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( C. I. E. H. )

INTER-AFRICAN COMMITTEE FOR HYDROLOGIC STUDIES

( I. C. H. S. )

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# ESTIMATION OF DISCHARGES OF TEN YEAR FLOODS FOR CATCHMENTS WITH A SURFACE AREA LESS THAN 200 SQ. KM. IN WEST AFRICA

J. RODIER
Engineer in Chief, E. D. F.
Head of the Hydrologic Service
of ORSTOM

C. AUVRAY
Director of Research
for ORSTOM

Translation by
W. E. HERRIDGE
Chief Hydrological Engineer
Public Works Department - Ghana

JULY, 1965

OFFICE DE LA RECHERCHE SCIENTIFIQUE ET TECHNIQUE OUTRE-MER

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# ESTIMATION OF DISCHARGES OF TEN YEAR FLOODS FOR CATCHMENTS WITH A SURFACE AREA LESS THAN 200 SQ. KM. IN WEST AFRICA

At the end of 1961, M. Claude AUVRAY, Director of Research for ORSTOM, made available to the Inter-African Committee for Hydrologic Studies, presented at the MONROVIA Conference and at the first meeting of I.C.H.S. at COTONOU a paper entitled : "Estimation of discharges of 10 yearfloods in tropical regimes".

This paper, forming the spearhead of our knowledge in this domain was made available to the top planners, simply allowing them to obtain correct estimates for 10 year frequencies.

Since then the development of studies in experimental catchments and the systematic study of storms in West Africa now permit the drawing-up of more precise and dependable rules for the estimation of 10 year floods in small catchments.

For this reason the I.C.H.S. decided to proceed with a remodelling of that first paper, starting from its data, without waiting on the general study of the behaviour of the experimental and representative basins of ORSTOM, which will take several years.

To this end an agreement was concluded on 19 th December, 1963, between the Minister - Delegate for Co-operation and the Director-General of ORSTOM, by which the latter organization was engaged to effect the following operation :

1. Bringing up-to-date, remodelling and confirming the paper of I.C.H.S. of December 1961, relating to the estimation of the discharges of 10 year floods in tropical regimes, as concerning catchments of less than 200 sq. kms. area.
2. The method of graphs will be maintained and if possible improved particularly (when rains) are concerned. It must be determined up to what value of annual rainfall this principle of estimation is applicable.
3. The study of the dispersion of the results in relation to the actual values from the known catchments will eventually lead to an investigation into the degree of precision of the proposed graphs.

4. An attempt must be made to define properly the natural coefficients of run-off by concrete examples.

The present paper takes into account that study. It is well understood that, in that paper the term "West Africa" must be taken in its widest sense ; that is, Africa West of the Congo and south of the Sahara, covering to a great extent the tropical regimes.

## General Conditions for the Formation of Floods in West Africa

The phenomenon of the formation (build up) of a flood, shown by the line of a hydrograph (curve of discharge as a function of time), depends on several factors conditional on the regime.

Firstly, the factors constant in time :

- topography of catchment (Area, slope configuration)
- nature of the soil.

Altitude, a factor essential in temperate regions often appears to be secondary in a tropical regime.

Next, the factors variable in quantity from one year to another, and from one time of year to another :

- Rainfall (amount, intensity, frequency)
- State of saturation of the catchment
- Vegetal cover
- Evapotranspiration
- Influence of underground aquifers,
- Flooding in the major beds (strata) or in interior sub catchments.

It is easy to see that these factors are physically interlinked, following complex rules.

Accordingly they are not independent variables. Contrariwise their actual effect on the amount of runoff may at different times work in opposite directions.

If one tries to interpret statistically the factor "rainfall" alone, over a period of several decades, one finds that it is generally possible to apply a simple mathematical law covering frequencies of the order of 1/20 for 24 hour precipitations, 1/50 or perhaps 1/100 for annual precipitations.

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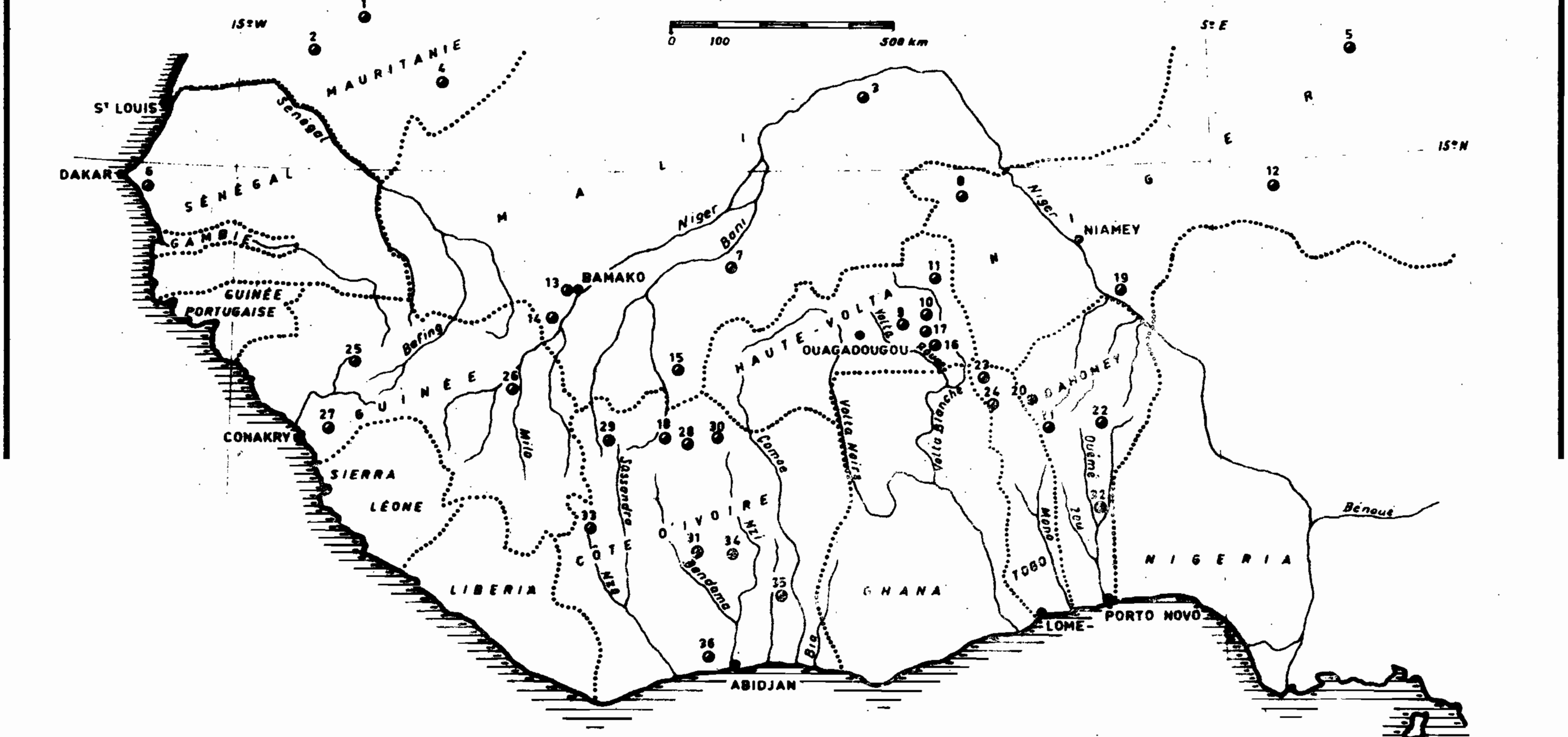
# _ AFRIQUE DE L'OUEST _

## Situation des bassins représentatifs et expérimentaux




1 _ OUED SELOUMBO { OUED MOKTAR / OUED ALI
2 _ DIONABA
3 _ TIN ADJAR
4 _ AFFOLÉ
5 _ IN TIZIOUEN
6 _ SEBIKOTANE
7 _ KOUMBAKA
8 _ CAGARA
9 _ ZAGTOULI
10 _ MORO NABA
11 _ BOULSA
12 _ HAMZA _ ALOKOTO
13 _ DOUNFING
14 _ DJITIKO
15 _ FARAKO
16 _ SELOGEN
17 _ BOULBI
18 _ BAGOE
19 _ KOULOU
20 _ BOUKOMBE
21 _ TERO (DJOUGOU)
22 _ TIAPALOU WENOU GORI BOUNIEROU
23 _ NADJOUDI
24 _ NAPABOUR _ KOUMFAB
25 _ TIMBIS
26 _ KANDALA
27 _ MAYONKOURÉ
28 _ SOLOMOUGOU _ KORHOGO
29 _ BAOULÉ (ODIENNÉ)
30 _ FERKESSEDOUGOU
31 _ KAN (BOUAKÉ)
32 _ LHOTO
33 _ NION _ GBOA _ LOUÉ
34 _ IFOU
35 _ BAFO _ SITOU _ MANSO
36 _ AGBEBY

If one considers the same test applied to the total amounts of maximum flood discharge one ascertains first of all that only relatively important stream, for example those for catchments greater than 10,000 sq.kms. privide flows of a sufficient duration to permit direct statistical studies.

For the average streams with favourable conditions a ten or fifteen years period of annual records allows correlations to be made, capable of leading to the evaluation of discharges of floods of relatively low frequency.

Finally for streams of catchments less than 200 sq. kms. there exists no series of records permitting direct statistical studies. The only means of determining the characteristics of floods of rare frequencies is by studying small experimental catchments for several years, the planner following through the rainfall to run-off cycle, and building up the floods of rare frequency, starting from their principal cause in small catchments storms of exceptional character. By this term we mean not only sudden storms of exceptional deposition but equally storms having deposition most spread out (in time), resulting in exceptional conditions of saturation.

## BASIS OF THE STUDY

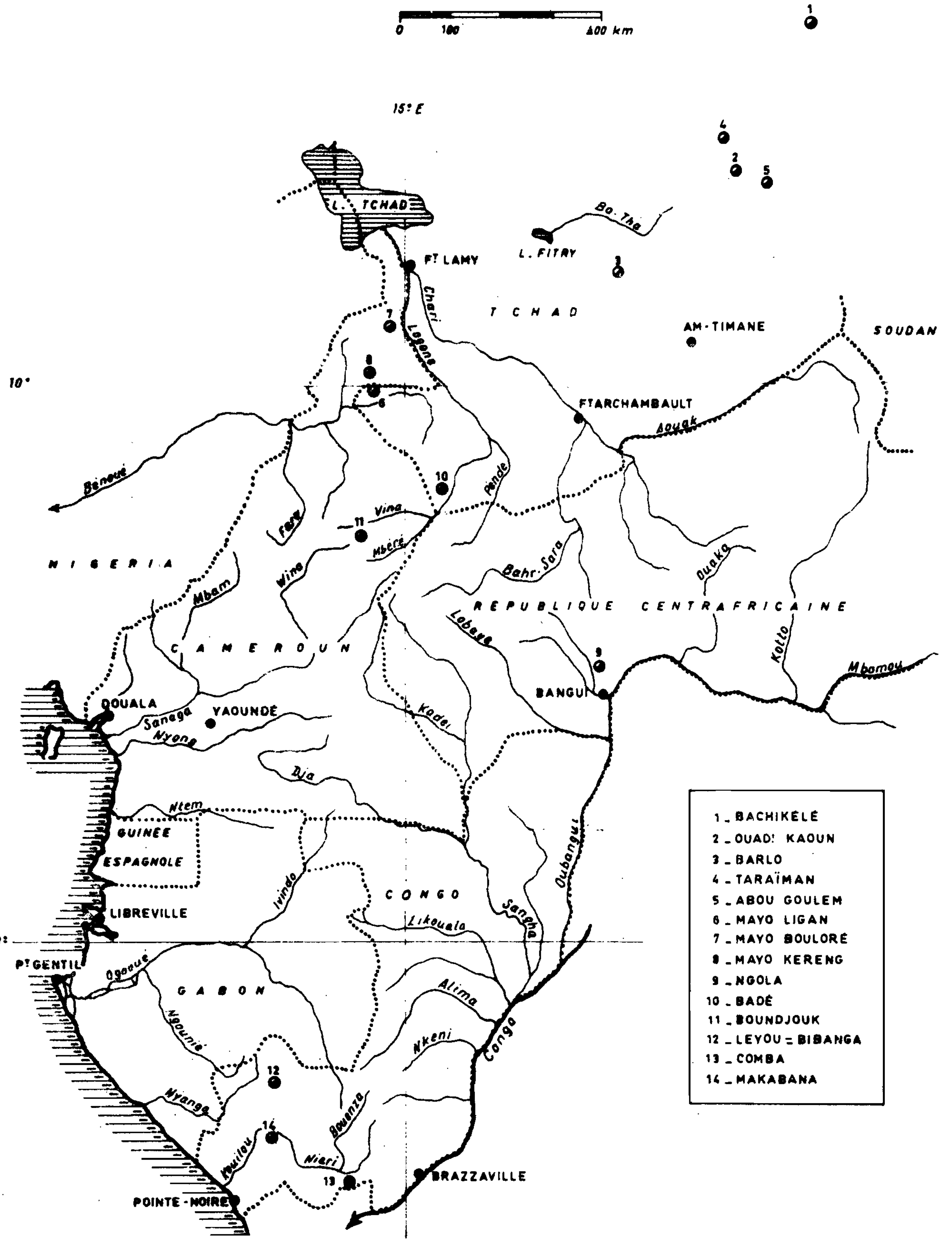
The obtaining of data for the estimation of exceptional floods has been one of the major concerns of the Hydrologic Service of ORSTOM since 1950. The many failures of bridges and dams occurring between 1950 and 1960 , as well as the concern of the Technical Services to supply water by surface reservoirs have all tended to help ORSTOM to the utmost in this course.

In this manner from 1955 the Federal Hydraulic Service has entrusted to ORSTOM the programme of setting up ten experimental catchments having in view the collection of essential data for the estimation of exceptional floods.

In total, 90 representative and experimental catchments have been set up since the end of 1964 for the French speaking African countries. Some have been concerned solely with the study of heavy floods, but with others the main object has been the determination of other hydrologic characteristics; in all these catchments it has to be seen that the management and measuring programme permits the study of the heaviest discharges : in particular the location of gauging stations had to be such that the rating curves had a simple form up to maximum values, and the hydrologists were asked to carry out measurements up to these maximum values.

