AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523
BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY
Batch 87

1. SUBJECT CLASSIFICATION
A. PRIMARY: Food production and nutrition — AP12-0000-G218
B. SECONDARY: Drainage and irrigation--Senegal

2. TITLE AND SUBTITLE
A hydrologic review of the proposed Bakel-Small Perimeters, Senegal River Basin, Senegal

3. AUTHOR(S)
(100) Dudley,E.D.; (101) U.S. Bureau of Reclamation

4. DOCUMENT DATE	5. NUMBER OF PAGES	6. ARC NUMBER
1976	59p. 51p	ARC

7. REFERENCE ORGANIZATION NAME AND ADDRESS
AID/AFR/SFWA

8. SUPPLEMENTARY NOTES *(Sponsoring Organization, Publishers, Availability)*

9. ABSTRACT

10. CONTROL NUMBER
PN-AAF-689

11. PRICE OF DOCUMENT

12. DESCRIPTORS
Dams
Hydrology
Bakel,Senegal?
Pumps
Senegal
Water flow
Water management

13. PROJECT NUMBER

14. CONTRACT NUMBER
AID/AFR/SFWA

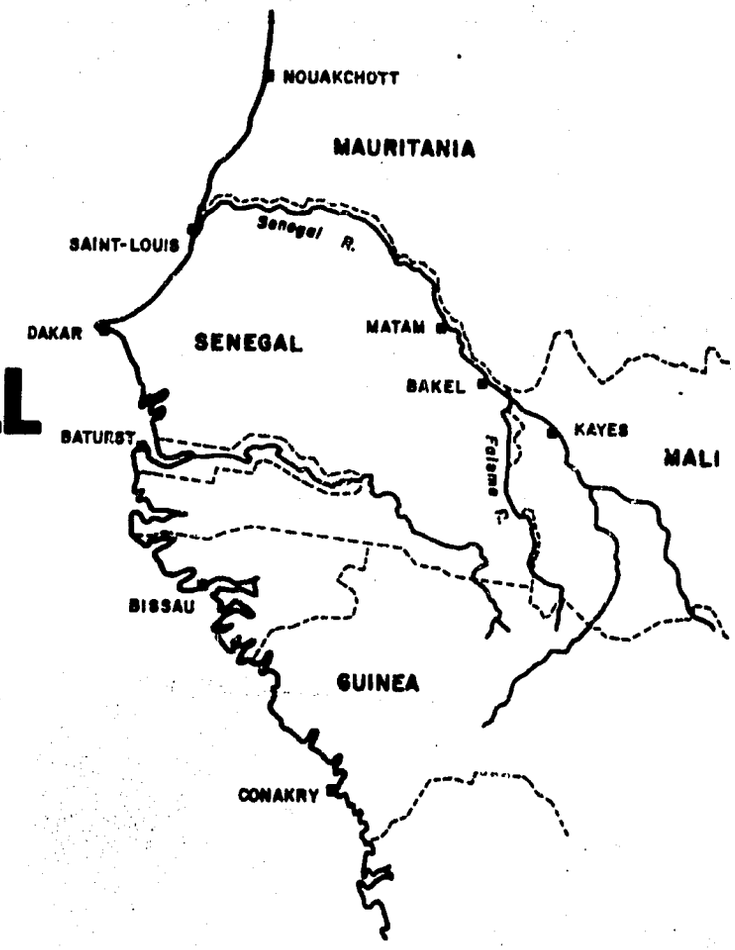
15. TYPE OF DOCUMENT

AID 590-1 (4-74)

AID/AFR/SFWA
PN-AAF-689

A HYDROLOGIC REVIEW OF THE PROPOSED BAKEL-SMALL PERIMETERS SENEGAL RIVER BASIN

AUGUST 1976



SENEGAL WEST AFRICA

prepared by
U.S. BUREAU OF RECLAMATION
for the
U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT

A HYDROLOGIC REVIEW
OF THE PROPOSED
BAKEL - SMALL PERIMETERS
SENEGAL RIVER BASIN
SENEGAL

Prepared by
EARLL D. DUDLEY
U. S. BUREAU OF RECLAMATION
for the

U. S. AGENCY FOR INTERNATIONAL DEVELOPMENT

August 1976

United States Department of the Interior

BUREAU OF RECLAMATION
WASHINGTON, D.C. 20240

IN REPLY
REFER TO: 1300
167.-Senegal

August 18, 1976

Mr. Stanley C. Scott, Jr.
Assistant Administrator
Bureau for Africa
Agency for International Development
Department of State
Washington, D. C. 20523

Dear Mr. Scott:

Enclosed are 25 copies of the report, "A Hydrologic Review of the Proposed Bakel-Small Perimeters, Senegal River Basin." The report is submitted in response to a request from the Agency for International Development for the services of a hydrologist to assist the AID Mission in Dakar in completing a technical analysis of the Bakel Irrigated Perimeter. The services were performed in Senegal by Mr. Earll D. Dudley from July 7 to 29, 1976, in accordance with Participating Agency Service Agreement IB/AR-135-5-76 and PIO/T 698-135-2-6117022.

Following an evaluation of previous studies and an appraisal of the area hydrology, the report recommends measures which should be taken to protect the irrigated perimeters from anticipated floods. The recommendations include suggested dike heights, plantings to protect the dikes from wave action, pumps to evacuate drainage water, and drainage channels.

If additional copies of the report are required, please let us know so that we can have them printed.

We appreciate the cooperation and courtesy extended to Mr. Dudley by all agencies and individuals with whom he dealt while in Senegal.

Sincerely yours,

Acting
Commissioner

Enclosure

AMERICAN REVOLUTION BICENTENNIAL 1776-1976

CONTENTS

	Page
STUDY OBJECTIVES	1
DIKE DESIGN INFORMATION	3
Perimeter Diking Requirements	3
Flood Frequencies	4
Flood Crest Elevations	6
River - Main Channel	6
Marigots	7
Villagers Observations	8
Mathematical Model	10
River Flow Regime	10
Effect of Dikes on Flood Crests	13
Freeboard	15
Recommended Dike Elevations	16
WATER REQUIREMENTS AND AVAILABILITY	20
Cropping Patterns	20
Water Requirements	21
River Flow Availability	23
Shortage Frequency	23
SURFACE DRAINAGE	25
Rainfall Frequencies	25
Drainage Within Perimeters	26
Tributary Drainage (intercepter drains)	27

FIGURES

Figure No.	Title	Follows Page
1	Location Maps (2 pages)	3
2	Flood Crest Frequency - Bakel	5
3	Flood Crest Frequency - Kidira	5
4	Flood Crest Profile - ORSTOM	6
5	Flood Crest Profile - Updated	7
6	Flood Crest Profile - SAED	8
7	Flow Hydrograph - 1950, Bakel and Matam	11
8	Flow to Marigots versus Flood Stage	12
9	Duration of Flood Crest versus River to Marigot Crest Difference	13

TABLES

Number		Page
1	Flood Crest Elevations	17
2	Recommended Dike Elevations	18

Contents

PHOTOGRAPHS

Number		Following Page
1	Looking upstream along the left bank of the Senegal River from the Old Fort at Bakel	2
2	Looking downstream on the Faleme at Balou	2
3	Irrigation pump on Senegal River at Diawara. Looking downstream with island in river to the right	4
4	Looking along west dike alignment towards the village of Balou (or river bank)	4
5	Preparing the irrigation plot at Diawara, looking south toward the marigot	20
6	French advisers at Diawara perimeter	20
7	First irrigation at Yafera. Looking east toward village	24
8	Planting rain-supported millet near Mouderi . . .	24

SUMMARY AND RECOMMENDATIONS

The study concerning the "Bakel-Small Perimeters" by the Senegal Government Agency, SAED, was reviewed with particular emphasis on verifying the recommended elevations for the flood protection dikes. The dike elevations were based on historical flood heights as remembered by the local villagers. The floods in the marigots, as observed by the villagers, were usually about 1.0 meter lower than the floods crests recorded on the main river channel.

A field check to evaluate the consistency of the villagers' observations revealed several incongruencies. Therefore, an analysis of the river flow regime between Bakel and Matam was used to verify the villagers' observations. Based on the regime analysis, it is recommended that the flood crests in the marigot areas be considered as only 0.5 meter lower than on the main river rather than the 1.0 meter used by SAED.

The frequency analyses of flood crests on the Senegal River and its tributary, the Faleme, used by SAED were based on the records available up to 1964. A reanalysis, using additional records up to 1974, lowered the estimated crest elevation for the 10 percent frequency flood by about 0.2 meter.

The construction of the dikes around the irrigated perimeters would restrict the overflow channel areas for the river and thereby increase the flood crest heights on the main channel. Therefore, it is recommended that the dike heights be increased by 0.2 meter on the Senegal River and by 0.3 meter on the Faleme River to protect against the additional flood heights.

The SAED study assumed a free-board of 0.5 meter for the flood protection dikes. It is recommended instead, as a safety factor, that a free-board of 0.9 meter be used along the main river channel and 0.7 meter in the marigot areas. It is further recommended that trees and/or bushes be planted in front of the dikes crossing the marigots to give additional protection from wave action.

The differences between the top-of-dike elevations recommended in this report and the SAED estimates vary from about the same for the Golmi perimeter to an increase of 1.3 meters for the Balou perimeter.

An analysis of the dry season flows in the Senegal River at Bakel indicate that sufficient flow would be available for irrigation of 3000 ha. in all months except April. The April requirement of 3.7 m^3/s would be shorted in about 2 years out of 100 years. The average annual farm delivery demand for 3000 ha. (double cropped) would total about 60,000,000 m^3.

The diked perimeters will be entirely enclosed. When the river is in flood, there will not be any outlet for surface drainage water unless it is pumped over the dikes. It is recommended that drainage pumps with the capacity of 0.0022 m^3/s per ha. of perimeter be provided for evacuating drainage water resulting from a 1 in 10-year frequency rainfall.

