (Kano State only)

1963-64, 1964-65, 1965-66, 1966-67, 1967-68	Kano State (Nigeria). Water Resources & Engineering Construction Agency. Hydrological yearbook. Kano, 1974.
1968-69, 1969-70, 1970-71	Kano State (Nigeria). Ministry of Works & Survey. Hydrological yearbook. Kano, 1972.

SENEGAL

1974-75	ORSTOM. Annuaire hydrologique. Dakar, 1976.
1975-76	ORSTOM. Annuaire hydrologique. Dakar, 1976.

TCHAD

1960	ORSTOM. Annuaire hydrologique du Tchad. Fort-Lamy, 1961.
1961/1962	ORSTOM. Annuaire hydrologique du Tchad. Fort-Lamy, 1965.
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1965/1966	ORSTOM. Annuaire hydrologique de la République du Tchad. Fort-Lamy, 1968.
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1973-74	ORSTOM. Annuaire hydrologique de la République du Tchad. N'Djaména, 1974.
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1975-76	ORSTOM. Annuaire hydrologique de la République du Tchad. N'Djaména, 1976.

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1961	ORSTOM. Annuaire hydrologique du Togo. Lomé, 1963.
1962/1963/ 1964	ORSTOM. Récapitulation des hauteurs d'eau des échelles limnimétriques du Togo. Lomé, 1965.
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