# _AFRIQUE CENTRALE_

## Situation des bassins représentatifs et expérimentaux

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Some of the basins have been under observation for too short a period to allow methodic interpretation ; for others it has not yet been possible to proceed with the analysis ; finally, some are of such a very peculiar (individual) character that they are of no help whatever in a general interpretation.

Eventually about 60 catchments will be able to actually provide usuable data for a study of runoff.

A general build up is foreseen for the exploitation of this data, it will extend over several years and will require in the field, important extension work, concerning most particularly geomorphology and pedology. But it has been possible to effect in a few months a preliminary build-up, leading to more precise and dependable data than that of 1961.

On the other hand, the 10 year depth of daily precipitation has been the object of systematic study in Senegal, Mali, Niger, Upper Volta, Tchad, and partial study in the Ivory Coast, Dahomey and other neighbouring countries.

A second basis for the study of exceptional floods has thereby been obtained.

<u>Principles of Determination of exceptional floods in small catchments</u>

If the flood depended only on rainfall, the 10 year flood would correspond exactly to the storm of 10 year intensity. In actual occurrence, the phenomena are very complex.

Suppose there is but one secondary factor : the soil saturation at the start of the storm. A 10 year storm can give a flood having a discharge greater or less than the 10 year flood if the saturation of the soil is abnormally high or abnormally low. On the contrary a storm of intensity less than the 10 year storm can give a 10 year flood if the soil is particularly saturated.

For simplicity we have in our calculations assumed that the 10 year flood (or annual flood) has been caused by a 10 year storm (or annual storm) having the characteristics of space and time distribution corresponding to the average conditions for heavy storms and coinciding with the conditions of soil saturation and vegetal cover corresponding equally to these average situations. The operation is made more chancy since factors others than intensity of deposition, above all degree of soil saturation play a very important role.

Fortunately in that part of Africa which concerns us, it does not occur in the zones giving the greatest runoff that the most serious errors are where the floods will be most particularly dangerous. It is equally fortunate that, generally, in the case of a tornado, the hyetograph has a form similar for different storms, for 25 square kms., the storm fairly well covering the whole basin, whereby the importance of two factors is reduced : spatial and time distribution of precipitation.

The storm being known, the corresponding flood must be determined. For catchments of less than 50 sq. kms. one can generally use the unit hydrograph method. The essential principles of this method are as follows : for a storm of equal spatial coverage of which the greatest duration and average intensity is less than a given limit (in practice less than the time of rise of the flood) all run-off hydrographs have the same form : they are refined curves.

A storm having a duration greter than the limiting duration can perhaps be split up into two or more storms of duration less than the limiting duration and the resulting hydrographs can be joined with a lag in time equal to the lag between the centres of gravity of the component storms. For each catchment there is therefore a corresponding type hydrograph which is called "diagram of distribution", and which can perhaps be practically defined by a small number of characteristics : the area falling between this diagram and the axis of abscissae, the shape of the diagram being roughly triangular : base time ($t_b$) or duration of run-off, and a third factor which we shall discuss later on, the degree of sharpness of its peak.

The first characteristic, area described by the hydrograph is equal to :

$$\int_0^{tb} Q.dt.$$

It can be obtained by starting from the total volume of precipitation Vp over the catchment, and multiplying Vp by the coefficient of run-off $K_r$.

In certain cases, particularly for permeable soils, various different forms of the standard method for measuring the infiltration capacity have been used : the loss by infiltration in mm/hr. is deducted from the intensity of the storm in mm/hr on the storm diagram, and the quantity of runoff is then determined. But it is necessary always to know the losses by infiltration for various times of the year, for different conditions of soil saturation, and for various storm durations. That method, more rational but much more difficult has been but little used, but it will perhaps come back into greater usage. For the time being it is of great value in particular cases.

But in the majority of cases the coefficient of run-off is used. This supposes, it is well known, that the 10 year value of Vp has to be estimated, that is the 10 year value of depth of precipitation spread evenly over the catchment : we will return to this later.

The second characteristic, base time, may be determined by systematic study of the distribution diagrams.

The third may be defined by a coefficient

$$K = \frac{Q \max \gamma}{M}$$

where $Q\max_\gamma$ = Peak discharge for the 10 year flood

M = Mean discharge calculated for the 10 year flood during a time equal to the base time

K = an overall function of geomorphological and vegetal coverage factors : very fortunately it varies little for any given type of catchment.

In these conditions the determination of the 10 year flood may be effected as follows :

1. The total precipitation of the 10 year storm at a point is measured
2. The mean depth of precipitation over the catchment with a 10 year frequency is determined by multiplying the point total precipitation by a coefficient of reduction or a coefficient of area reduction. : Thus Vp is obtained.
3. Knowledge of the catchment characteristics enables $K_R$ corresponding to the 10 year flood to be determined.
4. The catchment characteristics allow the base time to be determined, which makes possible the evaluation of M.
5. Having chosen the value of K ($K = \frac{Q \max}{M}$) corresponding to the catchment, Q max is determined (M being known)
6. Q maxr represents only the immediate run-off, the base flow is added to obtain the total maximum run-off.

Apart from surface run-off there is a sub-surface drainage which theoretically corresponds to drainage parallel to the ground surface and in the uppermost layers of soil, (in actual fact, the nature of such drainage is generally much more complex). In the following paragraphs the surface run-off and subsurface drainage are grouped together, this being in theory not very correct, but in practice does not introduce any appreciable errors in calculations. $V_R$, volume of run-off therefore includes subsurface drainage.

From the foregoing it is seen that determination of the 10 year flood requires knowledge of the following data.

1. The 10 year storm at a fixed point
2. The area coefficient (for the catchment)
3. The run-off coefficient Vr.
4. The coefficient $K = \frac{Q\ max\ r}{M}$

With regard to base flow or underground water flow, it would not be prudent to give general rules for its estimation. One must necessarily very often neglect it when the catchment is not too permeable, or when the annual rainfall is less than 800 mm.

Estimation of the amount of the 10 year storm at a point.

To the north of an oblique line crossing from latitude 8° to 9° in the Ivory Coast to latitude 4° in Central African Republic, the heavier storms are generally tornados, tempestuous storms presenting a main body of short duration and high intensity, followed by a drawn out tail of less intensity, and sometimes preceeded by a preliminary shower. It may happen that the storm will be double or that the main body (of the storm) is in two parts, but in general at a certain distance nearby the storm is of simple form. It may be equally considered that in most routine cases there is only one storm in 24 hours, of such a nature that the statistical study of tornados establishes itself as the study of daily (24 hour) storms.

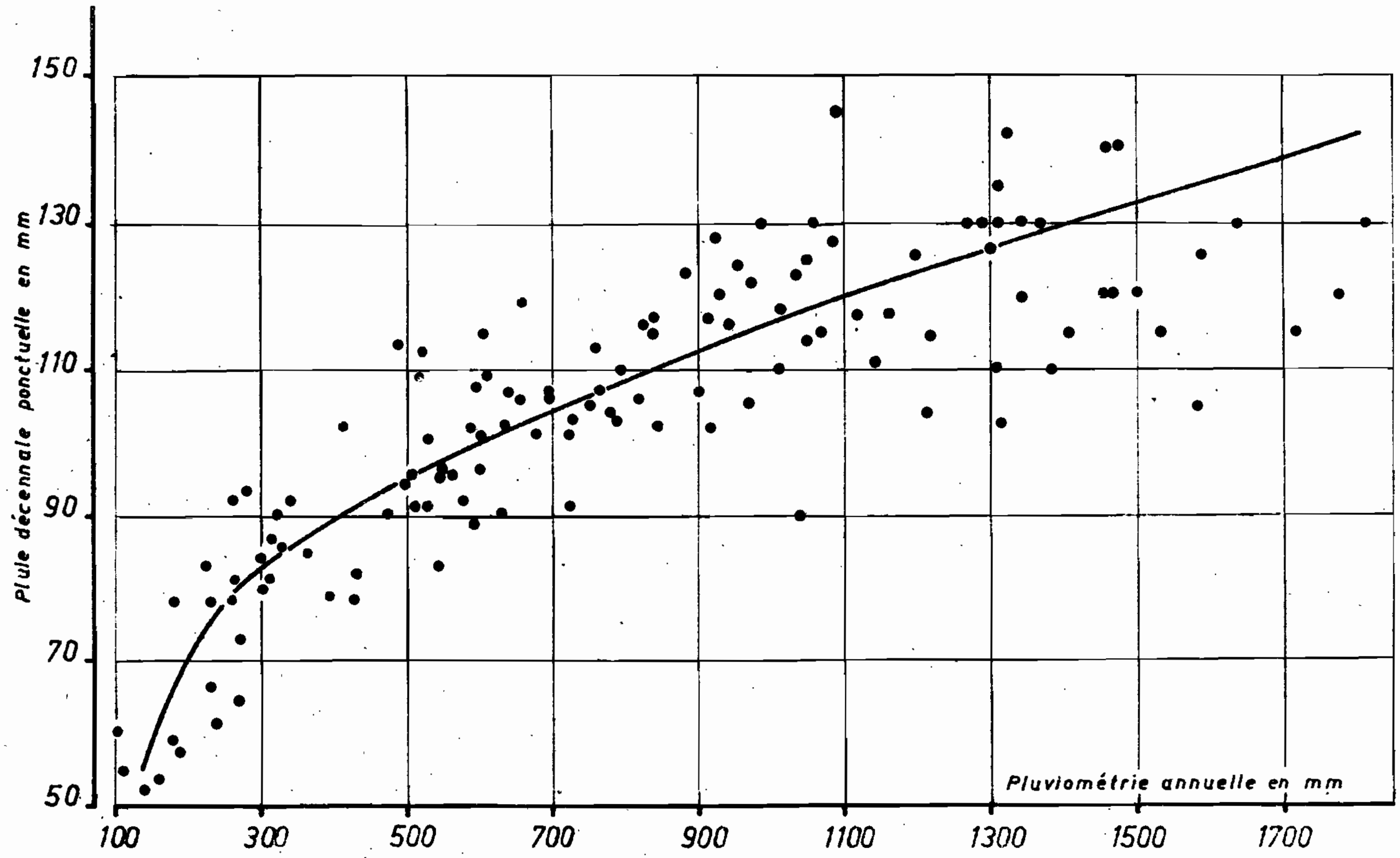
Individual tornados cover varying areas, but most often the area affected by the heaviest or near heaviest precipitation is of the order of 20 to 100 square kilometres.

Over a narrow belt immediately north of the oblique line already defined, the 10 year storm will be either a tornado of the same type **or** a storm of continuous character over several hours with maximum intensities not very much in excess of 50 to 60 mm/hr.

But, generally it is the tornadic type storm which leads to the highest instantaneous run-off (but not the greatest volume).

The storm of continuous character dominates in equatorial regions, that is to say over the southern part of the Ivory Coast, the extreme south of Togoland and Dahomey, the south of Cameroun, and the north part of Congo.

# Précipitations décennales de 24h en fonction de la hauteur des précipitations moyennes annuelles




Gr_1

The Coastal belt between St. Louis (Senegal) and Pointe Noire (Gabcn) has, over a breadth of 30 kilometres, storms of exceptionally long duration, which reach between 200 and 300 mm deposition for the 10 year frequency.

The amounts of 10 year precipitations have been the subject of systematic studies over the greater part of West Africa ; in the east, regional studies have led to the finding for similar climates, of very similar precipitations.

The annual amount of precipitation is related quite closely to the type of regime. If the equatorial regions and the coastal belt are set apart, the 10 yearly recurring daily amount of precipitation is an approximate function of the annuel amount of precipitation, but varies very little where annual precipitation amounts are more than 300 mm.

In the graph herewith (Graph 1), the 10 yearly daily precipitations are plotted as a function of annual precipitations : a certain amount of dispersion due to the peculiarities of exposure are noted ; particular areas are exposed to storms or, contrariwise protected from them.

This graph can be used for the determination of the 10 year point precipitation. The 10 year precipitation maps already established for Senegal, Mauritania, Mali, Upper Volta, Niger, Chad, and soon for the Ivory Coast and Dahomey can also be referred to. Certain regional studies by ORSTOM also give values of 10 year precipitations for particular areas.

The maps are established for general conditions. It is certain that a particular side of a hill exposed to storms will receive greater 10 year precipitations than those shown on the map, a sheltered side will receive lesser precipitations.

<u>Area reduction coefficient</u>

At first sight it seems that if P is the 10 year point precipitation, the average precipitation $\bar{P}$ over a surface area S is smaller than P and decreases proportionately as S increases.

The relationship $\frac{\bar{P}}{P}$ being called the "area reduction coefficient" experimental proof has to be looked for. But the methods used until now have not been correct :

the relationship $\frac{\bar{P}}{P_M}$

has in actuality been determined, where – $P_M$ is the maximum precipitation observed over the catchment wherever the point may be where $P_M$ is the outcome, and not at a fixed point in the catchment, which would be more correct.

In this way it will be found that the coefficient of area reduction is about 0.85 for 25 sq. kms, for example.

If a catchment of 500 to 1000 sq. kms. is considered, as an average over 10 years perhaps 3 or 5-10 year point storms are observed at different points, which facilitates confirmation that the average 10 year precipitation over the catchment corresponds to a storm of which the maximum point value (depth of precipitation) over the catchment area S is greater than the 10 year point precipitation.

A theorical study completed by a statistical summary study has shown that the true coefficient of area reduction was clearly greater than was believed. The following actual values of the coefficient of area reduction are given :

| | |
|---|---|
| $0 < S < 25$ sq. km | 1 |
| $25 < S < 50$ " | 0,95 |
| $50 < S < 100$ " | 0,90 |
| $100 < S < 150$ " | 0,85 |
| $150 < S < 200$ " | 0,80 |

This is valid for the 10 year flood. For the annual flood it cannot be ruled out that the Coefficient of area reduction can be a little higher than 1 (unity) for 5 $km^2 < S < 15$ sq. km.

## Classification of Catchments by their characteristics

Except for true mountain catchments, quite rare in the regions which concern us, 10 year precipitations are homogeneous, and as a first approximation not dependent on the catchment, particularly on its topography.