Two of the Phase I perimeters, Balou and Yafera, will require intercepting dikes and drainage channels to divert runoff from tributary drainage areas around the perimeters. The peak discharges for the design of the drainage channels for 1 in 10 year floods would be about 10 m^3/s for Balou and 12 m^3/s for Yafera.

STUDY OBJECTIVES

Several of the perimeters proposed for irrigation development will require diking for flood protection. Data as to the height of flood waters in the perimeter areas are limited to the remembrances of the local villagers. The engineers of SAED[1/] (Societe d'Amenagement et d'Exploitation des terres du Delta et de la Vallee du Fleuve Senegal) have related the flood height information for the Bakel area, as obtained from the villagers, to the recorded gage heights at the Bakel station. As adequate protection from flooding is crucial to the success of the irrigation perimeters, the primary objective of the hydrological study was to check the methodology for selecting the top-of-dike elevations.

The above objective plus other objectives outlined by A.I.D. in their request for the study are listed below:

"Verify data used by SAED to determine flood frequencies on the Senegal and Faleme Rivers from Kidira on the Faleme to Ouaounde about 50 km down river from Bakel on the Senegal River. Task includes:

A. Review rationale and methodology of SAED conclusions and recommendations.

B. Review data prepared by ORSTOM[2/] (L'Office de la Recherche Scientifique et technique outre-Mer) on Senegal River at Bakel and make judgement regarding its accuracy as far as flood heights and duration is concerned.

1/ Perimetre de Bakel - Amenagement Hydro-Agricole Petits Perimetres - Projet d'Execution, SAED, Saint Louis, Senegal - July 1976.

2/ Monographies Hydrologiques - LeBassin du Fleuve Senegal - ORSTOM, C. Rochette, Paris, 1974.

C. In Bakel discuss floods and flooding with farmers and inhabitants of area and correlate this data with ORSTOM data.

D. Develop recommendations for heights of dikes needed to give flood protection for 4 years in 5 and 9 years in 10. Give particular attention to the SAED thesis that floods from marigots are lower than floods on river itself, and give rationale for recommendations.

E. Consider the effects on flood regime of river due to construction of protection dikes.

F. Make analysis of effects of pumping water out of river for irrigation at three development levels: 1000 ha., 2000 ha., and 3000 ha."

An additional objective was added later. A study was needed to determine if there will be a surface drainage problem on some of the diked perimeters. In order to avoid flooding, the crops, any accumulation of drainage water would have to be pumped out over the dikes when the river is in flood.

No.1
Looking upstream along the left bank of the Senegal River from the Old Fort at Bakel.

No. 2
Looking downstream on the Faleme River at Balou.

DIKE DESIGN INFORMATION

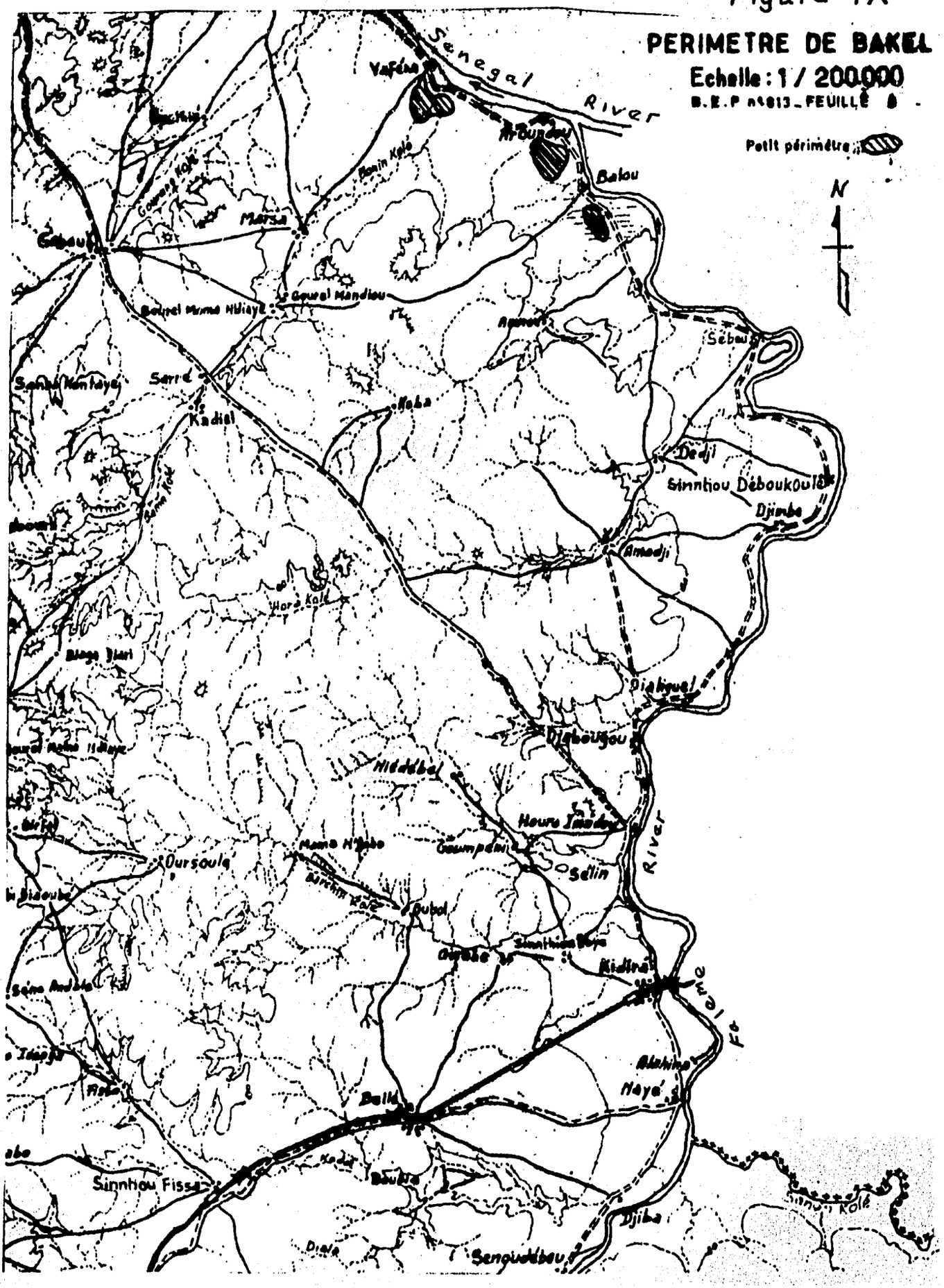
Perimeter Diking Requirements

The proposed irrigation perimeters generally extend from the banks of the Senegal River across a system of marigots (or over-flow channels) which parallel the main river channel. The river has built up natural levees along its main channel so that the land slopes away from the river to the chain of lakes and low swampy areas. Tributaries or other connecting channels punctuate the main river bank at intervals providing access for floods from the river to flow into the system of marigots. Some reaches of the river valley have 2 or 3 parallel chains of marigots each separated in places by low narrow mounds. Most of the villages are located at the higher places on the river bank where the flooding is less frequent.

Two of the proposed first phase perimeters, Balou and Yafera, would have two main dikes extending from the river bank across a marigot to the edge of the river flood plain. (See Figure 1 for a location map of the proposed perimeters). The two dikes, one upstream and one downstream of the perimeters, would cut off the marigots' access to the main river channel Additional short dikes would be required at low spots along the river bank of the main channel to prevent direct over-bank flood flows into the perimeters.

The perimeter at Mouderi-Diawara, which is proposed for Phase II and is not a part of this initial study, would be similar in plan to Balou and Yafera. The dike profiles for this perimeter have not yet

Figure 1A


PERIMETRE DE BAKEL
Echelle : 1 / 200.000
B.E.P n°813 _ FEUILLE
Petit périmètre
N
Senegal River
Vaféra
Balou
Marsa
Gourel Mandiou
Sébou
Sarré
Kadiel
Koba
Dedji
Sinnthiou Déboukoulé
Djimbe
Amadji
Hora Kolé
Diaguel
Djabougou
Niédébel
Houro Imadou
Goumpéni
Sélin
Oursoulé
Dubol
Kidira
Faleme River
Alahina
Nayé
Bellé
Sinnthiou Fissa
Djiba
Senoudébou

PERIMETRE DE
Echelle : 1 / 20
P.E.P 04813 _ FEUILL

Petit-périmètre

Figure 1B

been completed. A field inspection of the perimeter indicated that to protect the entire proposed area of over 1000 ha. would require dikes 4 to 5 meters high in places

The perimeter Tuabo II lies at the end of a chain of marigots and would require only one main dike to cut off the area from the river flooding.

The perimeters Koungani and Golmi would each have a pair of dikes extending from the main river bank across a single marigot to a low mound, beyond which lies a second larger marigot. For Koungani, a dike would be required on the mound which separates the two marigots to prevent flood flows, passing through the second marigot from the river, from backing into the perimeter. For the Golmi perimeter, the mound between the marigots is reportedly high enough to protect the perimeter.

Flood Frequencies

The frequency of maximum annual flood elevations (IGN) for the Faleme River at Kidira and the Senegal River at Bakel have been determined in a study by Mr. C. Rochette (ORSTOM)[1/]. The results of the study are given in the following tabulation. The period of record used in the analysis was from 1930 to 1964 for the Kidira station and from 1903 to 1964 for the Bakel station.

1/ Monographies Hydrologiques - Le Bassin du Fleuve Senegal - ORSTOM, C. Rochette, Paris - 1974.

No. 3
Irrigation pump on Senegal River at Diawara. Looking downstream with island in river to the right.

No. 4
Looking along west dike alignment towards the village of Balou (on river bank.)