On the contrary the coefficient of runoff, the base time and the coefficient K depend on the physical characteristics of the catchment and in the first place on the vegetal cover, the slope and the soil permeability. (The nature of the drainage network would not come into play, being a secondary factor).

Before continuing to study the data for the determination of the 10 year flood it is therefore important to prepare a classification of catchments.

Coefficient of run-off and distribution pattern vary from one catchment to another in the same climatic region, being governed by several factors of which the most important are : the nature of the soil, the geo-morphological characteristics and vegetal cover of the catchment. It would be ideal to define for any given catchment all these factors by a single numerical index.

At this stage of our study this is not possible. We must therefore be content with defining a certain number of classes of soil permeability, of slope and of vegetal cover, and to classify the catchments in these various categories.

The permeability of the soil of a catchment is the most important characteristic of a soil as regards run-off ; it is difficult to enumerate for the following reasons : natural catchment are nearly always more or less heterogeneous. If a small catchment is homogeneous, there is the risk that it is not representative. Besides, what counts is not the permeability measured in the laborary on a more or less disturbed sample, it is the permeability in place, under the conditions at the start of the storm. The most simple method for classifying permeabilities consists of using curves which for a catchment, define the effect of run-off as a function of the amount of precipitation and the index of saturation. For this a very simple form has been taken - the period of time in days from the preceding rain, greater than a given limit, 5 mm. for example.

Attached herewith is a series of curves corresponding to several catchments. The flatter the curve, the more impermeable the catchment. The permeability can also be defined by the position of the curves : for example the limiting precipitation for run-off after 3 days without rain. It is to be noted that this classification takes into account the combined effect of permeability and absorbtion by the vegetal cover, which is of not inconvenient for the study of the runoff. It would be preferable to replace the term "permeability" by that of "overall absorbtion capacity of the catchment".

In this manner 5 categories are defined :

P 1. Very impermeable catchments : catchments wholly rock or clay

P 2. Impermeable catchments with some permeable zones of small extent or homogeneous catchments almost impermeable.

P 3. Catchments fairly impermeable, having permeable zones of considerable extent, or homogeneous catchments not very permeable.

P 4. Fairly permeable catchments such as are found in zones of decomposed granite with considerable sandy areas.

P 5. Permeable catchments : gravels or very fissued lateritic cover.

Within any one category the soil may vary in permeability. By the same reasoning it is somewhat difficult to classify some catchments in a definite category. Resulting from this there is a certain "spreading" in our results. Points which are particularly deviating will be found for very heterogeneous catchments, for example those with parts being of impermeable clay and parts with highly weathered laterite crusts.

As it is no longer possible to lay down a single geomorphological index useful for run-off, catchments are at present classified by their cross-slopes and their longitudinal slopes, in 6 categories characterized by an index letter R.

R 1. with very flat slopes, less than 0.1 to 0.2 %

R 2. with flat slopes less than 0.5 % : these are flat country catchments

R 3. with moderate slopes between 0.5 and 1 % : these are for the land intermediate between flat country and rolling country

R 4. with rather steep slopes : longitudinal slopes between 1.0 % and 2.0 %, cross slopes greater than 2 %. Rolling country.

R 5. with steep alopes : longitudinal slopes between 2% and 5 %, cross slopes between 8 % and 20 %. Hilly regions.

R.6. with very steep slopes : longitudinal slopes greater than 5 %, cross slopes greater than 20 %. Mountainous regions.

To determine the slopes simple rules are set out, usable when only outline maps are available. To determine the longitudinal slope the longitudinal profile is taken following the principal water course of the catchment frot the watershed to the point on the river where works (bridge or outfall, etc ..) are to be constructed, this point forming the downstream limit of the catchment. On the longitudinal profile the upper 20 % and lower 20 % extremities are eliminated : the average longitudinal slope is then calculated over the 60 % of the total length of the profile. A similar process is used for the cross slope, considering half profiles across from the bed of the water course (at the top of the bank) to the edge of the catchment, eliminating the upper 20 % and lower 20 %. If a catchment has a flat longitudinal slope and a very steep cross slope (this sometimes happens xith a mountain catchment), the cross slope must be taken into consideration for classifying the catchment in a given R category.

As is well known a moderately compact catchment and an average drainage network are assumed. Very elongated catchments would produce abnormally low run-offs, for example.

Categories of vegetal cover have been judiciously related to climatic conditions.

These vary largely since the region under study covers from the south border of the Sahara to the heart of the equatorial forest ; it has been necessary to split up the catchments into several large categories corresponding to the overall classes of hydrological regimes.

- Sahelien and sub-desert catchments
- Tropical and tropical transition catchments
- Equatorial rainforest catchments.

Avantageously these categories correspond to a type well determined by vegetal cover, as has already been seen, such that within each category it may be said that the type of vegetal cover is representative of the factors rather closely related to run-off. This notwithstanding, from the south of the Sahalien zone and in the tropical zone, the vegetal cover only slightly retards run-off at the start of the rainy season, and retards it a lot at the end. For the category I, it is therefore of interest to study the coefficient of retardation, for example for the first part of the rainy season (D.S.P.) where the middle sahelien catchments are concerned and for category II to consider the data at the end of the rainy season (F.S.P.).

- For semi desert catchments the amount of the 10 year storm varies between 60 and 85 mm
- For sahelien catchments between 85 and 110 mm
- For tropical and tropical transition catchments also for equatorial savanah catchments between 110 and 130 mm
- For forest catchments between between 120 and 150 mm.

It is not necessary in practice to take into account altitude up to 1500 meters, that is not in all cases.

Study of Coefficient of Runoff

For a storm of given amount this factor varies with the permeability of the soil, the vegetal cover and the nature of the drainage network. For a homogeneous region it should vary little with the area of the catchment ; however in tropical Africa it decreases somewhat as the area increases. This takes into account theaerial coverage of storms and the losses to the ground. It ofen increases with the amount and intensity of the storm.

From effective studies of the same soils and of analogous conditions of relief, but with storms heavier and more prolonged than in Africa, the maximum limit of the run-off coefficient is in the neighbourhood of 85 - 90 %.

In certain earlier studies by ORSTOM the coefficient Kru was used, equal to the relation of the volume of run-off to the volume of utilizable precipitation,that is to say to the volume corresponding only to the most intense part of storms, the weaker tail ends (of storms) being ignored. But this concerned only a small number of cases and for homogenity of results wa have here considered the coefficient Kr ;the volume of precipitation concerned is equal to the total volume of the storm responsible for the flood.

The three following cases can be identified

a) Sahelien and sub desert regimes
(principally between the 150 and 750 - 800 mm annuel isohyetals)

Three variables have been considered : the area of the catchment, the slope, and the permeability. These last two variables cannot be represented numerically as we have seen earlier ; we must be content simply to separate the catchments into different classes. That will suffice for the present stage of our studies.

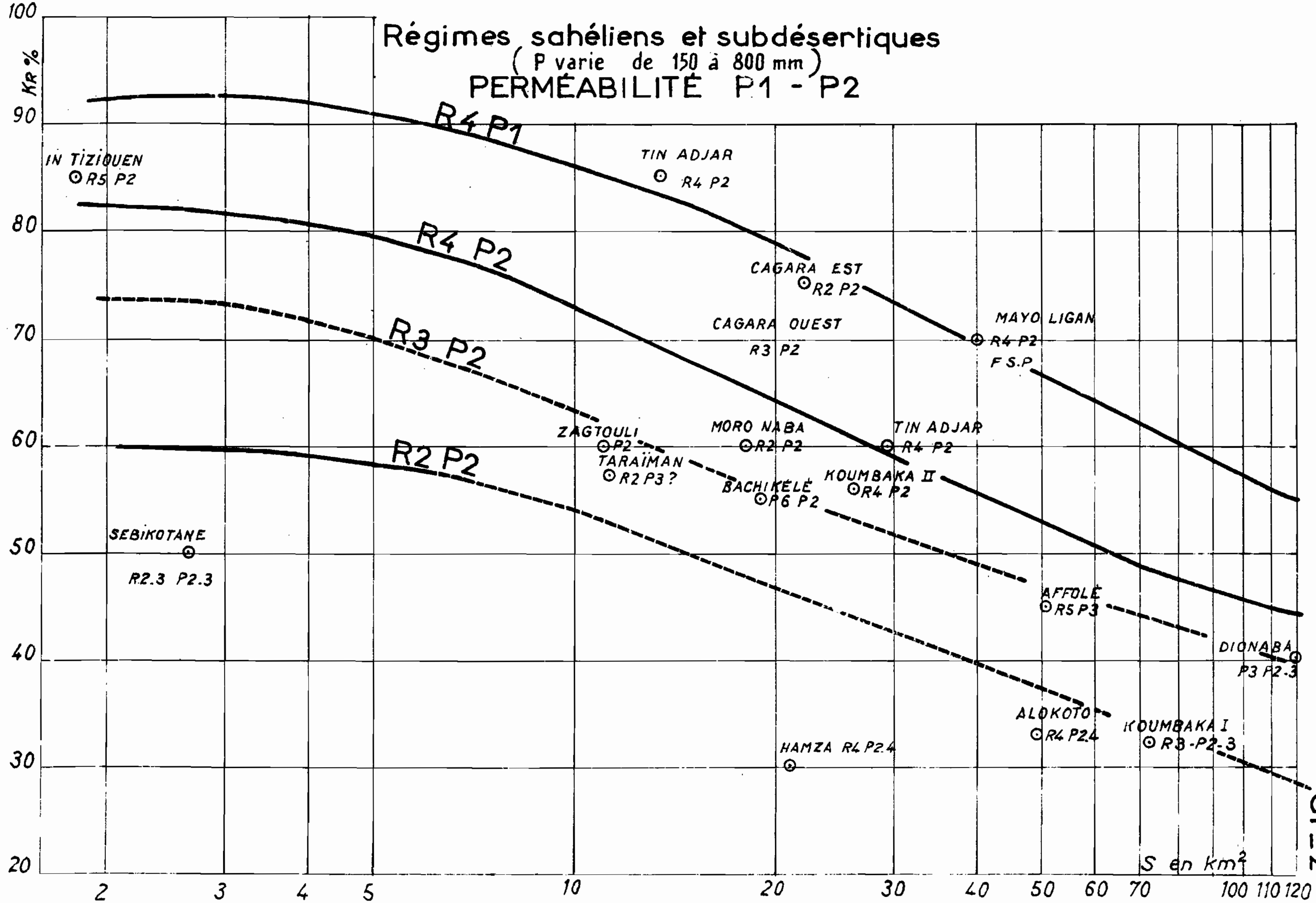
Coefficients of run-off have been drawn as ordinates and the catchment areas as logarithmic abscissae on the various graphs. The choice of the type of co-ordinates has been dictated by the need not to have representative points too close for the very small catchments, whilst in fact it tends to make the variation curves less simple than one would have obtained with cartesian co-ordinates.

Permeability being the most important factor, a series of graphs has been established, each corresponding not to a single permeability, but two permeabilities because it is not always certain that all catchments will be well covered by the class in which they are typed.

# COEFFICIENT DE RUISSELLEMENT

## Régimes sahéliens et subdésertiques
( P varie de 150 à 800 mm )

## PERMÉABILITÉ P1 - P2




F.S.P. : Fin saison des pluies

Gr_2

Graph 2 was established for P1 and P2 - impermeable soils ; being given the range we do not have to look at the lines of all the curves corresponding to various combinations of R and P. We have only to look for an approximate line corresponding to the extreme situations met with in practice : R 4 P 1 which corresponds to the highest coefficients of that category and R2 P2 which corresponds to the lowest observed values. The curve R 4 P 2 has been delineated, corresponding to the catchments which are most frequently encountered.

Curves R4 P1 and R4 P2 being taken, for S = 2 km2, the highest values of the coefficient of run-off : 85 - 90 % are used. They show a steep falling off from 10 to 40 sq. km ; it is this which points to the degradation of the drainage network, well known in the Sahelien regimes where evaporation plays a very great part ; for catchments a little larger, part of the area escapes the storm. But approaching 100 sq. kms., the coefficient of run-off again flattens out. The relatively flat slope of the curve R2 P2 must be noted. Every catchment does not give results for the slope R1, but it is known that from 2 or 3 sq. kms., the drainage is practically nil, water stagnating in swamps. But in such a case, once a single drainage route has been established on slope R 2, the coefficient of run-off becomes fairly high, as has been shown with slopes a little steeper, in the catchment CAGARA -East, for example. A large proportion of representative points clearly deviate from the curves, but the reasons are perfectly well known and in certain cases a correction coefficient can also be determined. The following cases are cited :

1. Dryest sub desert catchments (IN TIZIOUEN, BACHIKELE) have 10 year floods correspondingto storms of only about 50 mm., whilst all other catchments receive a minimum of 85 mm, their coefficients of run-off being very low

2. Certain catchments near the 800 mm. isohyetal on the contrary are on the borders of the tropical and sahelien regimes : this is the case for BARLO, MORO NABA, NADJOUNDI, MAYO LIGAN, for example ; they can supply useful indications, but must be used with caution. In P2 terrain for example, provisional results are a little too high for the large catchments (BOULSA, MAYO LIGAN), too low for the very small ones.

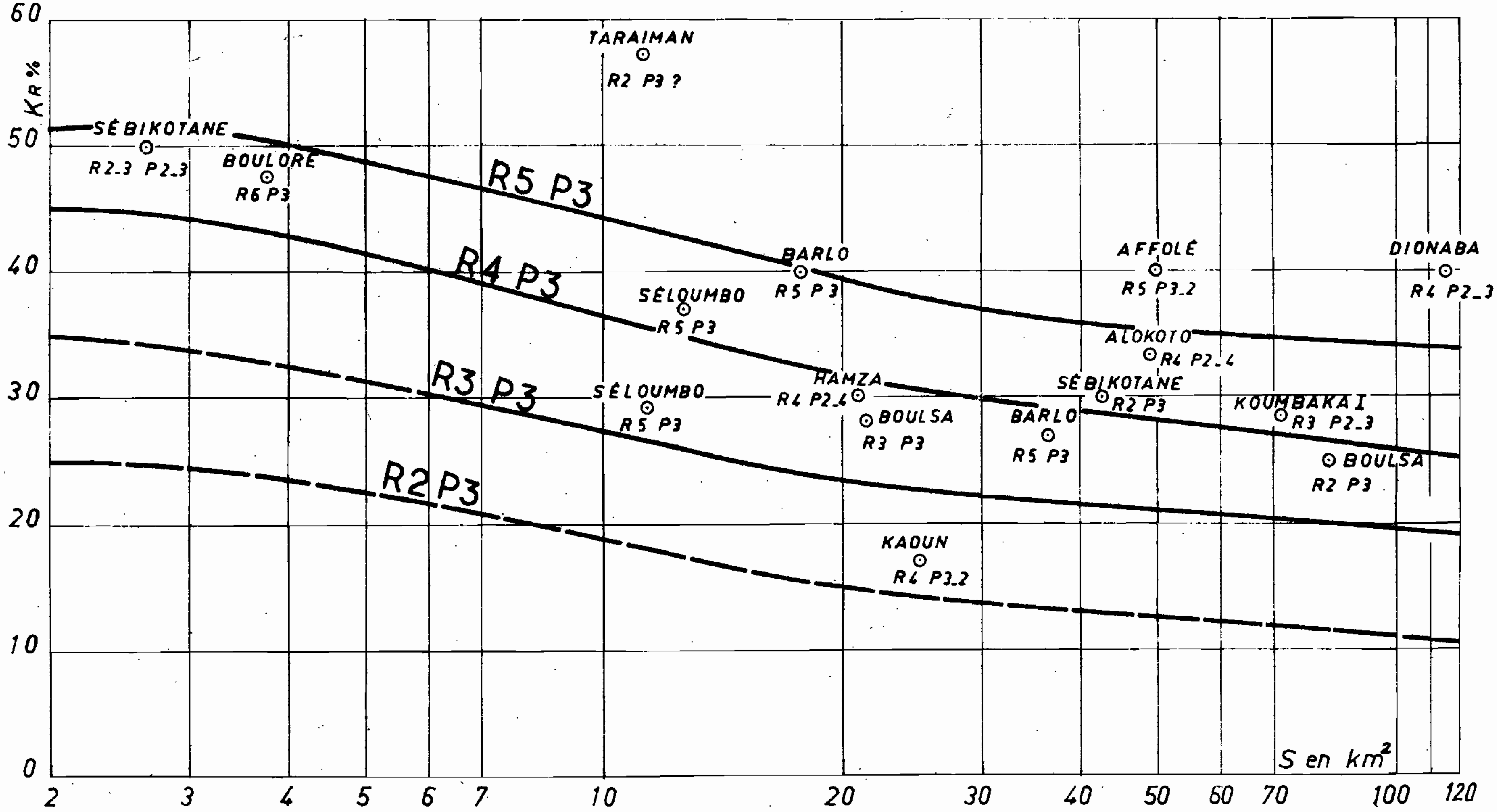
3. The three catchments of HAMZA, ALOKOTO and KOUMABKA 1 are very heterogeneous. They all have lateritic crusts more or less broken up, corresponding to P4 ; the remaining part of the surface is of type P2 or P1. In fact only part of the catchment has intense run-off characteristics ; if all the catchment were of P 2 classification, it would be necessary to multiply the coefficient of run-off by 2 or 3 for HAMZA and increase it considerably for ALOKOTO and KOUMBAKA 1.

4. The calculations for TIN ADJAR minor and CAGARA east are not very precise, the boundaries of the catchments being difficult to determine.

# COEFFICIENT DE RUISSELLEMENT

## Régimes sahéliens et subdésertiques
(P varie de 150 à 800 mm.)

## PERMÉABILITÉ P3




Gr_3

5. The catchment of TARAIMAN is formed by a range of classification, in P3 at the start of the rainy season and mostly in P 2 at the end, but where the dividing line stands is a question as yet unanswered.

We see that these curves would be more reliable if our indice R and P could be more accurate and equally more dependable, and if some of our hydrologists would not have had to arbitrarily overestimate some coefficients of run-off, above all for the impermeable catchments which they have hesitated to classify correctly. But, among these figuratively represented points we recall some corresponding to 10 year floods effectively observed (the case of KOUMBAKA II for example) and others extrapolated to a small degree.

Graph 3 is for permeability P3 ; dispersion is still high, but the curves are clearly lower than those of graph 2. It is well known that very high coefficients of run-off will not be found as for permeability P1 and P2 areas of less than 20 sq. km. This is best evidenced by the two catchments of SEHOUMBO. These two catchments are equally interesting from another viewpoint ; one of them is manifestly more permeable than the other, the proportion of fractured sandstone in it being very high, but for the time being the two cannot be classified other than in P3. Here is seen the precision which would be obtained by a more precise classification of permeabilities. The two points for SEHOUMBO need to be moved slightly higher. In effect they correspond to the semi-desert regime and have a 10 year storm of only 82 mm., a little lower than the lower limit of the Sahelien regime. The graphical point for TARAIMAN is in this case changed in the opposite direction : in a heavy rainy season, its permeability approaches that of P2.

For l'Ouadi KAOUN (Sub-Catchment) the area cannot be defined precisely and the determination of the coefficient of run-off has been very provisional.

The curve P2 P3 as given is purely indicative. There is no practical data to trace it.

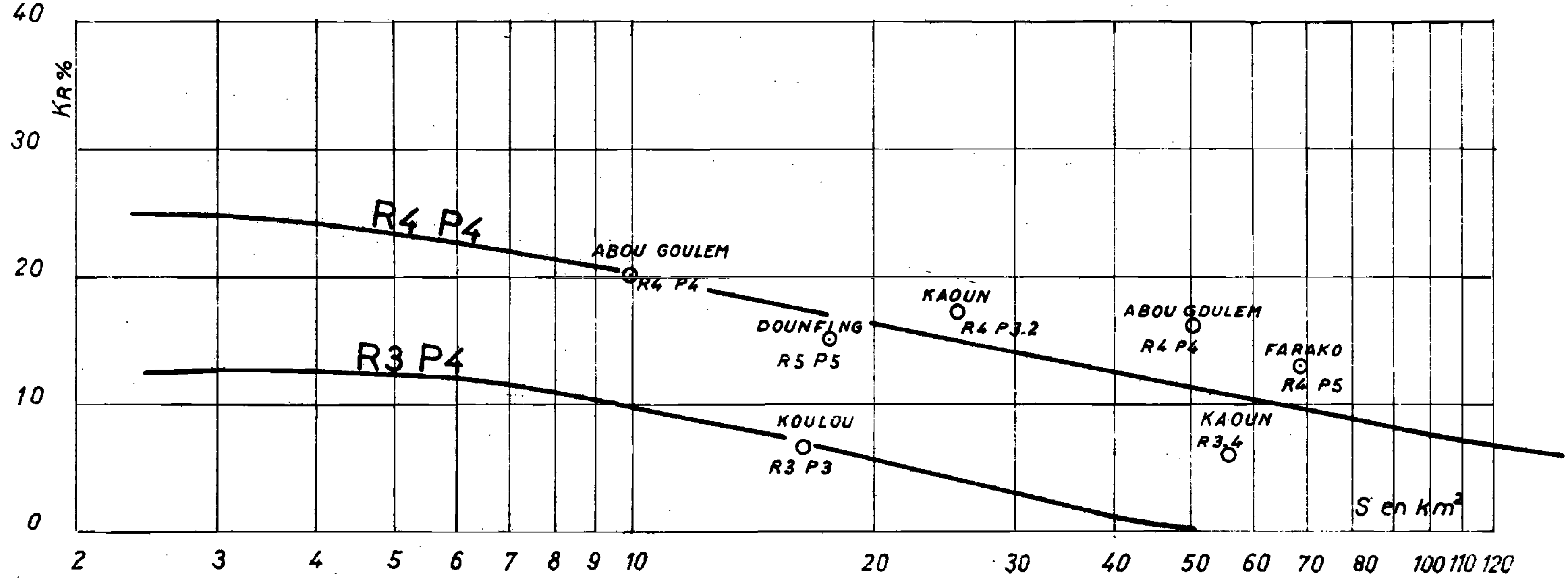
Graph 4 is for terrain of permeability P4. Run-off is only practical for heavy storms and for catchments which are with steep and fairly steep slopes. Two catchments having very high permeability P5 are represented : these being FARAKO and DOUNFING. In fact these are tropical catchments having ten year storms of 110 and 130 mm. respectively. In sahelien climates, their coefficients of run-off should be clearly lower. The curve P. 4 P5 would probably take the position of curve R 3 P 4 or could even be below it. It is to be noted that ground of permeability P5 in sahelien zones will not give any effective run-off for areas of more than a few sq. kms.

# COEFFICIENT DE RUISSELLEMENT

## Régimes sahéliens et subdésertiques

(P varie de 150 à 800 mm.)

## PÉRMÉABILITE P4

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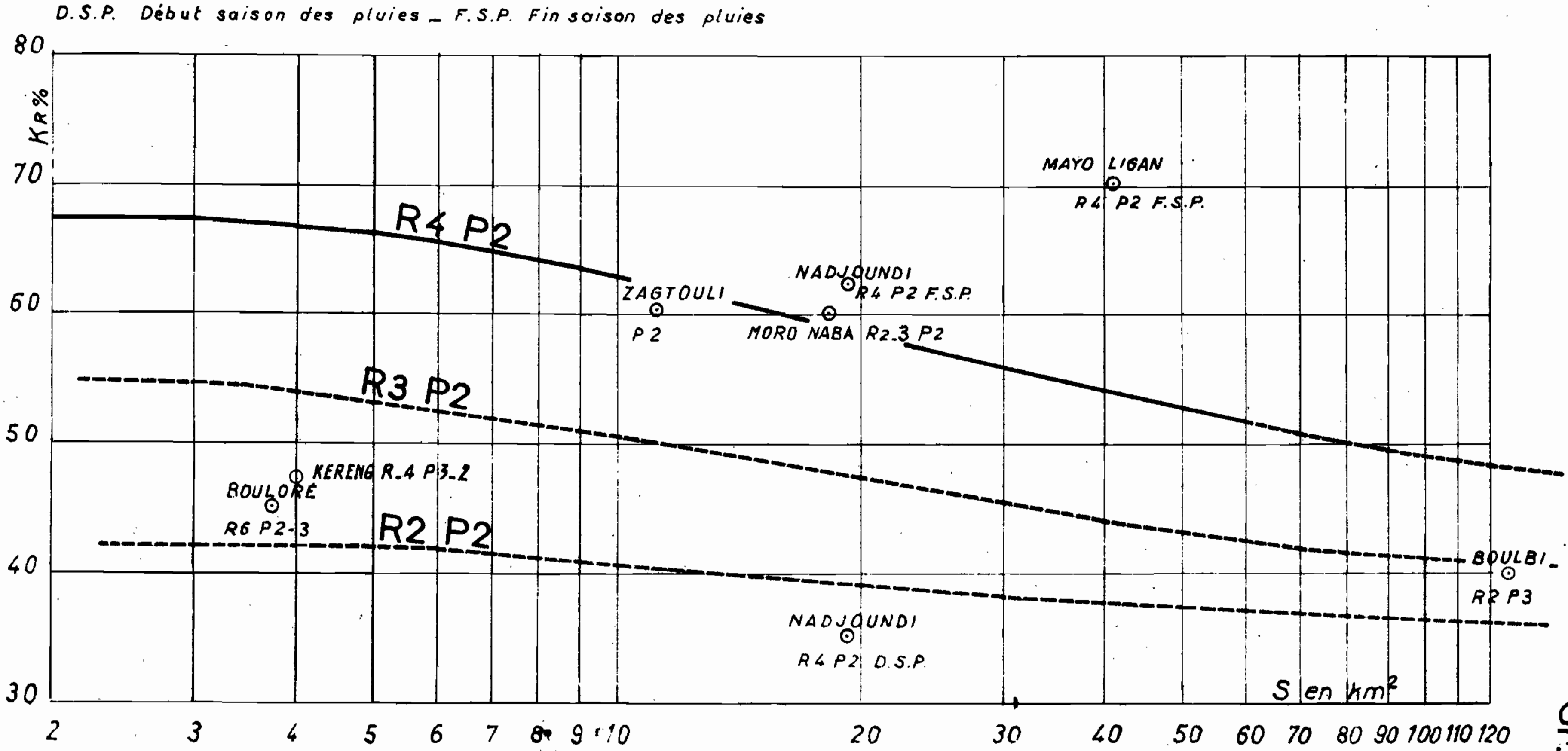
# COEFFICIENT DE RUISSELLEMENT

## Régimes tropicaux et tropicaux de transition

(P varie de 800 à 1600 mm).

## PERMÉABILITÉ P2

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Gr_5

Similarly for permeability P4, it can be said that there is but little run-off, even for heavy floods, for slopes flatter than R 3 catchments slopes.

b) Tropical and tropical transition regimes

We recall in this category the catchments situated at the border of the tropical regime and the sahelien regime (between isohyetal curves 800 mm and 1000 mm). We also have in this category equatorial savanah catchments which have the same type of ten year storm, the same soil, the same vegetation as tropical transition catchments.

In classifying these catchments the vegetation plays a certain role. In fact, the permeability index P takes into account both loss by infiltration in permeable soil and the water absorbed by the vegetal cover.

Another characteristic point for tropical catchments is the difference in behaviour of the catchment between the beginning and end of the rainy season. On our graphs the coefficient of run-off for the end of the rainy season, which is the highest is generally considered. Against this, the times of concentration are longer.

Few catchments of permeability P1 or P2 are found, and these moreover are between annual isohyetals 800 mm and 1000 mm at the edge of the sahelien regime. This is because the vegetal cover is more dense, and also because the very impermeable soils are less frequent in zones which are well watered, and are better protected by vegetation.

Graph 5 is for permeability P2. There are no P2 catchments with surface area less than 2 sq. kms. but the indications of Mayos KERENG and BOULORE for which permeability is close to P2, though a little greater, show that the curve passes a little below their representative points. In as far as the number of representative points permits confirmation, the coefficient of run-off would be lower for the very small catchments than for those of a sahelien regime. It would be nearly the same for catchments of 100 sq. km.