Frequency %	Senegal at Bakel El. in m. maximum	Senegal at Bakel El. in m. 15 day	Faleme at Kidira El. in m. maximum
1	24.61	23.90	31.85
5	24.11	23.36	31.10
10	23.78	22.91	30.70
20	23.31	22.46	30.10
50	22.11	21.11	29.00
80	20.76	19.61	27.60
90	19.91	18.76	26.75
95	19.06	17.91	25.85
99	17.26	16.51	23.85

Additional years of gage height records (up to 1974) were available for the two stations. A new flood crest (water surface elevation) frequency analysis was made for both stations to determine if the addition of the recent drought years would have changed the frequency values computed by Rochette. Figure 2 presents a plot of the updated flood frequency for both the maximum and the 15-day (water surface higher than indicated for 15 days) elevations for Bakel. Similar data for the flood crests for Kidira are shown on Figure 3. The results are summarized in the following tabulation for comparison with Rochette's values:

requency %	Maximum Flood Crest Elevations m. Rochette's Bakel	Rochette's Kidira	Revised Bakel	Revised Kidira
10	23.78	30.70	23.6	30.5
20	23.31	30.10	23.2	30.0

NO. 3127. ARITHMETIC PROBABILITY. DESIGNED BY HAZEN, WHIPPLE & FULLER. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS

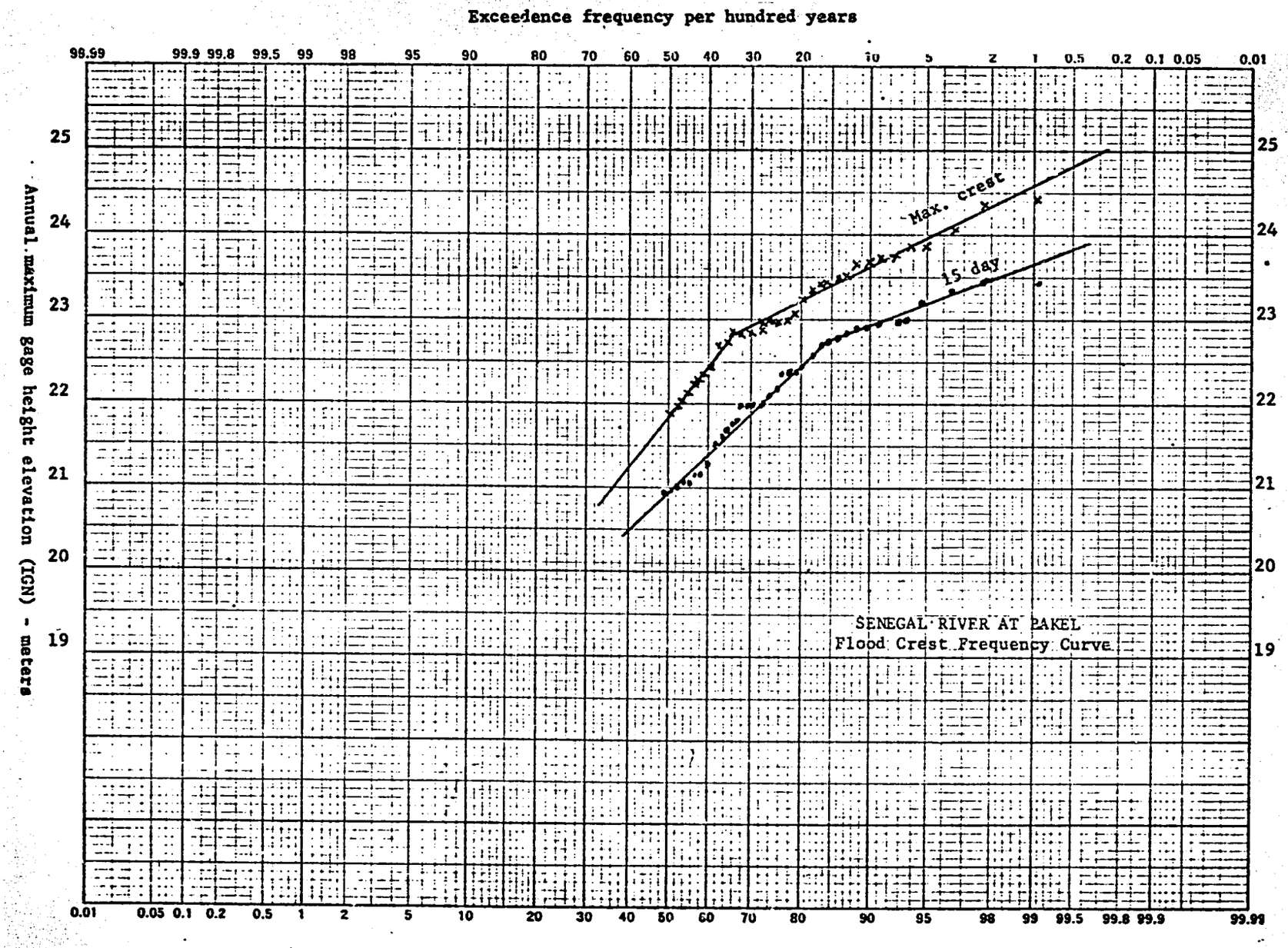


FIGURE 2

NO. 3127. ARITHMETIC PROBABILITY. DESIGNED BY HAZEN, WHIPPLE & FULLER. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS

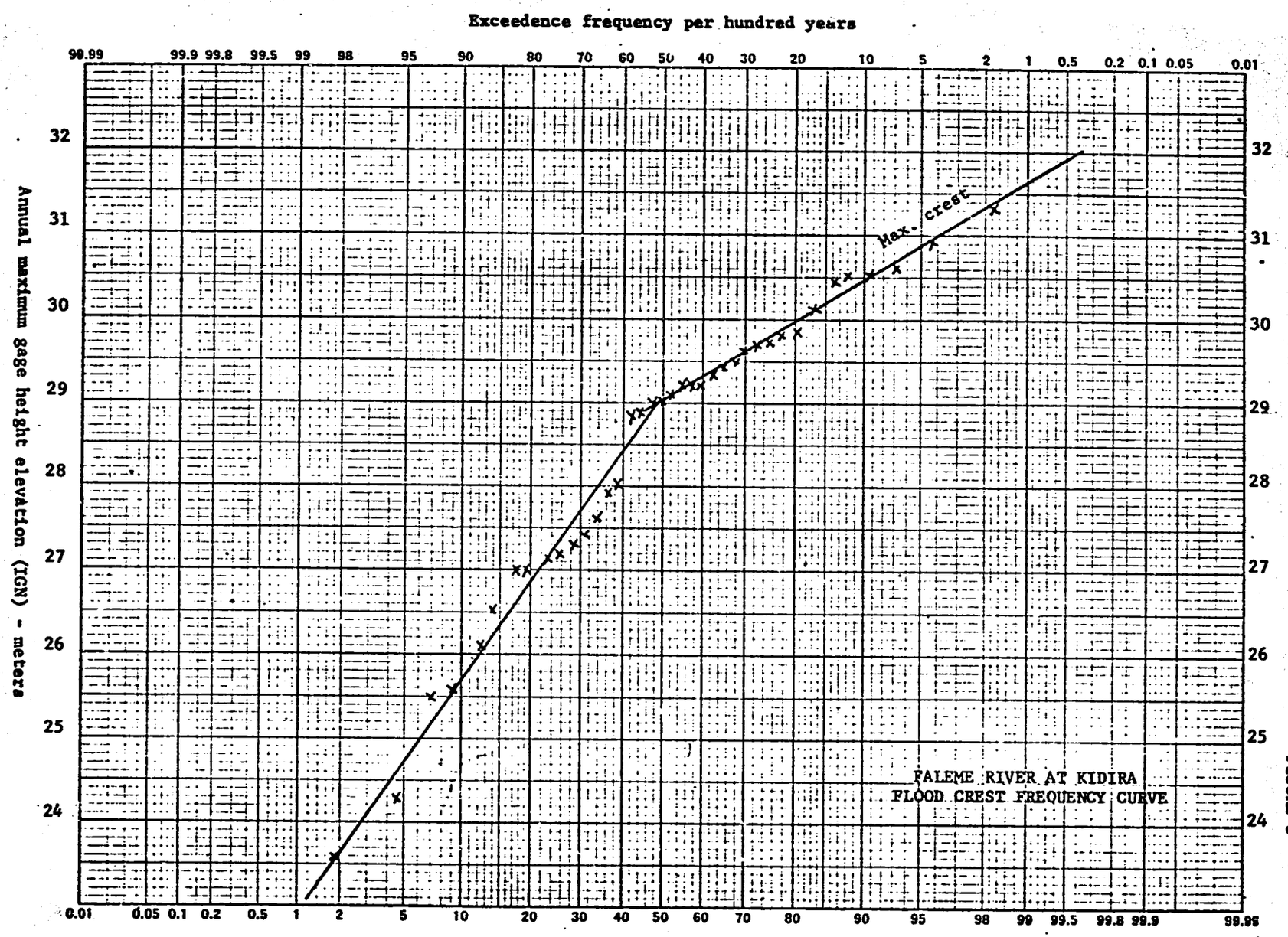


FIGURE 3

The additional years of record lowered the elevation of the maximum flood elevations at Bakel by about 0.2 meter for the 1 in 10 year frequency, and 0.1 meter for the 1 in 5 year frequency. The results did not change for the 15-day flood elevations.

It should be noted that the difference in providing protection for the 1 in 10 year flood rather than the 1 in 5 year flood amounts to about 0.4 meter additional height of the dikes.

Flood Crest Elevations

River - Main Channel -- Records of flood water surface elevations in the vicinity of Bakel exist at several gaging stations along the main channel of the Senegal River and its tributary, the Faleme. The following tabulation lists the stations and their channel distance from the river mouth.

Station	River	River Distance km	ORSTOM 10% Frequency Flood Crest Elevation
Matam	Senegal	623	16.17
Ouaounde	Senegal	715	19.68
Bakel	Senegal	794	23.78
Kidira	Faleme	873 1/	30.70
Kayes	Senegal	923	31.76

1/ 50 ± km from Jct. of Faleme with Senegal River.

The station distances are plotted on Figure 4 and show the flood elevations (IGN) for 1 in 10 year (10 percent frequency) flood as computed by Mr. C. Rochette (ORSTOM). It should be noted that the 1 in 10

K+E 10 X 10 TO THE INCH 46 0706
7 X 10 IN. • ALBANENE®
KEUFFEL & ESSER CO.