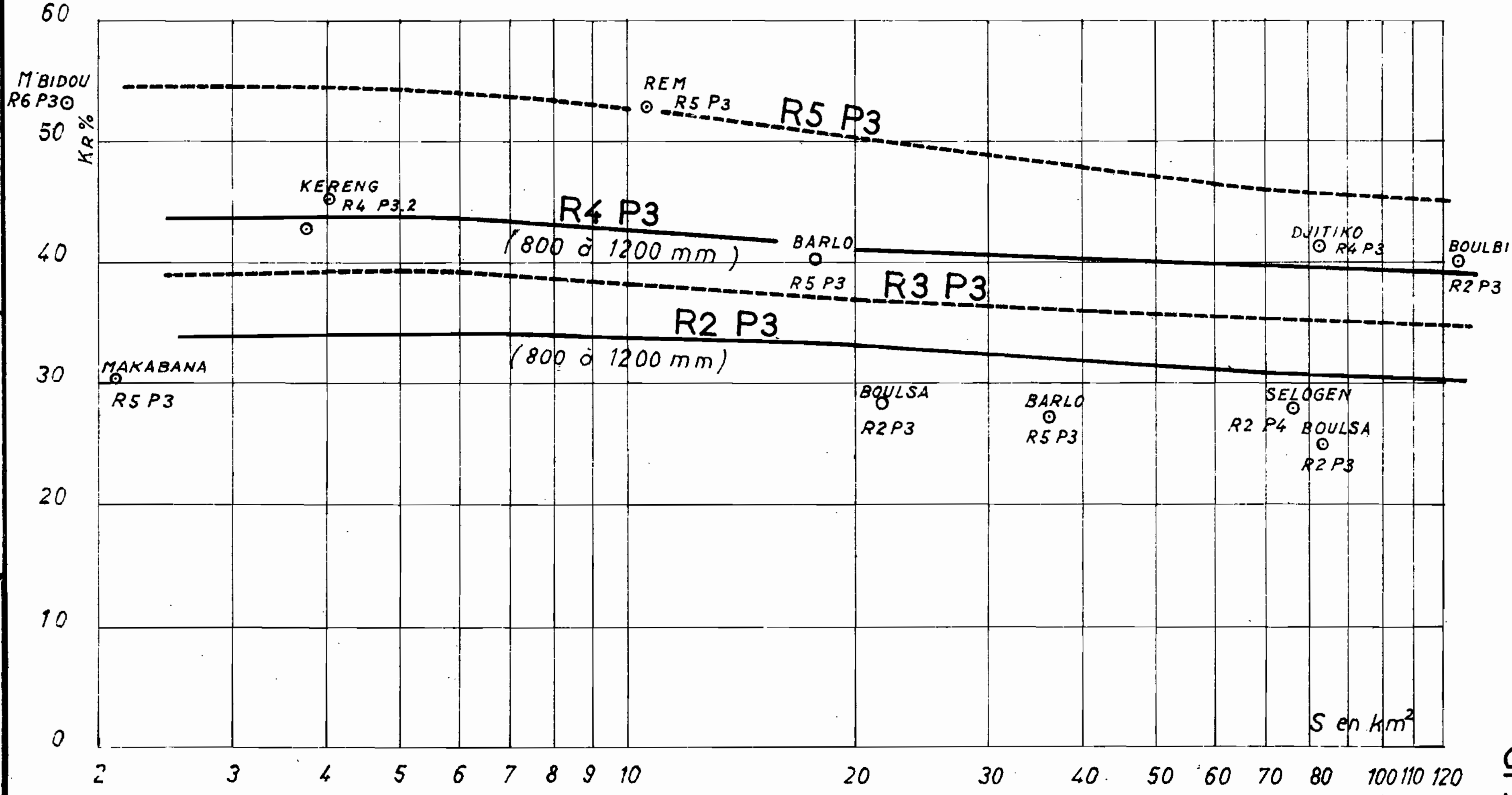
For now it is sufficient to attempt to trace the curve R4 P2 ; meanwhile the curves R3 & R2 have been traced in indicative form, but they are very imprecise. Shown on this graph are the figurative points for NADJOUNDI at the beginning and end of the rainy season, to show adquately the difference between the two conditions.

# COEFFICIENT DE RUISSELLEMENT

## Régimes tropicaux et tropicaux de transition

(P varie de 800 à 1600 mm)

## PÉRMÉABILITE P3

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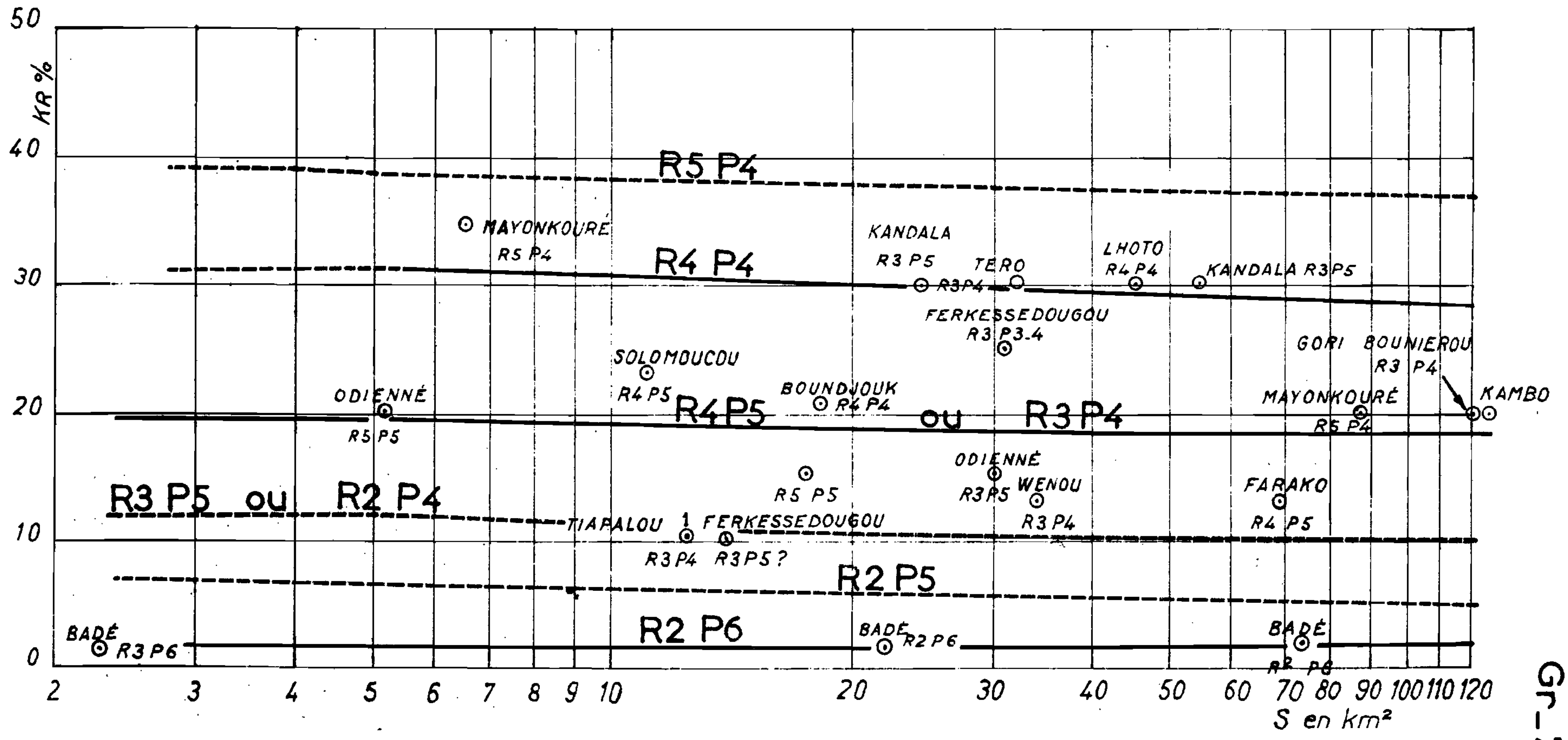
# COEFFICIENT DE RUISSELLEMENT

## Régimes tropicaux et tropicaux de transition

(P varie de 800 à 1600 mm)

## PERMÉABILITÉ P4 et P5




1. Galerie epaisse

Graph 6 is for permeability P3. Here have been used the catchments at the northern boundary of the tropical regime which have already been used with reservations for the sahelien regimes.

Curve R4 P3 is sufficiently well known. The coefficient of run-off varies only a little with area. But this curve corresponds generally to catchments having an annual rainfall between 800 and 1200 mm ; it would be the same for catchments having from 1200 to 1600 mm the more dense vegetal cover directing it toward the lower values as tends to be indicated in the case of BOUNDJOUK and MAKABANA outside the limiting belt between the sahelien and tropical zones.

Graph 7 is for permeabilities P4 and P5. The tracing of the curves as given presented some considerable difficulty due to the wide dispersion of results, most of all in the tropical regime, for several reasons :

1. Forested areas lead to losses which are not negligible. A comparison can be made between the coefficient of run-off for TIAPALOU where they (the forested areas) are fairly dense and that of GORI BOUNIEROU where they are very scattered.

2. Permeable terrain is somewhat frequent in occurrence, but it is often difficult to make a distinction between categories P4 and P5 and sometimes between P3 and P4.

3. The amount of annual precipitation varies between 1200 mm and more than 2.000 mm.

Secondly, all other factors being equal, storms closest together give rise to somewhat higher coefficients of run-off. All the same, for equal amounts of precipitation, the equatorial regions where the rains are distributed over a great part of the year give a lower coefficient of run-off than the tropical transition regions where the rainy season rarely lasts more than 6 months.

The set up of the curves of graph 7 shows that the coefficient of run-off tends to become independent of the catchment area, which is normal when the good drainage network does not lead to large losses, and the hydrographs, more regular than for a sahelien regime do not change very quickly from upstream to downstream.

c) Forest Régions

Undeniably the experimental data is insufficient to permit the variations of coefficient of run-off to be graded as a function of the various parameters. There are eleven catchments, too few even for the rough graphs which we are presenting. We give hereafter the table of data relevant to the 10 year floods of these catchments.

What we call "run-off" in a forest zone is moreover a form of drainage unlike that of the sahelien regime ; it would be more comparable to sub-surface drainage.

10 Year Floods for small forest Catchments

| CATCHMENT | ANNUAL RAINFALL (mm) | SURFACE AREA km2 | 10 YEAR FLOOD $l/s.km^2$ | COEFFICIENT OF RUN-OFF % | BASE FLOW Qo(m3/s) |
|---|---|---|---|---|---|
| NION | 1.800 | 10 | 2,000-2200 | 28 | 2,4 |
| R6 P6 | 1.800 | 62 | 600-700 | 42 | 6 |
| GBOA R6 P6 | 2.300 | 11,5 | 2 500 | 50 | 0,75 |
| LOUE R6 P6 | 2.300 | 17 | 2,500-2800 | 32 | 1 |
| IFOU R3 P5 | 1.200 | 38 | 350 | 10 | 1,25 |
| BAFO R2 P4 | 1.600 | 27 | 1,800 | 65 | 2 |
| SITOU R2 P4 | 1.600 | 29 | 2,000 | 70 | 2 |
| MANSO R2 P3 | 1.600 | 92 | 1 600 | 60 | 4 |
| AGBEBY R4 P6 | 2.200 | 11 | 550 | 6 | 1 |
| LEYOU R5 P4 | 1 800 -2 000 | 6 | 1,000 - 1 100 | 11 | 0,35 |
| BIBANGA R2 P4 | 1 800 -2 000 | 25,2 | 200 a 300 | 12 | 0,65 |
| MALA R6 P3 | 2.250 | 9,2 | 17.500 | 46,5 | 0,50 |
| MALA R6 P3 | 2.250 | 6,7 | 10.500 | 30 | 0,30 |

On the other hand the influence of the vegetal cover considerably masks the permeability of the soil. For instance the three catchments of BAFO, SITOU and MANSO are classed in P3 and P4, whilst study of the soils shows that they would be classed in P3 and P2 had they not been forested. The forest certainly curbs the flow, and this is easily seen in the study of the rise time, but the humid climate limits the losses by evaporation and the 10 year storms (160 mm) are very much heavier than in the previous cases.

If the slope is very steep (R6), permeable soils would moreover be found having coefficients of run-off of 35 to 50 % as for NION GBOA, LOUE in the Ivory Coast (catchments with higher run-off have been found in the Monts de CRISTAL). But it must be noted that in this case the storms are heavier than 200 mm.

For much more moderate slopes (BAFO, SITOU, and MANSO) but on impermeable soils, coefficients of run-off of 60 to 70 % are found for catchments of 25 to 100 sq. kms.

It does not seem however, that for such precipitations, the coefficient of run-off in forest areas will reach values of 80 % as are found in sahelien zones.

Setting aside these extreme cases, if the soil is not too impermeable, which is the general case, and with slopes less than R5, the coefficients of run-off vary between 5 and 15 % : the first value corresponds to moderate slopes and very permeable soils (P6 if there is no forest); the second to a slope R 5 and a soil of class P 3 if there is no forest. These are really low values when it is considered that the 10 year storms are at least equal to 130 mms.

But one must be suspicious of very impermeable soils (P2 if there is no forest), and very steep slopes of the order of R6. Moreover, in tropical cyclone countries coefficients of run-off in excess of 80 % are observed for catchments with a relief R6. A simple examination of the drainage network indicates moreover if it is located in a dangerous (ie high flood potential) catchment or not.

## Run-off Time and Rise Time

The determination of these elements of the unit hydrograph should be more exact than that of the coefficient of run-off, as they do not result from extrapolation. Nevertheless there are some difficulties.

First, the unit hydrograph method is only an approximate method, it works best for homogeneous catchments, which are not often found.

Moreover it frequently happens that the same catchment has several distribution patterns : for example, one for weak floods, another for very heavy floods, which is quite normal ; in the first case the flow consists of a sheet of water fairly thin on the ground ; in the other case the flow forms itself into a nappe (watercourse) and follows the normal hydraulic laws giving rise to very different results.

Sahelien catchments, the wettest, and tropical catchments, the dryest show equally two types of run-off ; that at the beginning of the rainy season (D.S.P.) with soil very little covered, a flash hydrograph and often a fairly low coefficient of run-off ; that at the end of the rainy season (F.S.P.) with a fairly dense vegetal cover, a fairly high coefficient of run-off, and a fairly flat, extended hydrograph. Generally one considers the first hydrograph for sahelien catchments, the second for tropical catchments. The distribution pattern has always been studied only for heavy floods ; by such study the graphs corresponding to a run-off which covers only a part of the catchment can be eliminated, except when they are characteristic of the catchment and the region (for example the cases of the catchments of HAMAZA and ALOKOTO).

There has been hesitation over the choice of the parameters suitable for the characterisation of the hydrograph : that is to say the time of rise, the time between the beginning of the flood and its peak, or the base time of the run-off, the time between the start and finish of the superficial runoff. These times are determined only for unit floods, that is to say, theoretically for short and intense storms. It is often a delicate matter to determine unit floods with certainty. From a group of floods it is necessary to reject those which are not unitary (time too long or on the other hand too short to provide more than a partial run-off). For the base time the division between the run-off and the subsurface flow is somewhat arbitrary, particularly in a tropical transition regime, of such nature that it is not always known if the end of the run off hydrograph is in fact of the direct run off or of another form of drainage.

We have represented in the following paragraph the time of rise or of run-off as a function of the areas of catchments, and divided them into 3 categories :

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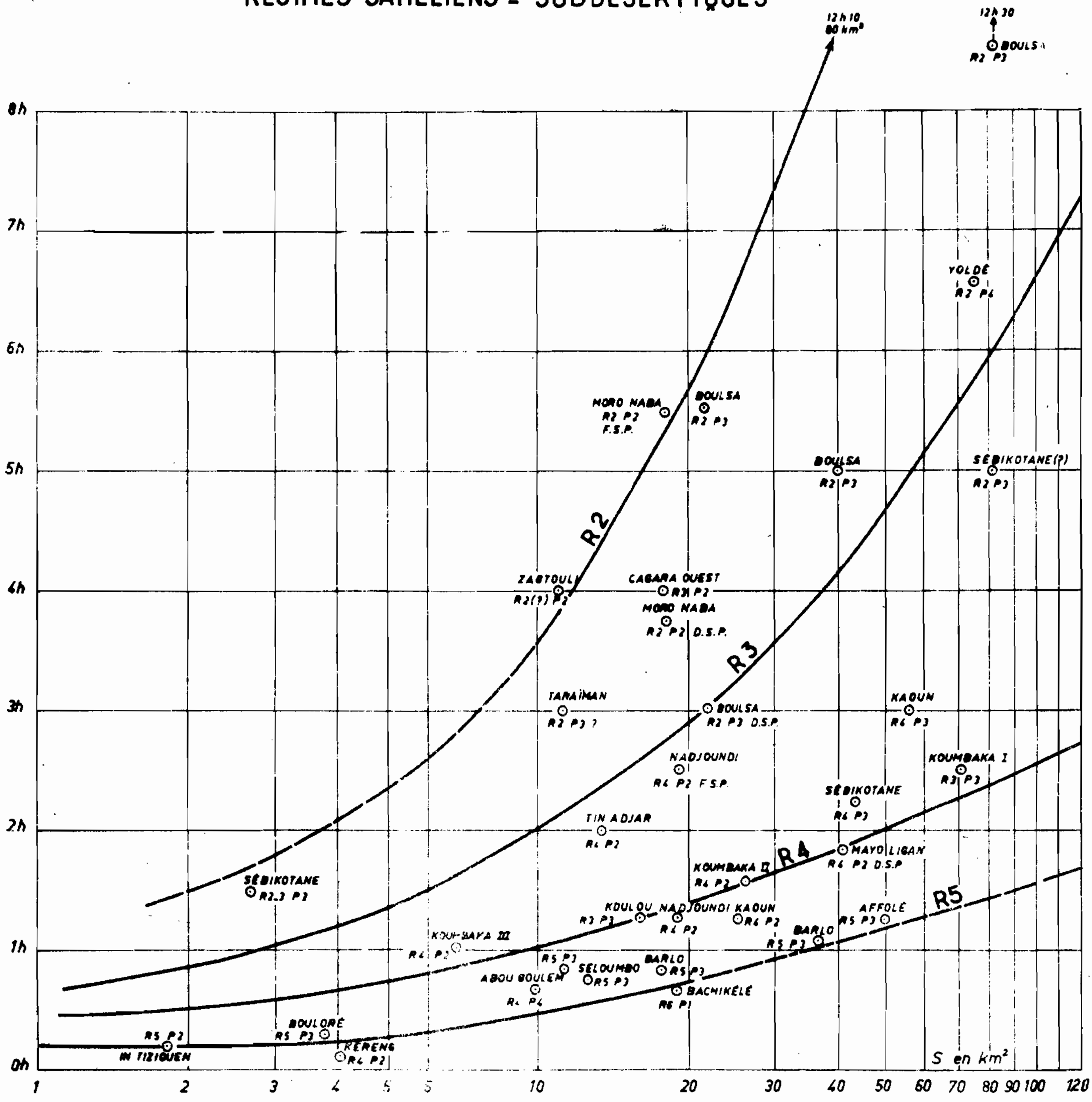
# Temps de montée en fonction de R et de S

## RÉGIMES SAHÉLIENS – SUBDÉSERTIQUES




D.S.P. Début saison des pluies – F.S.P. Fin saison des pluies

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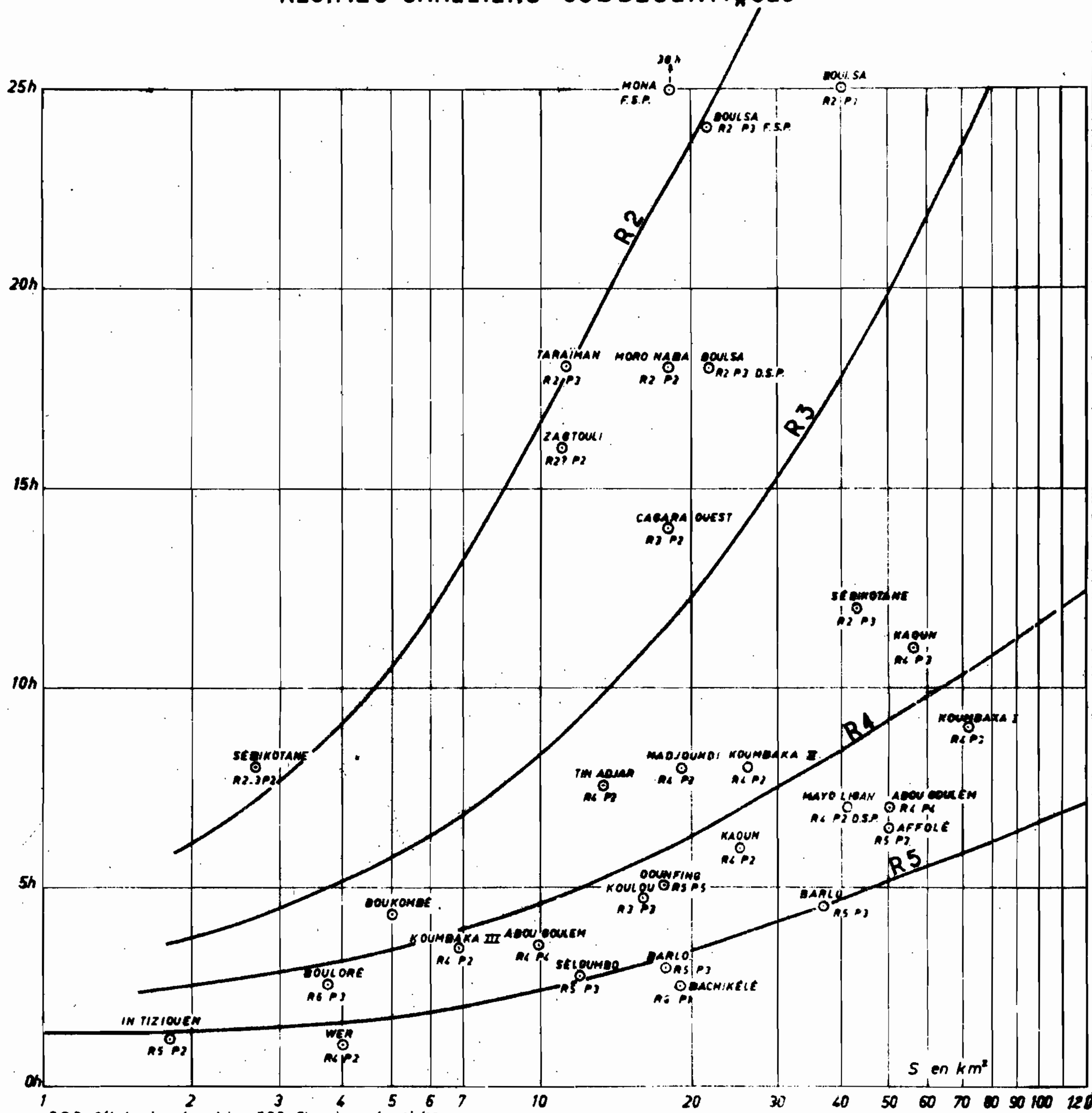
# Temps de base en fonction de R et de S

## RÉGIMES SAHÉLIENS-SUBDÉSERTIQUES

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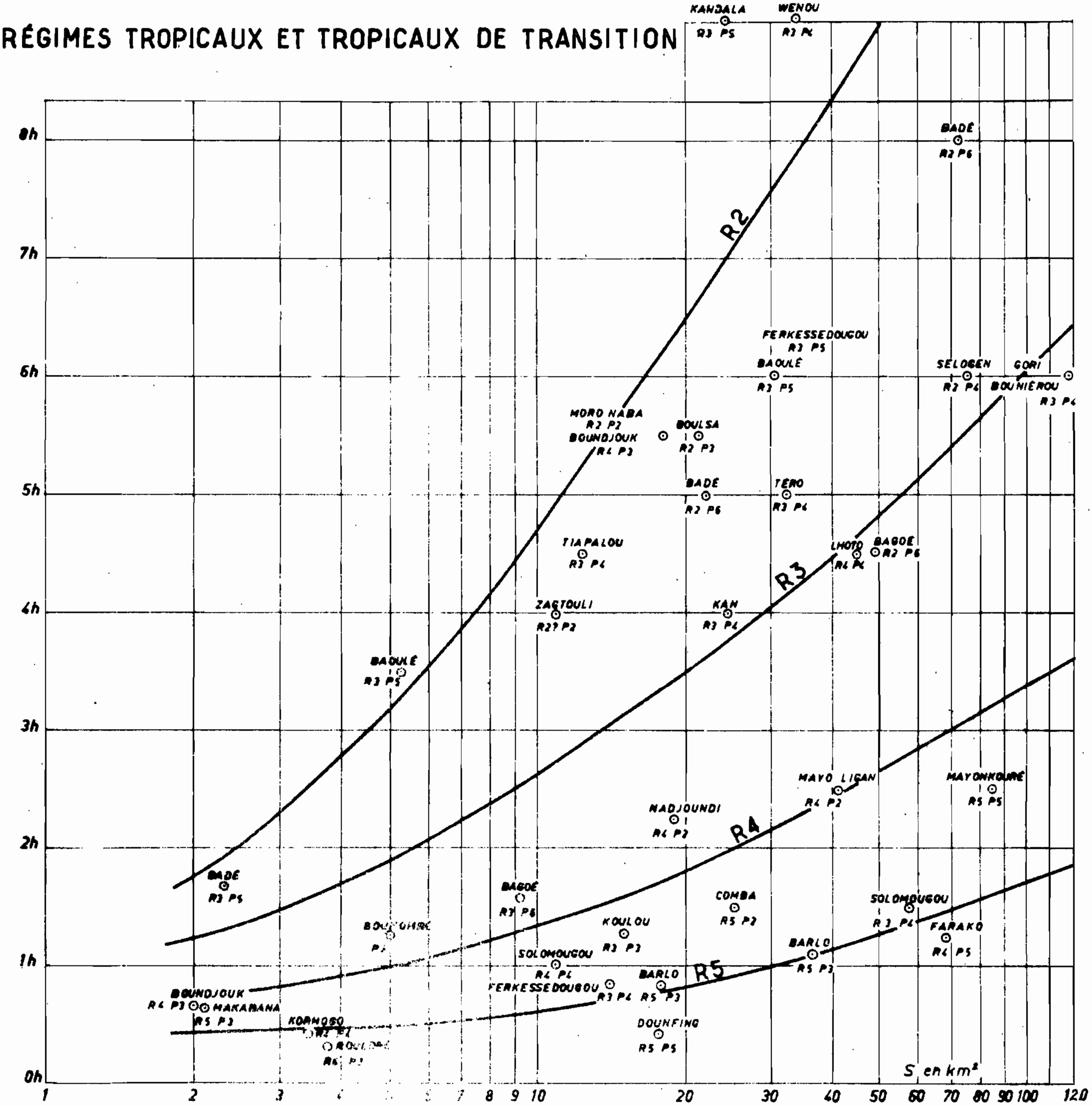
# Temps de montée en fonction de R et de S