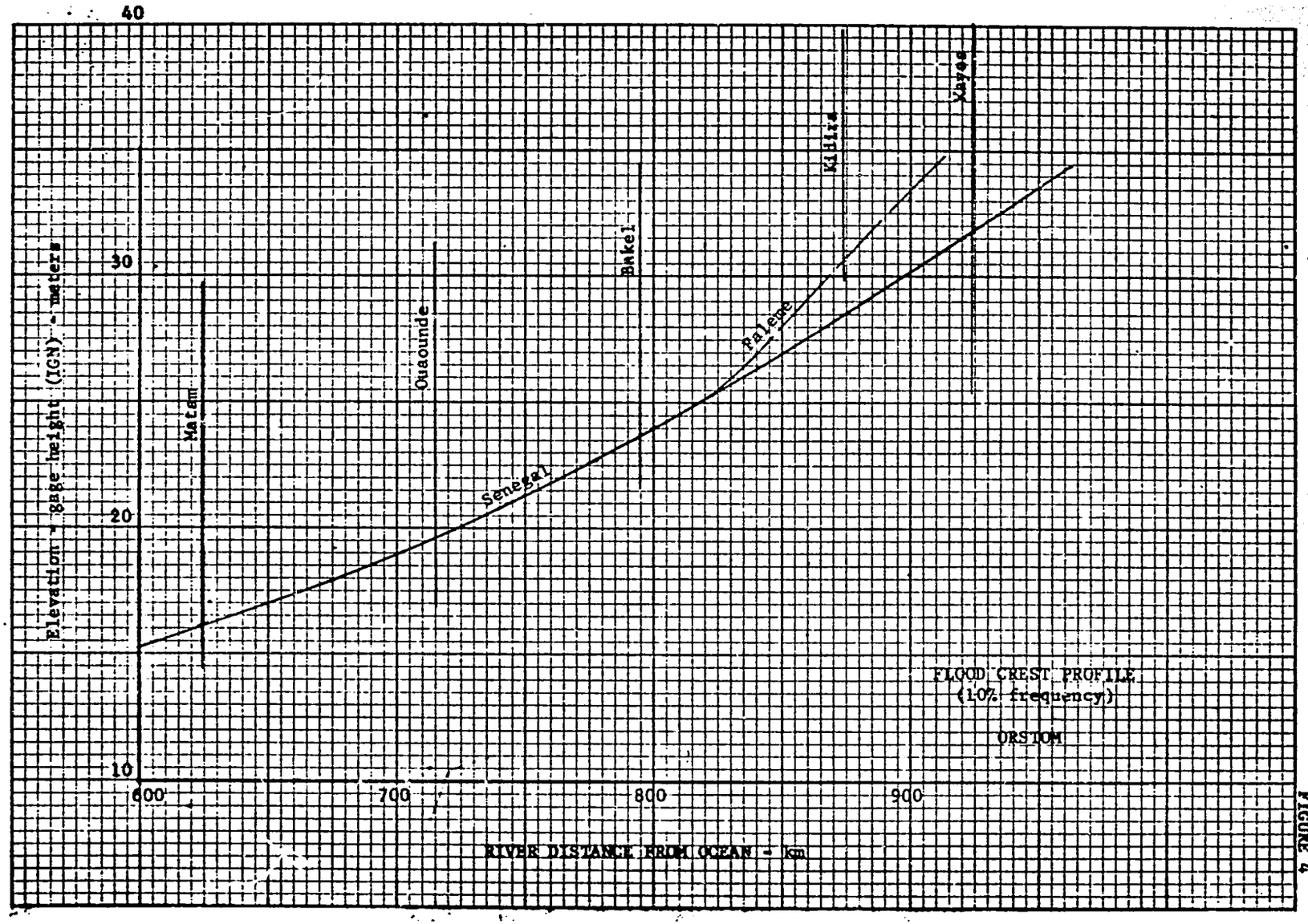


FIGURE 4

year frequency flood is not representative of a single flood. A flood can have a different frequency of occurrence as it passes different stations. The volume of a flood and its rate of increase can effect its maximum crest height at different stations depending on the antecedent conditions of flooding in the marigots.

The proposed irrigation perimeters are located within about 30 to 35 km upstream and downstream of the Bakel gaging station.

The flood crest profile for the 1 in 10 year frequency has been repeated on Figure 5 to a larger scale to show river flood elevations adjacent to the various perimeters. The flood profile has been interpolated as a smooth curve between the different gaging stations. Undoubtedly, constrictions and riffles in the river channel do cause some variations from the assumed smooth profile. However, the Bakel station is situated in the center of the group of perimeters and the assumed elevations should be adequate for determining river flood crests at the perimeters.

As discussed under the preceeding paragraph on flood frequencies, the addition of the last 10 years of hydrologic record reduced the flood crest heights for the 1 in 10 year frequency flood as computed by Mr. C. Rochette, by about 0.2 meter for both the Bakel and Kidira stations. Therefore, the 1 in 10 frequency flood crest elevations, as plotted on Figure 5, are shown as 0.2 meters lower than those plotted on Figure 4.

<u>Marigots</u> - Data as to the heights of the flood crests in the marigot areas are limited to the remembrances of the local inhabitants. The

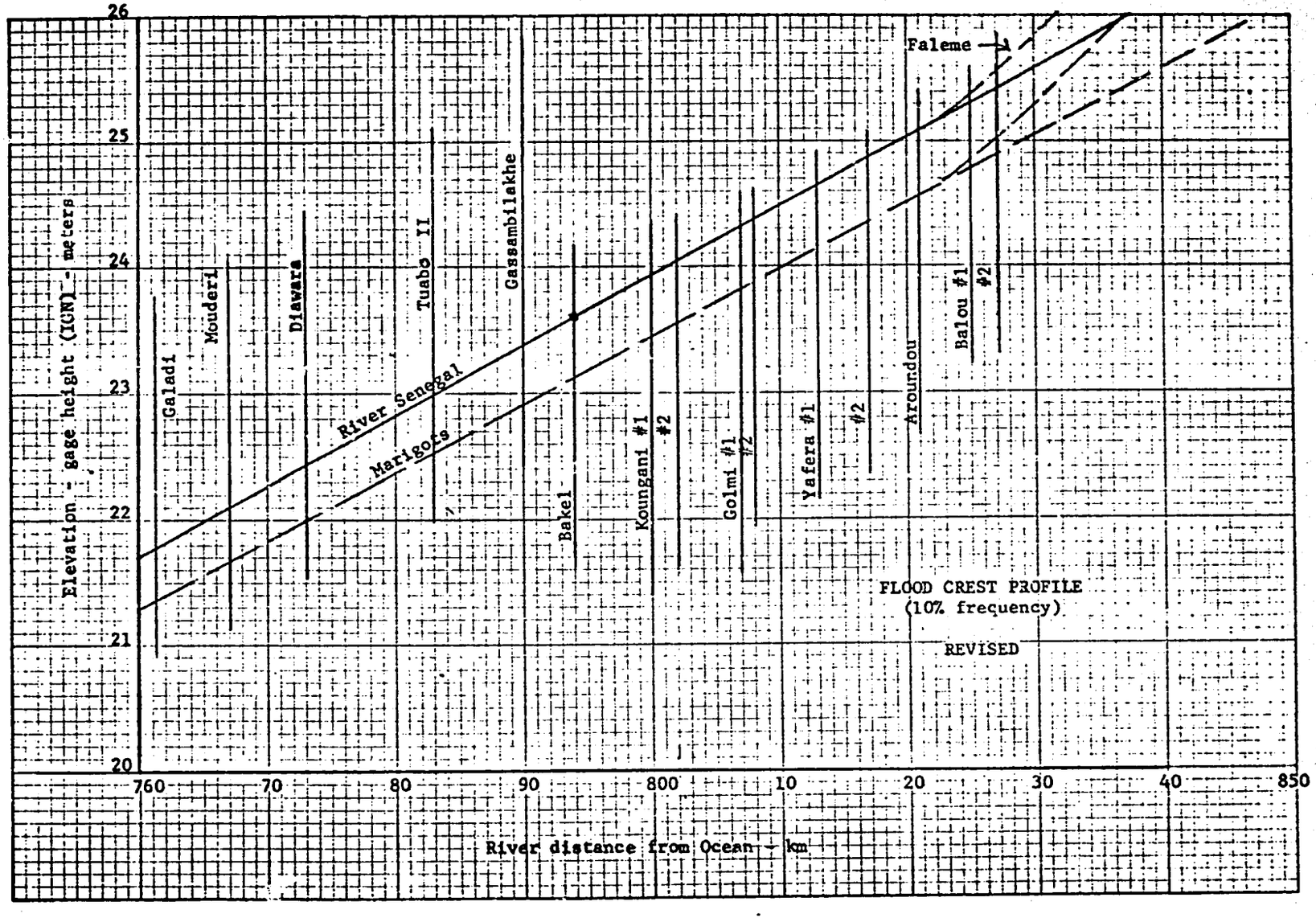

Elevation - gage height (IGN) - meters
26
25
24
23
22
21
20
Galadi
Mouderi
Diawara
Tuabo II
Gassambilakhe
Bakel
Koungani #1
#2
Golmi #1
#2
Yafera #1
#2
Aroundou
Balou #1
#2
Faleme
River Senegal
Marigots
FLOOD CREST PROFILE
(10% frequency)
REVISED
760
70
80
90
800
10
20
30
40
850
River distance from Ocean - km

FIGURE 5

elevations of the flood crests would determine the required heights of the perimeter dikes where they cross the marigots.

The SAED engineers[1/] interviewed the villagers near each proposed perimeter to determine the maximum point reached by recent large floods in the marigot areas.

Villager's Observations -- Information was requested concerning the 1974 flood, which had a frequency of occurrence at Bakel of about 1 in 4 years (25%) and the 1950 flood with a frequency of about 1 in 14 years (7%). The villagers stated that concerning the flooding of the marigots, the 1950 flood was the highest in their memory. The SAED engineers ran levels from the indicated points to known bench marks to determine the flood crest elevations. Where local opinions differed or where nearby indicated points gave different flood crest elevations, an average of the elevations was assumed.