## RÉGIMES TROPICAUX ET TROPICAUX DE TRANSITION

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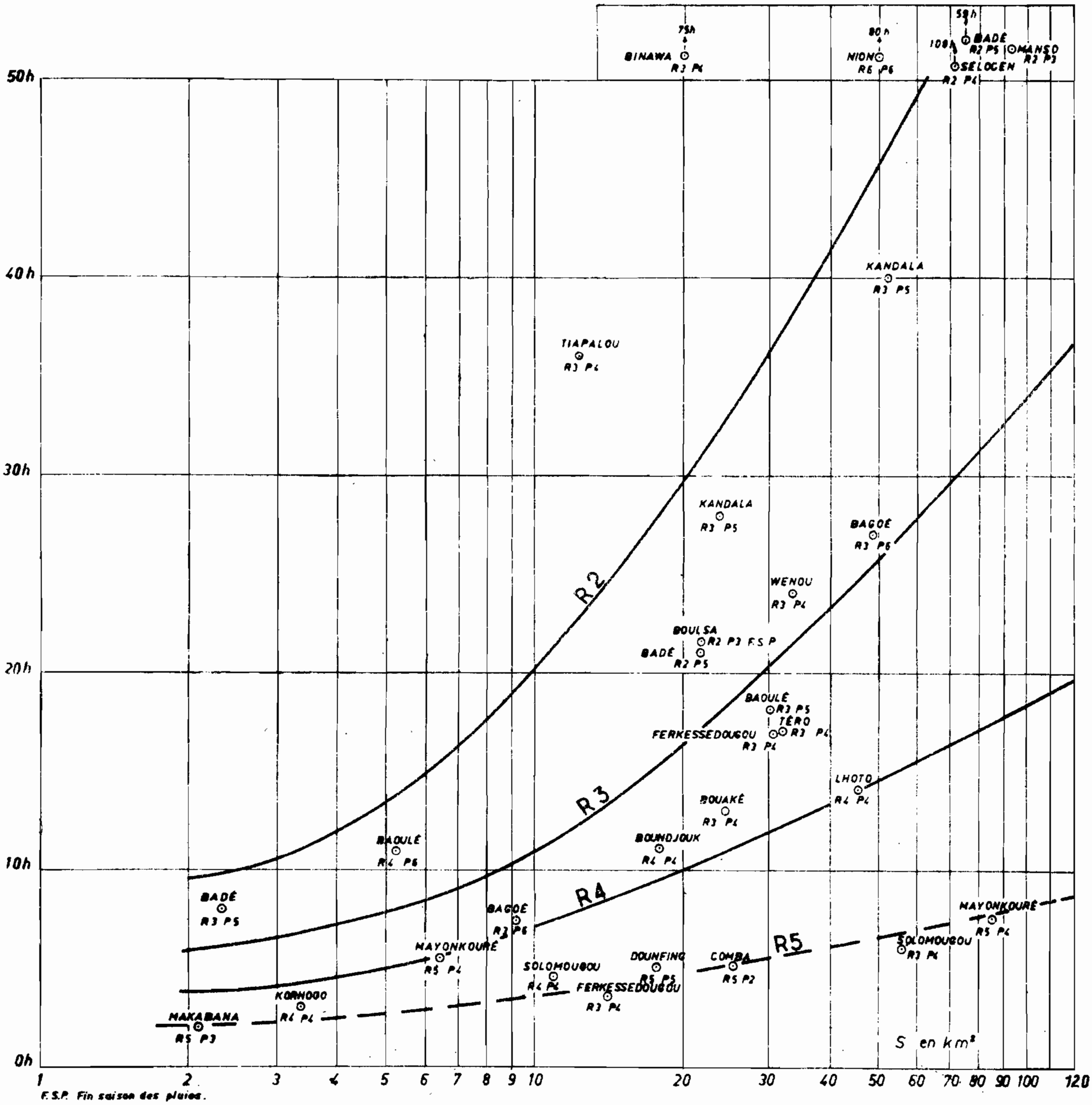
# Temps de base en fonction de R et de S

## RÉGIMES TROPICAUX ET TROPICAUX DE TRANSITION

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a) Sub desert and sahelien Regimes

In graph 8 and 9 are found the curves of variation of time of rise and base time as functions of the area. It is quickly seen that the influence of the permeability P was of little importance within a given category, which is logical when at a time of soil saturation all the soils are similar (sufficiently so for a first approximation), this affecting the rate of the runoff. Four curves for R 2, R 3, R 4 and R 5 have therefore been drawn : each representative point carries the two references R and P. A notable dispersion is moreover seen, which is generally self-explanatory. Three principal causes are indicated

| | | |
|---|---|---|
| - abnormal elongation of catchments | : | SEBIKOTANE (43 sq. km) |
| - dense forest areas at the lower end of the catchment | : | KOUMBAKA I |
| - catchments which never give contribution from their entire area | : | SEBIKOTANE, YOLDE, KAOON |

Playing an equal part in the dispersion of the representative points is the fact that certain catchments have slopes intermediate between R2 and R3 for example.

A considerable deviation from normal is observed for points at the end of the rainy season : BOULSA (F.S.P.), NADJOUNDI (F.S.P.) which we have put on the graph to show clearly the difference from the points for the D.S.P. (start of the rainy season).

It is recalled that these points correspond to unit storms. These storms are not 10 year one for catchments :

- R2 less than 2 sq. km
- R3 " 3 sq. km
- R4 " 15 sq. km
- R5 " 25 sq. km

Naturally, these graphs are valid for catchments of not too elongated form with a drainage network which is neither too favourable in form nor too unfavourable for run-off, that is, an average network.

Naturally also, if a swamp occurs in the course of the principal river of an R4 catchment, the rise time and base time are very much increased. It is sufficient to compare the catchments of DOUNFING in which there are several low-lying swamps and of Mayo KERENG where there are none.

For certain very small steeply sloping catchments, abnormally low values for the rise time are observed, the case of Mayo KERENG for example. This is due to flood wave phenomenon. The drainage coming from the most distant parts of the catchment channels more quickly than that from the closest parts, which tend to travel more slowly along a dry stream bed whilst re-saturating it. In any one case it is evidently difficult to give rules for the precise calculation of the rise time.

b) Tropical and tropical transition Regimes

Earlier, the curves of variation of base time and rise time have been drawn. The data for catchments situated near the borders of the sahelien and tropical regimes has been used, already taken into account in the preceding study.

For the area between the 900 mm and 100 mm isohyetals we have taken as a matter of preference the data at the end of the rainy season. Further to the south this has but little importance.

The dispersion seems greater than for the former category : this is due to the presence of forested areas. This has been clearly seen for example for the catchments of TIAPALOU and WENOU which have the same characteristics as that of GARI BOUNIEROU, but this latter does not have forested areas.

The highly cultivated catchments of KORHOGO and SOLOMOUGOU have very short rise times, compared with those of sahelien catchments.

As a general rule the rise times are longer than for tropical catchments. This is due to the retarding effect of the vegatation.

This is less clear for catchments of more than 25 sq. kms and for catchments, having flat slopes R2 and R3, for in such sahelien catchments the degradation of the drainage system has an effect in the forementioned cases, retarding the drainage in the streams beds, whilst in their upper parts they drain more rapidly than for a tropical regime.

The base times for tropical regimes are the shortest. This is due in part to the rule by which the surface run off and the subsurface drainage are separated because in a tropical regime there is nearly always subsurface drainage. One tends to determine too short a run-off time, whilst for a sahelien regime one often ignores the subsurface drainage, grouping it with the surface runoff, this leading to an excessively long base time.

But the degradation of drainage channels in the sahelien region acts equally in the same sense and here it is even more noticeable for flattish sloped catchments R2 and R3.

c) <u>Forest catchments</u>

These are too few in number for it to be possible to draw a group of curves.

Following hereafter is a table, showing for the catchments named, the two indices R and P, the surface area S, the rise time Tm and the base time Tb.

| CATCHMENTS | INDICES | S ($Km^2$) | Tm | Tb |
|---|---|---|---|---|
| NZANG (Mala) | R6 P3 | 9,2 | 0 h 40 | 3 h 30 |
| MITZIBE | R6 P3 | 6,7 | 1 h | 3 h 40 |
| NION | R6 P6 | 10 | 6 h | 16 h |
| | R5 P6 | 62 | 30 h | 80 h |
| GBOA | R6 P6 | 11,5 | 3 h. 30 | 17 h |
| LOUE | R6 P6 | 17 | 3 h | 13 h |
| LEYOU | R5 P4 | 6 | 2 h 15 | 17 h 45 |
| AGBEBY | R4 P6 | 11 | 3 h 30 | 11 h |
| IFOU | R3 P5 | 38 | 7 h | 17 h |
| BIBANGA | R2 P4 | 25,2 | 19 h | 35 h |
| BAFO | R2 P4 | 27 | 13 h | 40 h |
| SITOU | R2 P4 | 29 | 13 h | 26 h |
| MANSO | R2 P3 | 92 | 15 to 20 h | 52 h |

It is necessary to place catchments in zones having the steepest possible slopes. The first four catchments are true mountain catchments. Unfortunately GBOA and LOUE are very elongated catchments, the rise time and base time tending to be shorter than the time actually found for these catchments. But, by placing the representative points on the curves of graphs 10 and 11 it is verified(with difficulty, as there are several points which do not conform) that Tm is 2 to 5 times as great for a forest regime as for a tropical regime, the difference being probably greater for very small catchments. The proportionate relationship would be a little less for base time, varying from 2 to 4. It is here that one sees the effect of the regulating influence of the forest. Meanwhile in the case of very steep slopes : R 5 or R6, the difference from the tropical catchments is not so great. For catchments of slope R6 the curve R4 of graph 11 can be used.

## Study of the Coefficient $K = \frac{Q}{M}$

We have seen earlier that to take account of the shape of the hydrograph we use the factor :

$$K = Q/M.$$

where Q is the maximum value of the unit runoff hydrograph and M is the mean flood discharge, taken as uniform over the whole duration of the base time Tb.

It is assumed for simplicity that there is no subsurface drainage ; the surface run-off only is considered. Being given that condition for the study of KR the surface runoff and sub-surface drainage have been considered jointly, thus bringing in a new cause of dispersion (of results), but at this stage of the study it is not possible to proceed further with refinements; and errors in the results for the flood discharges as calculated, and which result from this simplification are small.

It is easily seen that the hydrograph is a simple triangle $\frac{Q}{M} = 2.$

If the hydrograph is very pointed with a rather wide base which is the case for many catchments having a high runoff, the volume of the flood will be less than that of the triangle and following from this $\frac{Q}{M}$ will be somewhat greater than 2.

If the hydrograph has a very rounded peak the volume of the flood will be much greater than that of the triangle, $\frac{Q}{M}$ will be less than 2. This is so in the case of forest catchments.

If the hydrograph, without being very pointed, has a narrow base, such as in the case of catchments having a good run off, but with the run off considerably retarded, $\frac{Q}{M}$ will equally be less than 2.

Finally it is noted that the relationship $\frac{Q}{M}$ can be used for the calculation of 10 year floods, it being necessary to calculate for very small catchments not from a unit hydrograph, but from the hydrograph corred-ponding to the 10 year storm, which is no longer unitary. This is valid almost exclusively for sahelien catchments xith moderate slopes, steep slopes and above all very steep slopes for which the base time is very short. For these very small areas the appropriate parts of the curves of graph 9 are used.

The parts of the curves to be used can be defined simply by the ordinates corresponding to the abscissae for 2 kms$^2$ and their inter-sections with the curves of graph 9. The abscissae of the intersections have been given before, and are repeated here.

| | | |
|---|---|---|
| for R2 | = | 2 Km$^2$ |
| R3 | = | 3 Km$^2$ |
| R4 | = | 15 Km$^2$ |
| R5 | = | 25 Km$^2$ |

The ordinates of the point S = 2 Km$^2$ are as follows

| | | |
|---|---|---|
| for R5 | = | 2 h. |
| R4 | = | 3 h. 15 |
| R3 | = | 4 h. 35 |
| R2 | = | 6 h. 30 |

The curves are moreover determined with very little precision and are representative of average catchment shapes with average drainage networks.

The calculation of the values of $K = \frac{Q}{M}$ for the experimental catchments studied has provided evidence of considerable dispersion. As could be foreseen, the number of catchments available does not permit a systematic study of the action of the various factors. The curve of average variation is set out by the following points for the sahelien regime :

| 2 km$^2$ | 10 km$^2$ | 25 km$^2$ | 50 km$^2$ | 100 km$^2$ |
|---|---|---|---|---|
| 2.6 | 2.6 | 2.5 | 3 | 3.10 |

The increase of $\frac{Q}{M}$ from catchments of 25 km2 to those of 100 km2 is explained by the fact that as the flood progresses downstream the drainage gradually becomes less and less adapted and the hydrograph base is elongated, that is to say as the surface area of the catchment increases the hydrograph develops a steeper peak fairly quickly ; which leads to a wide base with a peak not too falttened. For small catchments of less than 10 Km2 the hydrograph is no longer unitary, its shape varying little between 2 and 25 sq. kms.

Catchments with a particularly good run off : especially the categories R4 P2 and R5 P2, above all those between annual isohyetals 700 mm and 900 mm at the borders of the sahelien and tropical regimes have moreover a fairly long base time and a very sharp flood peak, leading to a very high value of $\frac{Q}{M}$.

It seems wise, for this category and in the case of drainage networks favourable to the runoff (fan shaped networks) to use the following figures.

| 2 $Km^2$ | 10 $Km^2$ | 20 $Km^2$ | 50 $Km^2$ | 100 $Km^2$ |
|---|---|---|---|---|
| 3 | 3 | 3 | 4.5 | 4 |

For tropical and tropical transition catchments a value of 2.5 may be used for $\frac{Q}{M}$ , whatever the area of the catchment, without the risk of serious errors. For forest, values of $\frac{Q}{M}$ about 1.7 are quite often found.

## Calculation of 10 year floods

We now have available all the materiel for the calculation.

Consider a catchment under the annuel isohyetal 700 mm. To fix it we will place it in Upper Volta 10 Km. north of Kaya. For this amount of precipitation the climate is sahelien. The 10 year precipitation given by the map of 10 year precipitations for Upper Volta (see General study of Storms in West Africa) is seen to be 102 mm in 24 hours.

We assume that the catchment is impermeable (permeability P 2) and that a quick ground survey enables us to classify it in category R4 (longitudinal slopes averaging between 1 and 2 % ; cross slopes greater than 2 %, less than 8 %). The area, planimetered from a 1/50,000 map and from aerial photographs, is 25 km2.

The drainage network is normal, not too elongated, degradation of the drainage scarecely noticeable.

Such a catchment does not necessarily exist exactly at these geographic co-ordinates, but it is used as a simple example.

The coefficient of area reduction is = 1 (unity). If on graph 2 the vertical line for $S = 25\ km^2$ is followed, it meets the curve R4 P2 which corresponds to our catchment at ordinate point 61 % : this is the coefficient of run-off for our 10 year flood.