The resulting flood profiles in the marigot areas, as determined by SAED through the above procedures, are plotted on Figure 6 taken from the SAED report.[1/]

In general, SAED found that the flood crests in the marigots were about 1 meter lower than the flood crests in the adjacent reach of the main channel. The reason for the difference in flood crests is because of the time required to fill the marigots. As a flood crest moves down the river, its spills over through restricted channels to fill the marigots. Several days are required to fill the marigots depending on

1/ Perimetre de Bakel - Amenagement Hydro-Agricole Petits Perimetres - Projet d'Execution, SAED, Saint Louis, Senegal - July 1976.

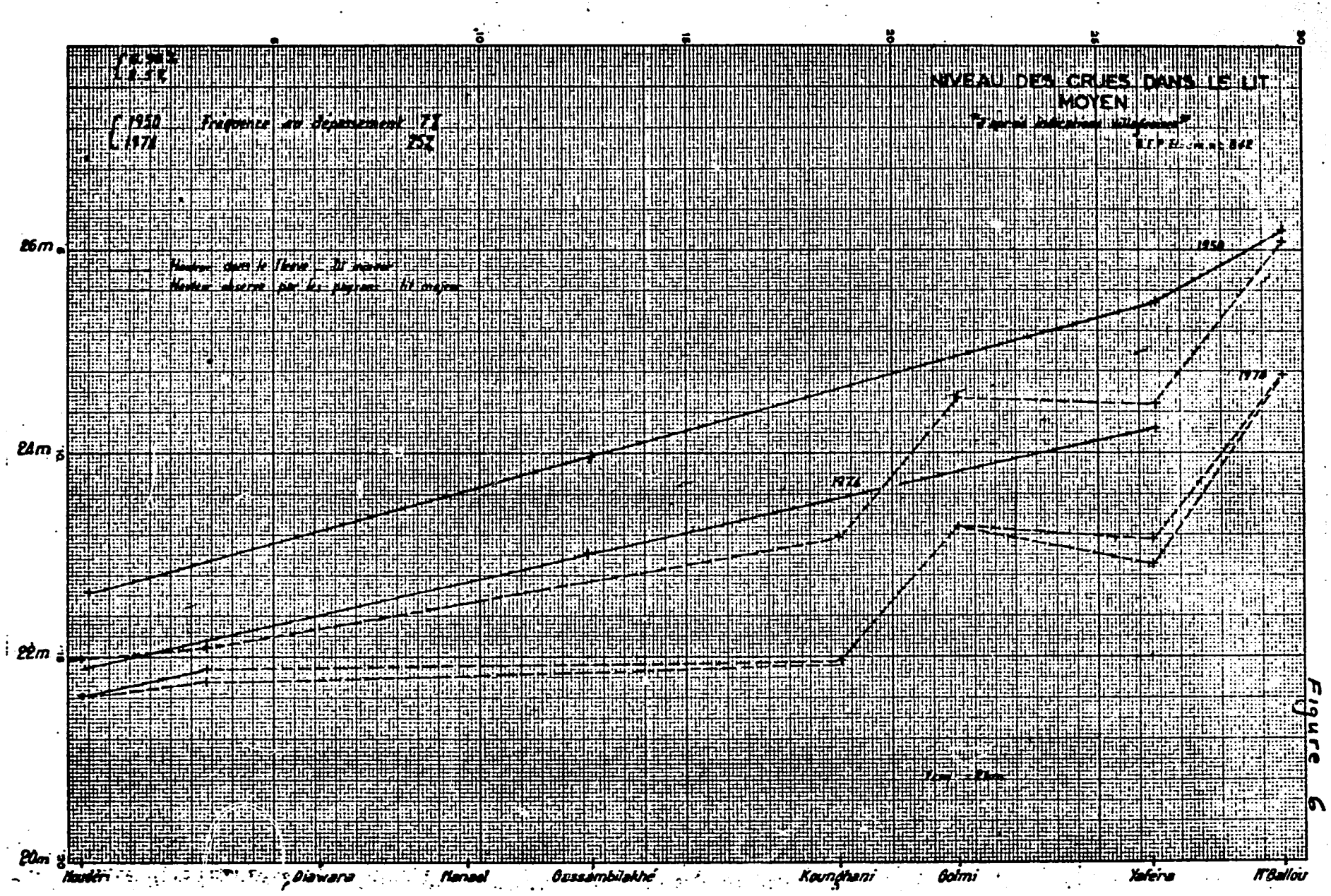

NIVEAU DES CRUES DANS LE LIT MOYEN
1950
1974
Fréquence au dépassement 7%
25%
26m
24m
22m
20m
Houdéri
Diawara
Manaal
Gassambilakhé
Kounghani
Golmi
Yafera
N'Ballou

Figure 6

the height of the river flood crest and the amount of water already in the marigots. In any event, the highest part of the river flood crest is past by the time marigot flood levels reach an equilibrium with the river water levels.

As protection from flooding is crucial to the success of the irrigation perimeters, it is necessary that a sound method be used to determine an adequate height for the dikes. At the same time, it is desirable to keep the dikes as low as possible to achieve a lower construction cost.

Several different methods as well as an available mathematical model could be used to estimate the marigot flood crests. However, the best and most practical method is obviously the historical observations, if they are reliable.

Therefore, a field check was made on the perimeters, accompanied by SAED personnel, in an attempt to evaluate the reliability of the villagers' observations. The subject was also discussed with the SAED surveyor who made the survey. The reliability was very difficult to evaluate. Undoubtedly, some of the observed flood crest points are correct. However, there was sufficient diverse opinion or incongruency with local topography to warrant a further evaluation of the problem. Also, as would be expected, most of the observed flood heights were in or next to the villages rather than in the marigot areas or at the locations of the proposed dikes.

Two other methods of determining the marigot flood crest elevations were considered in order to verify the villagers' observations. One

method was a mathematical model of the Senegal River system developed by SOGREAH.[1/] The other method was an analysis of the river flow regime between Bakel and Matam.

Mathematical Model - The mathematical model has been used to reproduce historical floods on the river as well as to predict typical floods for annual frequencies of 1 in 10, 1 in 100 and 1 in 1000. The model channel network includes the marigot systems as well as the main river channels. A portion of the limited time available for this study was spent in attempting to trace down promising leads as to the location of pertinent data derived by the model studies, but to no avail. Many of the reports contained flood crest elevations along the river and related data in the marigots, but not the marigot elevations for the Bakel vicinity. The desired data undoubtedly exists in the SOGREAH office in Grenoble France, but the time available did not permit attempting to obtain it. It is recommended that before construction of the dikes, the model data, if available, be obtained in order to check the conclusions of this study.

River Flow Regime - Because of the complex network of the river and marigot channels, a detailed mathematical model (such as developed by SOGREAH), is really needed to adequately compute channel flows and water surface elevations. However, an approximate solution can be obtained through an analysis of the river flow regime between Bakel and Matam. (Although Ouaounde is the next gaging station below Bakel, its records were too incomplete to use.)

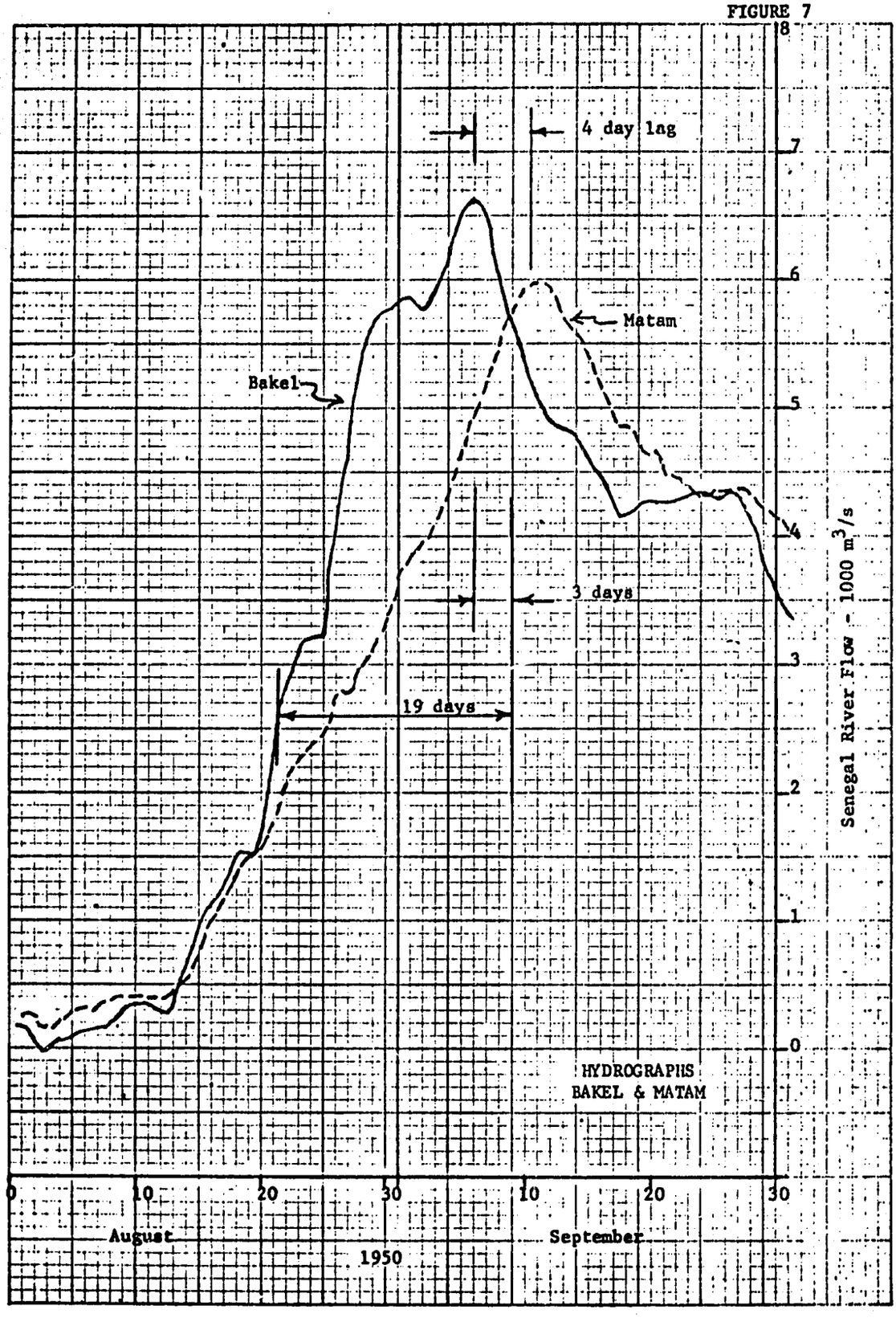
1/ Societe Grenobloise d'Etudes et d'Applications Hydrauliques - Modele Mathematique de la Vallee du Senegal - Grenoble, France - Nov. 1970.

The important question is how long, for a particular flood crest, does it take to fill up the marigots and overflow channels. If only a day or so is required, then the maximum flood crest elevations in the marigots could approach those in the main channel. If several days are required, then the main channel flood crest could have dropped well below its maximum elevation by the time the marigot water levels reach a quasi-steady relationship with the river stage.

Several of the larger floods were analyzed to determine the time required to fill the marigots. The required filling time was about 20 to 25 days for the floods studied. The filling time was estimated by determining the differences in flow between Bakel and Matam.

For example, daily plots of the 1950 flood flows for Bakel and Matam are presented on Figure 7. The lag in flood peak between the two stations is about 4 or 5 days which is assumed to be the approximate travel time for the flood flows. If the flows did not leave the main channel to fill the marigots, then the flow at Matam should be at least as great as the flow at Bakel 4 days previously. As indicated on Figure 7, a considerable loss in flow occurred between the two stations for about 19 days from August 21 to about September 9. On September 9, the flow at Bakel again approximately equaled the flow at Matam 4 days later. From that date on, as the flood crest receded, the flow at Matam was greater than the previous 4 day flow at Bakel, indicating that some of the flow lost to the marigots was draining back to the main channel. On September 9 to September 13, the water surface elevations in the

FIGURE 7


4 day lag
Matam
Bakel
3 days
19 days
HYDROGRAPHS
BAKEL & MATAM
Senegal River Flow - 1000 m³/s
0
1
2
3
4
5
6
7
8
0
10
20
30
10
20
30
August
September
1950

marigots would have been approximately in equilibrium with the main channel for the reach from Bakel to Matam.

As shown on Figure 8, the rate of loss (inflow to the marigots) between Bakel and Matam varies fairly consistently with the flood stage elevation at Bakel and with the net amount of water already stored in the marigots.

The net amount of water stored in the marigots was computed by accumulating the daily net loss between Bakel and Matam (considering the 4 day lag in flow time).

The above analysis disregards the unknown intervening tributary inflow, which is small compared to the river flood, and the unmeasured flow in the marigots which bypasses the Matam gage. However, the two unknowns tend to compensate each other. Also, the actual flow through the marigots is probably about an order of magnitude smaller than the rate of flow to fill the marigots.

On September 9, the water surface in the marigots near Bakel would have approached the elevation in the main channel as evidenced by lack of a net loss of flow between Bakel and Matam. The water surface elevation at Bakel of about 23.5 meters on September 9 was about 0.4 meter less than at the maximum flood crest of 23.87 on September 6. Therefore, it is believed that for the 1950 flood, the maximum water surface in the marigots probably was within 0.4 meter of the maximum flood crest on the river.

The network of marigots varies in depth and complexity along the river. Undoubtedly some areas fill up and reach an equilibrium with

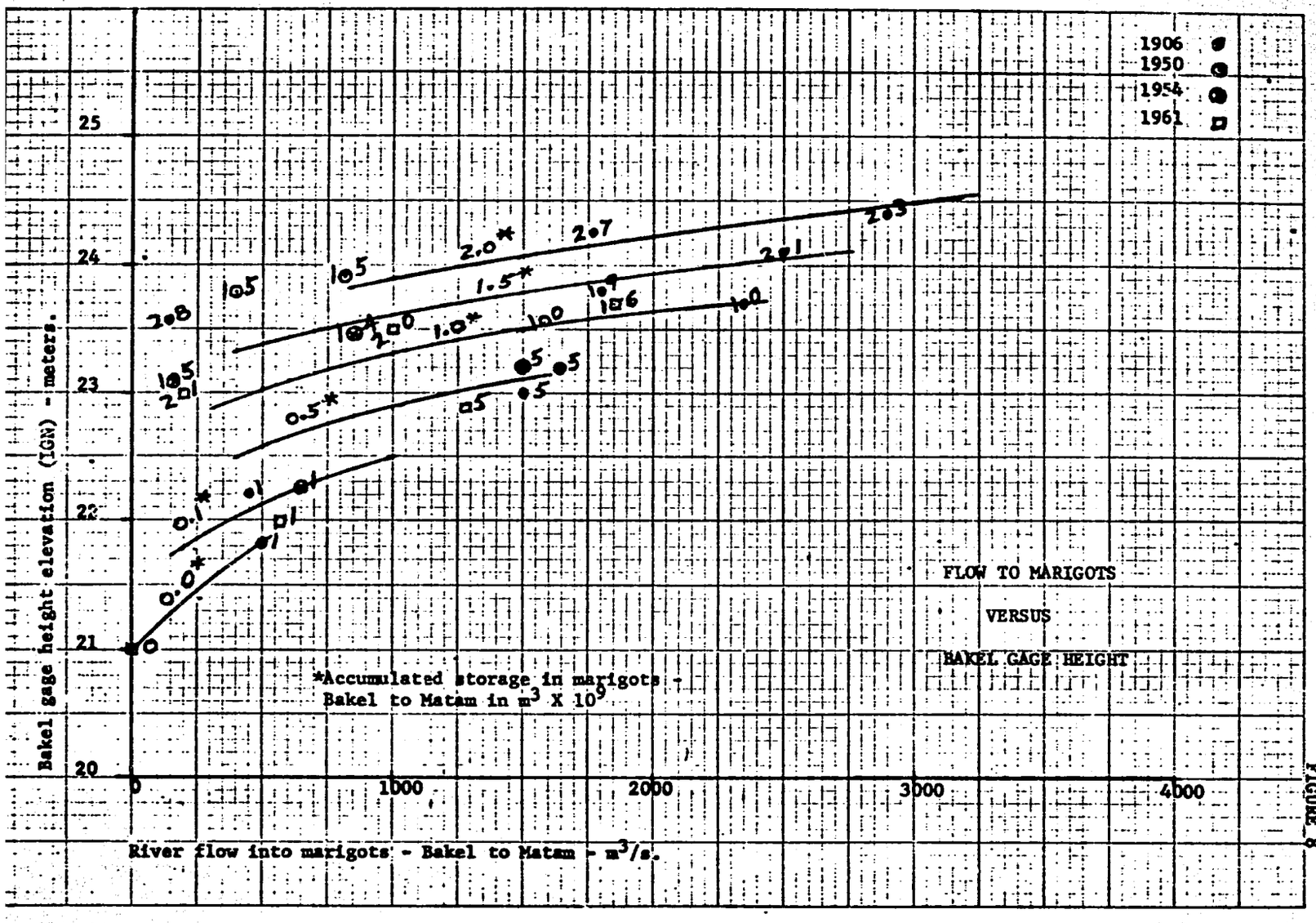

1906
1950
1954
1961
25
24
23
22
21
20
0
1000
2000
3000
4000
Bakel gage height elevation (IGN) - meters.
River flow into marigots - Bakel to Matam - m³/s.
FLOW TO MARIGOTS
VERSUS
BAKEL GAGE HEIGHT
*Accumulated storage in marigots - Bakel to Matam in m³ X 10⁹
2.0*
1.5*
1.0*
0.5*
0.1*
0.0*

FIGURE 8

the river faster than others. However, in general, the complexity of the marigot system increases downstream to Matam and the average filling time for the reach should be conservative for the Bakel area.

The relationship between the maximum flood crest in the river and the elevation where the marigots and river reach equilibrium is not only a function of the maximum flood crest, but also the duration of the higher flows. The flood of 1950 had a large volume discharge as well as a high maximum rate of flow. For the flood of 1961, which had a low volume compared to its maximum flow, the apparent difference between the flood crest and the elevation where equilibrium was reached with the marigots was much greater (about 1.0 meter). Therefore, an adjustment was made in estimating the difference in maximum flood crest elevations between the river and marigots based on the duration of the flood crest.

Figure 9 shows for selected historical floods, the relationship at Bakel between the maximum crest and the duration of lower water surface elevations (for 15 days) and the elevations where it is estimated that the marigots were in equilibrium with the river. Assuming a similar relationship for the point of equilibrium for the 1 in 10 year frequency flood the estimated maximum flood crest in the marigots would be about 0.5 meter below the river flood crest.

Effect of Dikes on Flood Crests

Enclosing some of the perimeters with dikes will reduce the overflow storage capacity in the river flood plain. In the case of Balou and Yafera, dikes would completely cut off any flow through the marigot (on the left bank). These restrictions would increase the water depth in the main channel and thereby require additional dike heights for the

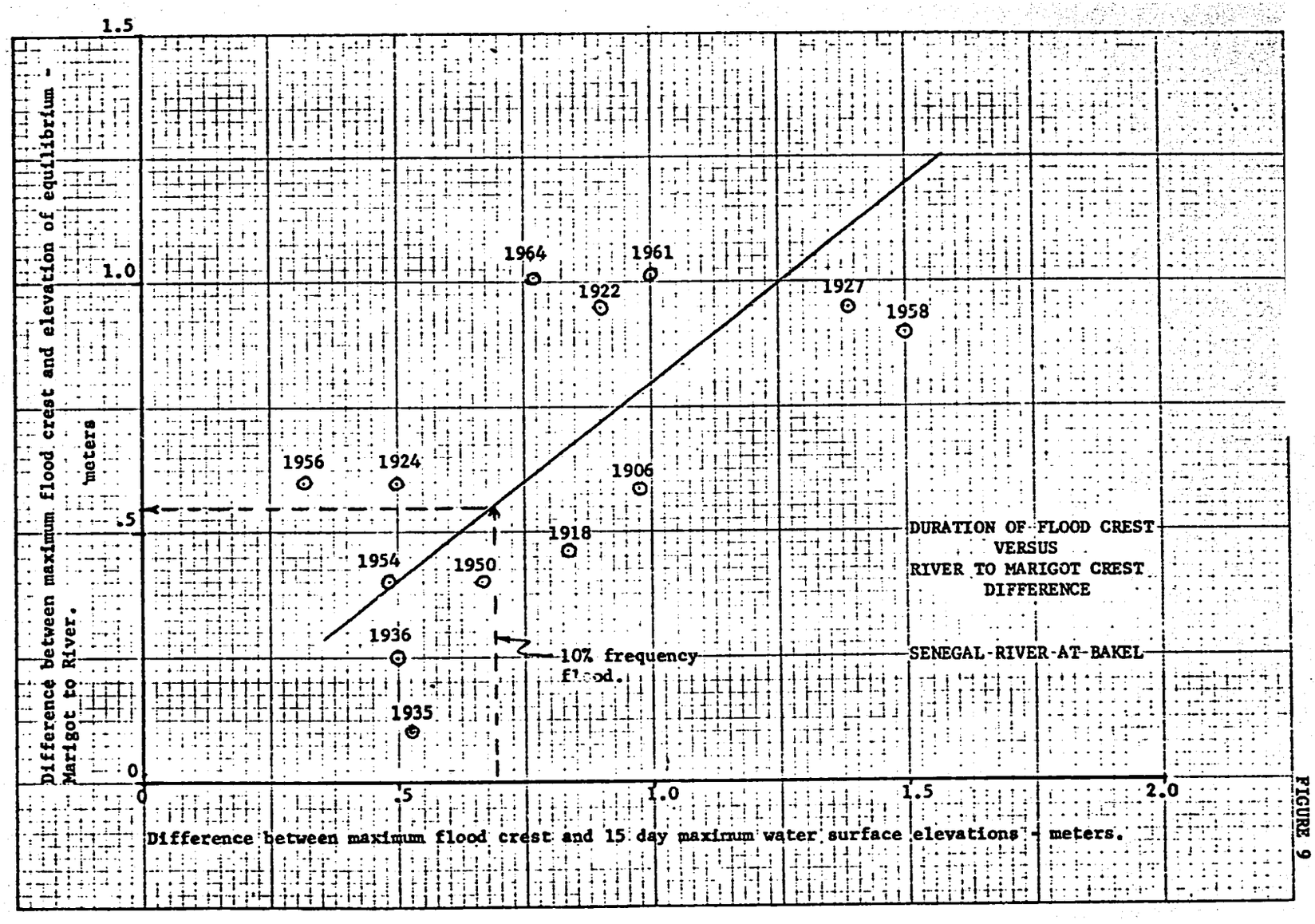

1.5
1.0
.5
0
0
.5
1.0
1.5
2.0
Difference between maximum flood crest and elevation of equilibrium - Marigot to River. meters
Difference between maximum flood crest and 15 day maximum water surface elevations - meters.
1964
1961
1922
1927
1958
1956
1924
1906
1918
1954
1950
1936
1935
10% frequency flood.
DURATION OF FLOOD CREST
VERSUS
RIVER TO MARIGOT CREST
DIFFERENCE
SENEGAL-RIVER-AT-BAKEL

FIGURE 9

perimeters. An estimate was therefore made of the impact of the perimeter dikes on the flood crests.

Near Yafera about 5 percent of the flood (1 in 10 year frequency) was computed as being transported through the left flood plain. Assuming a similar river stage-flow relationship at Yafera as for the Bakel station, dikes blocking off the marigot would increase the flood crest by about 0.2 meter.

Near Balou on the Faleme River, it was estimated that about 12 percent of the flood on the Faleme with a 1 in 10 year frequency would be carried by the marigot which is to be diked off. The river stage-flow relationship is not known for this location which is about 3 km. above the Faleme junction with the Senegal River. Undoubtedly the flood crest elevation is influenced by backwater from the Senegal River. If the stage-flow relationship for Balou were the same as at Kidira (50 ± km. above the junction), the dikes would raise the flood crest by about 0.6 meter. However, because the main channel cross-section at Balou is probably much greater than at Kidira, the dike effect was assumed at about 0.3 meter or one-half that of Kidira.

For the other diked perimeters which would not block off the marigots, but would only reduce the marigot storage capacity, the impact of the dikes would be insignificant compared to other unknowns in computing dike heights.

A previous study on the effect of dikes on flood crests of the Senegal River for the proposed Matam perimeter was made by SOGREAH[1/] using the

1/ Etude Hydro-Agricole du Bassin du Fleuve Senegal - Schema de Principe detaille - Casier Pilote de Matam - SOGREAH, Grenoble, France - Dec. 1972.

mathematical model. The perimeter dikes evaluated in the SOGREAH study were all downstream of Bakel. The study did include the Diawara-Mouderi perimeter which is to be included in Phase II of the Bakel small perimeters The results of the SOGREAH analysis indicated that the dikes assumed in their study would increase the 1 in 100 year flood crest at Matam by 0.[illegible] meter and at Ouaounde by 0.2 meter. No increase was noted at the Bakel station.

Freeboard

The SAED report[1/] assumed a freeboard of 0.5 meter in the design of the dikes. The SAED engineers related that in their 20 years of experience of building dikes along the Senegal River, a 0.5 meter freeboard has proven adequate.

Based on the wind records at Matam and Kayes and a minimum assumed fetch, the minimum freeboard, using the procedures recommended by the publication "Design of Small Dams,"[2/] is about 3 feet or 0.9 meter.

It is recommended that the 0.9-meter freeboard be used along the main river channel. Also, additional protection, such as riprap or "brush-mats" will be required where river currents impinge against the dikes.

In light of SAED local experience and recommendations, together with the low height of the dikes (average of about 2 meters), a freeboard of 0.7 meter is recommended for the dikes across the marigots. With the

1/ Perimetre de Bakel - Amenagement Hydro-Agricole Petits Perimetres Projet d'Execution, SAED, Saint Louis, Senegal - July 1976.
2/ Design of Small Dams - U. S. Bureau of Reclamation.

freeboard reduction from 0.9 to 0.7 meter it is recommended that trees or bushes be planted in front of the dikes crossing the flood plain to reduce wave action. The 0.7 meter in place of the 0.5 meter for the marigots is still recommended for the following reasons:

(1) The uncertainty in the estimates of the flood crest elevations for the assumed 1 in 10 year frequency.

(2) The lack of precision in estimating the effect of the dikes on the flood crest elevation.

(3) Allowances for settling of the dikes.

(4) Erosion due to rain, wind, and use as a path by animals.

(5) Unfavorable orientations to the wind resulting in an increased fetch.

Recommended Dike Elevations

Table 1 lists the estimated river and marigot flood crest elevations for the various perimeters, both Phase I and Phase II. The elevations have been adjusted for the revised 10 percent (1 in 10 year) flood frequency. The adjustment for the impact of the dikes on the flood crest has not been added to the table values.

Table 2 lists the estimated river and marigot flood crests for the Phase I perimeters for which dikes are planned. The elevations are again for the revised 10 percent frequency flood and include an adjustment for the impact of dikes on the flood crest. Where the dikes for a perimeter are sufficiently far apart, specific elevations are noted for each dike location.

Table 1. Flood Crest Elevations
(10% Frequency)

Station or Perimeter	River Distance (km)	Maximum Crest Elevations: River[1/] Revised (m)	Marigot: Recomm. (m)	Marigot: SAED (m)
Ouaounde (station)	715	19.5	-	-
Mouderi-Diawara				
West	767	22.1	21.7	22.00
East	773	22.4	22.0	22.10
Tuabo II - East	783	22.9	22.5	-
Bakel (Station)	794	23.6	-	-
Koungani				
West	800	23.9	23.4	23.23
East	802	24.0	23.5	23.23
Golmi				
West	807	24.3	23.8	24.56
East	808	24.4	23.9	24.56
Yafera				
West	813	24.6	24.1	24.45
East	817	24.9	24.4	24.45
Balou (Faleme)				
West	1.5	25.4	24.9	24.76
East	3.5	25.6	25.1	24.76
Kidira (Faleme Station)	50	30.5	-	-
Kayes (Station)	923	31.5	-	

Note: 1/ Does not include impact of proposed dikes on maximum flood crest.

Table 2. Recommended Dike Elevations
(Phase I Perimeters)

Perimeter	River Distance (km)	Max. Flood Elev. River 1/ (m)	Max. Flood Elev. Marigot 1/ (m)	Dike Elevations SAED (m)	Dike Elevations Recomm. (m)
Tuabo II					
Marigot			22.7	-	23.4
River		23.1		-	24.0
East	783		22.7	-	23.4
Koungani					
West	800		23.6	23.73	24.3
Marigot			23.6	23.73	24.3
River		24.2			25.1
East	802		23.7	23.73	24.4
Golmi					
West	807		24.0	25.06	25.1
Marigot			24.0	25.06	25.1
River		24.6			25.5
East	808		24.1	25.06	25.1
Yafera					
West	813		24.3	24.95	25.0
River		24.8-25.1			25.7-26.0
East	817		24.9	24.95	25.7
Balou (Faleme)					
West	1.5		25.2	25.26	25.9
River		25.9			26.8
East	3.5		25.9	25.26	26.6

Note: 1/ Flood elevations include adjustments for effect of dikes on flood crest.

Also listed on Table 2 are the recommended top-of-dike elevations which include allowances for freeboard. Where appropriate, different elevations are specified for the dikes of a perimeter; whether on the river side, marigot side, the upstream (east) end, or the downstream (west) end. Also listed in Table 2 for comparison are the original dike elevations used by SAED. The differences between the elevations recommended in this report and the SAED estimates vary from about the same for the Golmi perimeter to an increase of 1.3 meter for the Balou perimeter.

In setting the top of the upstream dike elevations for Balou and Yafera, where the dikes would completely block off the marigots, the river flood crest elevation was used as a base instead of the marigot flood crest. With the marigots blocked off, the reduced flood plain in front of the upstream dike should fill relatively fast. The marigot dike freeboard of 0.7 meter was still used however.

There would be a transition zone where the higher elevation dike along the river would grade to the lower elevation across the marigot.

WATER REQUIREMENTS AND AVAILABILITY

Double cropping is planned for the Bakel perimeters with the second irrigated crop to be grown during the dry season. In drought years, the Senegal River goes dry toward the end of the dry season. The following analysis was made to determine the frequency that a water supply would be available from the Senegal River for a second irrigated crop. The study assumed different development levels of 1000, 2000, or 3000 ha.

Cropping Pattern

The feasibility of the project has been tested assuming the following cropping pattern for the perimeters:[1/]

Season	Crop	% in Crop
June-September	rice (paddy)	100
December & January	cowpeas (niebe)	10
January-April	maize	50
January-April	sorghum	50

Although, about 60 percent of the soils on the perimeters are of the lighter "fonde" type soils, the villagers are mainly interested in growing rice. Therefore, the economic analysis and the water requirements were computed assuming that all the perimeters would be planted to rice during the rainy season, June through September. Considering the additional water required to grow rice on the lighter soils and the high cost of pumping water, future economic conditions might cause a change in the cropping pattern on these soils.

1/ Economic Evaluation of Bakel Irrigation Project, Senegal - C. J. Miller, July 1976.

No. 5
Preparing the irrigation plot at Diarawa. Looking south toward the marigot.

No. 6
French advisers at Diawara perimeter.

The perimeter soils consist of the following types:[1]

Soil Type	% of the Area	% Clay Content
Fonde	60	30-44
Faux Hollaldes	30	45-50
Hollaldes	10	51-60

Water Requirements

The basic water requirement estimates for the crops to be grown on the perimeters were taken from an earlier study by SOGREAH[2] for the Matam perimeter. The following tabulation lists the monthly farm requirement values in m^3/ha for the different crops without consideration of effective rainfall. The values were computed using the base monthly evapo-transpiration values and crop coefficients listed in the SOGREAH report. The growing season, however, was adjusted to fit that assumed for the Bakel perimeters.

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rice						2310	4750	3515	1510				12085
Cowpeas	1402											542	1944
Maize	797	1809	3496	3462									9564
Sorghum	809	2095	3004	2280									8188

The values include allowances for pre-irrigation, deep percolation, and drainage (for rice). The irrigation efficiency is approximately 65 percent, except for rice on the "faux hollaldes" and "fonde" soils.

1/ Data from USAID Project Planning Team Report.

2/ Etude Hydro-Agricole du Bassin du Fleuve Senegal - Schema de Principe detaille - Casier Pilote de Matam, SOGREAH - Grenoble, France, December 1972.

The requirement for rice grown on the "faux hollaldes" soils was estimated at about 10 greater than for the "hollaldes" soils because of greater loss to percolation. The rice water requirement for the "fonde" soils was assumed as 20 percent greater than for the "hollaldes" soils.

As was assumed in the SOGREAH report, 50 percent of the average monthly rainfall was assumed effective in meeting the farm requirement for rice. The average monthly rainfall in m.m. for Bakel is listed in the following tabulation:

Month								m.m.
Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Total
2	15	78	157	236	152	36	4	680

The following tabulation lists the farm delivery demand in m^3/ha for an average hectare on the perimeter (after consideration of effective rainfall):

Crop	%	Jan	Feb	Mar	Aug	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	m^3/ha. Total
Rice														
Hollaldes	10						192	396	234	75				897
F. Holl.	30						645	1331	806	270				3052
Fonde	60						1429	2946	1823	631				6829
Cowpeas	10	140											54	194
Maize	50	398	905	1748	1731									4782
Sorghum	50	405	1047	1502	1140									4094
Total		943	1952	3250	2871		2266	4673	2863	976			54	19,848

The total annual farm delivery demand is about 2.0 m. with 1.1 m. required for the rice crop during the rainy season.

The following tabulation lists the required water to be pumped from the river in m^3/s during the dry season for assumed developments of 1000, 2000, and 3000 ha.:

m^3/s

Perimeter Size - ha.	Month Dec	Jan	Feb	Mar	Apr
1,000	.02	.35	.81	1.21	1.11
2,000	.04	.70	1.62	2.42	2.22
3,000	.06	1.05	2.43	3.63	3.33

River Flow Availability

The following tabulation lists the frequency of the low flows in m^3/s for the Senegal River at Bakel. The flows are monthly averages for March and April, as computed for the period of record of 1903 to 1974.

m^3/s

Frequency (%)	River Flow March	April
1	11	3
10	26	9
20	32	12
50	43	17

Shortage Frequency

The last irrigation on the perimeters would usually be completed before the middle of April. For a 3000 ha. development, the average rate of water to be pumped from the river is 3.63 m^3/s in March and 3.33 m^3/s in April. A peaking factor of 10 percent to allow for variations in the estimated monthly evapo-transpiration rate gives a maximum pumping demand of about 4.0 m^3/s and 3.7 m^3/s respectively for March and April. Comparing the water requirement with the available river flow, indicates that the only probable shortage would occur in April. The shortage would occur about 2 years out of 100 years. This analysis assumes that there would be no new

depletions upstream of the project and that the Bakel projects would have a "senior" right over downstream users.

SURFACE DRAINAGE

The diked perimeters will be entirely enclosed. When the river is in flood, there will not be any outlet for surface drainage water unless it is pumped over the dikes. The following analysis was made to determine the amount and frequency of drainage water which would have to be pumped.

Rainfall Frequencies

The requirement for drainage is determined by the amount of rainfall which is in excess of the rate lost to evapo-transpiration and deep percolation.

The following tabulation lists the maximum amount of rainfall which occurs at Bakel (usually in August or September) in 1-, 2-, 3-, and 10-day periods at different frequencies:

m.m.

Frequency (%)	1 day	2 days	3 days	10 days
1	170	173	175	
10	108	113	120	216
20	83	94	100	
50	60	65	73	

The frequencies for the 1- to 3-day periods were based on the daily rainfall records at Bakel for the period 1918 through 1972. The frequency for the 10-day period was extrapolated in proportion to similar 1-, 3-, and 10-day values for Matam.

The runoff coefficient of 0.6 was assumed for the perimeters, based on a similar study made for the Matam Perimeter by SOGREAH.[1/] The coefficien

1/ Etude Hydro-Agricole du Bassin du Fleuve Senegal - Schema de Principe detaille - Casier Pilote de Matam, SOGREAH - Grenoble, France, December 1972.

allows for evaporation from the soil, rainfall intercepted by the plants and deep percolation through the soil.

Drainage Within Perimeters

The criteria for the rate for draining the perimeters were also taken from the SOGREAH[1/] study for the Matam perimeter, with some modifications, and consisted of the following:

(1) All the excess rainfall occurring within 10 days would have to be evacuated in 10 days.

(2) The rice crop could tolerate an additional 15 cm of flooding for the 10 days.

(3) Additional flooding of the rice, above 15 cm, can only be allowed for 3 days.

(4) It was assumed that maximum 3-day rainfall occurred at the start of the 10 day period (designed for 10 percent frequency).

The "hollaldes" soils are the heavier low-lying lands which make up about 10 percent of the perimeters. The probable worst assumption would be that all the excess rainfall would accumulate to this 10 percent of the area. A 120 mm rainfall for the 3-day maximum period, with a runoff coefficient of 60 percent, would concentrate the water to a depth of 0.72 meter on 10 percent of the area. The water would have to be pumped out at a rate of 0.0022 m^3/s per ha. of perimeter in order to evacuate all but 0.15 meter of the standing water within 3 days. If the percent of the area in which the drainage water is concentrated were larger, smaller capacity pumps would suffice. A detailed topography map of each diked

1/ Etude Hydro-Agricole du Bassin du Fleuve Senegal - Schema de Principe detaille - Casier Pilote de Matam, SOGREAH - Grenoble, France, December 1972.

perimeter would be necessary to determine the actual area of concentration.

To evacuate all the excess rainfall in the 10-day period (216 mm @ .60 coefficient) would require a drainage capability of 0.0015 m^3/s per ha. Therefore, the drainage capability should be between 0.0015 to 0.0022 m^3/s depending on the perimeter topography.

Tributary Drainage (Interceptor Drains)

The perimeters of Balou and Yafera will have dikes extending from the river bank across the marigots to the edge of the river flood plain. Local drainage from small areas tributary to the river flood plain would flow into the perimeters if not diverted. The tributary drainage area to Balou is about 6 km^2 and to Yafera about 8.4 km^2.

It is proposed to construct an intercepting dike and drainage channel between the tributary drainage area and the perimeter to divert the runoff around the perimeter. To reduce (by one-half) the size of the diverting dike and channel, each perimeter would have two channels starting from the same point, one diverting upstream around the perimeter and the other downstream.

The capacity of the diverting channels was estimated for the maximum daily rainfall occurring with a frequency of 1 in 10 years. The 108 mm of rain was assumed to all occur in 6 hours with 30 percent in one hour. A runoff coefficient of 0.6 was used. The general slope of the tributary basins for Yafera is about 10 m. in 2 km, and about 10 m. in 1 km. for Balou. Assuming a triangular runoff-curve and concentration times of

1.1 hours and 1.5 hours, the peak flow rates for Balou and Yafera would be about 10 m^3/s and 12 m^3/s respectively. The above estimates are for one-half of each of the tributary drainage areas.

The Mouderi-Diawara perimeter, which is planned for Phase II and is not a part of this study, would have a tributary drainage of about 55 km^2. This perimeter will require a more detailed study to determine an economical solution to its tributary drainage problem.