The depth of run-off is $102 \times 0.61 = 62.5$ mm. The volume of run-off is :

$$62.5 \times 25 \times 10^3 = 1,560,000 \text{ cubic metres}$$

The base time is given by graph 9 curve R4 : it is 7 hours.

$$M = \frac{1,560,000}{7 \times 3.600} = 62\ m^3/sec$$

The value of $K = \frac{Q}{M}$ for this catchment with good run off (R4,P2, sahelien) can be taken as equal to 3.

Then
$Q = 62 \times 3 = 186\ m^3/$ sec. or otherwise 7500 l/sec./km2.

For P2 catchments there is neither sursurface drainage for underground flow to be added to surface runoff. The figure of 186 m3/sec is the true figure, a figure found habitually for this type of catchment.

It would not do to give too definite a significance to this result ; to our way of thinking, in reality it would be preferable to say that the runoff of the 10 year flood is between 150 and 225 m3/sec.

Consider a catchment of Guinea type in the south of Upper Volta, 50 kilometres south west of Banfora, being under the annual isohyetal 1250 mm, taken from the map given in the general study of storms in West Africa. The regime is tropical transition. The 10 year precipitation, taken from the same map as before, is 130 mm.

The catchment is taken to be permeable, (index P 4) and having a fairly flat slope R3 ; average longitudinal slopes being between 0.5 and 1 % ; cross- slopes less than 2 %.

The surface area is taken to be 70 $Km^2$, the drainage network normal, with few swamps.

The coefficient of area reduction is equal to 0.90. The average amount of precipitation to be taken into account is :

$$130 \times 0.9 = 117 \text{ mm.}$$

Graph 7 (Curve R3 P4) shows that for the 10 year flood for an R3 P4 catchment of 70 $km^2$, the coefficient of runoff is 18.5 %.

The depth of run-off is 117 mm × 0.185 = 21.6 mm.

The volume of runoff for 70 $km^2$ is

$$21.6 \times 70 \times 10^3 = 1{,}520{,}000 \text{ m}^3$$

The base time from graph 11 is 30 hours (it is taken that the forested areas are not too thick, which could double or triple the base time).

$$M = \frac{1{,}520{,}000}{30 \times 3600} = 14 \text{ m}^3/\text{sec.}$$

The value of $K = \frac{Q}{M}$ for this tropical transition catchment will be taken as 2.5.

Then

$$Q = 14 \times 2.5 = 35 \text{ m}^3/\text{sec, corresponding to } 500 \text{ l/sec/Km}^2.$$

A base flow of 2m3/sec must be added which cannot very well be determined until after an on the spot examination of the flow of ground water, in the absence of an examination of base flow in a full rainy season.

One gets Q 10 = 37 $m^3$/sec. as a final result, this being 530 l/sec/$km^2$.

It is noted that this figure corresponds to ground with its natural cover. If all the area has been cultivated without attention to drainage requirements, it would be necessary to give attention to a change in the conditions of runoff, all of which would become similar to those for a catchment having a permeability P 3 or perhaps even P2, depending on the type of soil.

Take now an example of a very small catchment of 2 $km^2$, which we imagine to be in Niger, under the annual isohyetal 550 mm, west of Madaoua. The climate is sahelien type. We assume that the slope is in the R 4 range, and that the catchment consists almost entirely of the clays common in that region, which can without hesitation be classed as P2. We have not thought of any particular catchment, but it would be fairly easy to find on of this type in the region indicated. It is noted that it is not always easy to define with precision the boundaries of a catchment of 2 km2.

The 10 year point precipitation, taken from a map established for Niger is 100 mm.

The coefficient of area reduction is 1, the average amount of precipitation is therefore 100 mm.

Graph 2 (curve R 4 P2) shows that for the 10 year flood for an R 4 P 2 catchment of 2 km2, the coefficient of run-off is 82 %.

The depth of run-off is 100 × 0.82 = 82 mm.

The volume of run-off for 2 $km^2$ is $82 \times 2 \times 10^3 = 164{,}000\ m^3$

For a catchment so small we have seen earlier that the flood would not be unitary, consequently the base time will be given by the special curve corresponding to the curve of graph 9. For 2 km2 the base time is 3 h. 15.

$$M = \frac{164{,}000}{3.25 \times 3600} = 14\ m3/sec.$$

For an R 4 P 2 catchment of 2 km2, $K = \frac{Q}{M} = 3.$

$Q\ 10 = 14 \times 3 = 42\ m3/sec.$

This is the true 10 year discharge for a P2 catchment, there is no subsurface flow.

This runoff corresponds to 21.000 l/sec/km2, a figure often found for these impermeable catchments of 2 km2.

Consider a catchment of 120 km2 which we take to be in Senegal, 40 kilometres to the East of KEDOUGOU, under the annual isohyetal of 1300 mm. The hydrological regime will be tropical transition.

For a catchment of this size, in a region where the relief is not very accentuated, one assumes a slope corresponding to category R3. Assuming that the ground is not too permeable, the catchment can be classified as P3. The 10 year depth of precipitation, taken from the maps of the I.C.H.S. is 135 mm. For 120 sq. km. the coefficient of area reduction is 0.85.

The average depth of precipitation over the catchment will be 135 mm × 0.85 = 115 mm.

Graph 6 (curve R3 P3) corresponding to category P 3 shows that the coefficient of runoff is 34 % for the 10 year flood.

The depth of run-off is

115 mm × 0.34 = 39 mm.

The volume of run-off for 120 km2 will be $39 \times 120 \times 10^3 = 4,700,000$ m3

The base time taken from graph 11 is 37 h. 12 m.

$$M = \frac{4,700,000}{37.2 \times 3600} = 35 \text{ m3/sec.}$$

The value of $K = \frac{Q}{M}$ for this tropical transition catchment will be 2.5.

Then $Q = 2.5 \times 35 = 87.5$ m3/sec.

A base flow of 2.5 m3/sec. can be assumed.

Then the final Q 10 = 90 m3/sec., that is 750 l/sec/km2.

Finally we take as a representative type, an example of a forest catchment in the Ivory Coast ; area 10 km2, fairly steeply sloped, R4, moderate permeability (for the forest) P4.

Assume a 10 year storm of 160 mm. The coefficient of area reduction is 1. The vaerage storm over the catchment is 160 mm. A coefficient of run-off of 12 % is likely. The depth of run-off is 19.2 mm. The volume of runoff for 10 km2 is $19.2 \times 10 \times 103 = 192,000$ $m^3$.

In a tropical regime the base time will be 7 hours ; we allow here that it is doubled, which is perhaps a little low, but acts as a safety factor.

$$M = \frac{192.000}{14 \times 3600} = 3.8 \text{ m3/sec.}$$

It has been seen earlier that generally $\frac{Q}{M}$ is in the region of 1.7.

$$Q = 3.8 \times 1.7 = 6.46 \text{ m3/sec.}$$

A base flow of 1 m3/sec. may be assumed.

The 10 year flood discharge Q 10 will be in the order of 7.5 m3/sec., that is 750 l/sec/km2. But in this instance it is simply a question of order of size.

The calculation of exceptional floods for catchments exceeding 120 $km^2$ requires a different procedure in each case.

The small number of experimental points, the fact that the unit hydrograph method is more and more difficult to apply (most of all with this type of storm) brings in a great amount of imprecision :

a) In the case of sahelien and semi desert catchments greater than 120 sq.kms, the calculation of the averages as proposed herein can lead to very erroneous results. The degradation of the drainage network interferes from the start, spoiling the results. Moreover heterogenity of catchment is very common for these relatively large areas, and likewise leads to errors. We note that very often the meximum discharge of 10 years frequency is due to a flood occuring over one of the tributaries of the downstream part of the catchment. One must therefore be most careful in calculating the 10 year floods for these small tributaries and if they come to a confluence at a short distance from the study station, one should compare their floods with the 10 year flood for the whole of the catchment if it is greater than 40 sq. km. For the volume of the 10 year flood on the other hand, it will often be necessary to consider a flood for the entire catchment.

If the catchment is very homogeneous, if there is only small degradation of the drainage network, and if the runoff is sufficient, one can determine the specific run-off in l/sec. sq.km. proportionate to areas, between the 120 sq. km., point which can be calculated from the graph, and the 200 sq. km., point for which we give specific run-off for 10 year floods for the various types of catchments :

| | | | | | |
|---|---|---|---|---|---|
| R4 P2 | = | 2.000 l/sec/sq. km. | R4 P3 | = | 1.100 l/sec./ sq.km. |
| R3 P2 | = | 700 l/sec/sq. km. | R3 P3 | = | 325 l/sec./sq. km. |
| R2 P2 | = | 400 l/sec/sq. km. | R2 P3 | = | 110 l/sec./sq. km. |
| R4 P4 | = | 225 l/sec/sq. km. | | | |
| R3 P4 | = | 0 | | | |

Catchments R 5 and P 1 are very rare for such areas ; at the same time it appears that the upper limit of the 10 year flood corresponds to 3000 l/sec/km2, probably for catchments of types R5 P2 or R4 P1.

Taking the case of a sahelien catchment R 3 P2 of 150 km2 with a good drainage network and very homogenous. The 10 year point rainfall is 100 mm. A calculation similar to those carried out earlier shows that the discharge of the 10 year flood is 1000 l/sec/km2 for 120 sq. km.

We have seen that for 200 km2 it is 700 l/sec./km$^2$

The specific discharge for 150 km2 will be :

$$\left(700 + 300 \times \frac{50}{80}\right) \text{ l/sec.} = 89P \text{ l/sec/km2}$$

that is 900 l/sec/km2, corresponding to 135 m3/sec.

One cannot give to this number more than an indicative value and moreover not without the requirement of a strict check of the conditions obtaining on the ground.

b) For tropical or tropical transition catchments, homogenity is often greater, and the degradation of the drainage network much less, giving therefore, better results. But the following simplified method of calculation is used.

The coefficient of runoff will be taken as constant between 120 and 200 km2. The following values will be used :

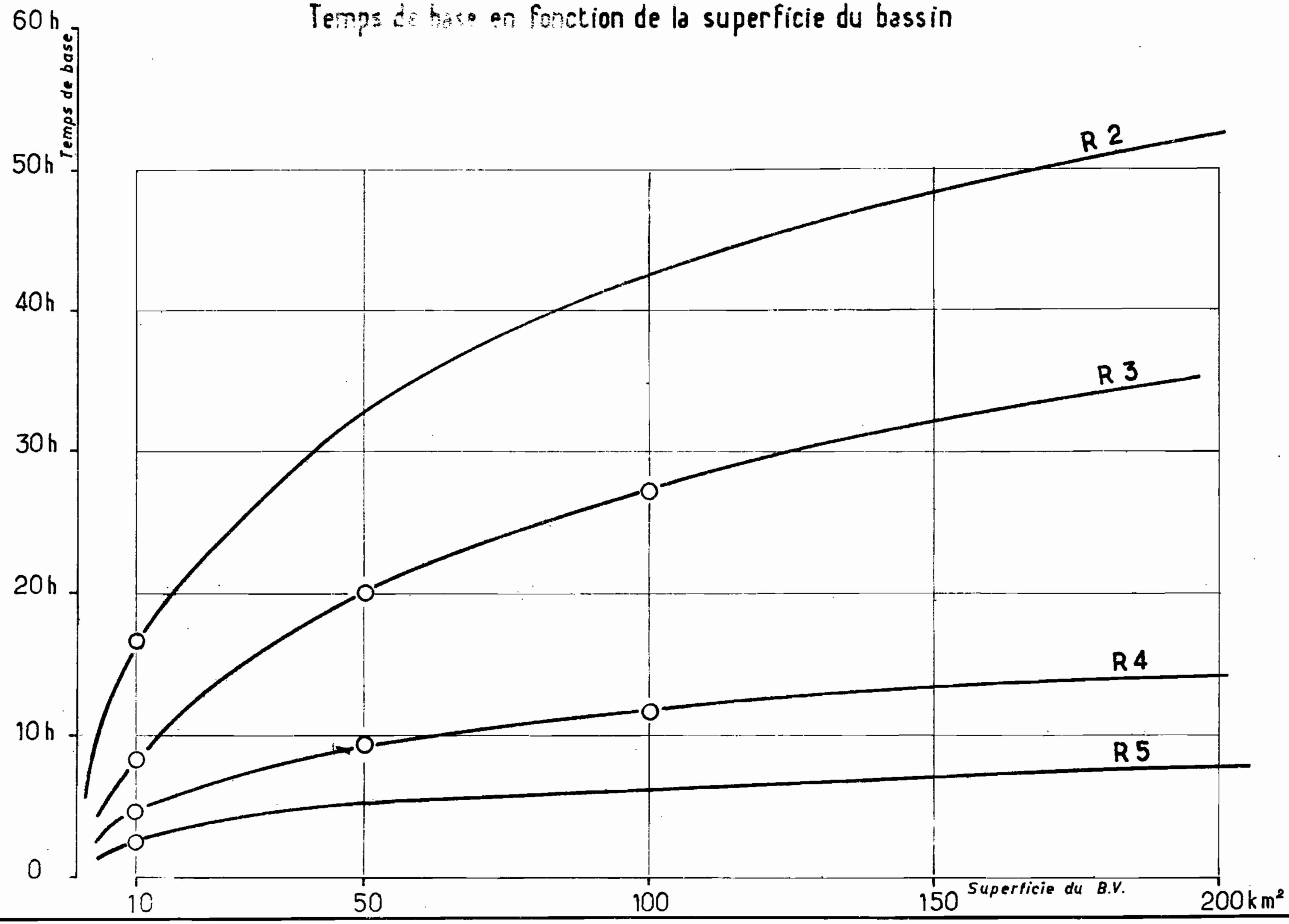
| | |
|---|---|
| R4 P2 = 48 % (Forest areas insignificant) | R4 P3 = 46 % (forest areas insignificant) |
| R3 P2 = 40 % | R4 P3 = 38 % |
| R2 P2 = 36 % | R3 P3 = 34 % |
| | R2 P3 = 29 % |
| R5 P4 = 36 % | R5 P5 = 26 % |
| R4 P4 = 28 % | R4 P5 = 18 % |
| R3 P4 = 18 % | R3 P5 = 9 % |
| R2 P4 = 9 % | R2 P5 = 5 % |

R2 P6 = 2 %.

The base time will be given by graph 13.

Régimes subdésertiques et sahéliens

Temps de base en fonction de la superficie du bassin

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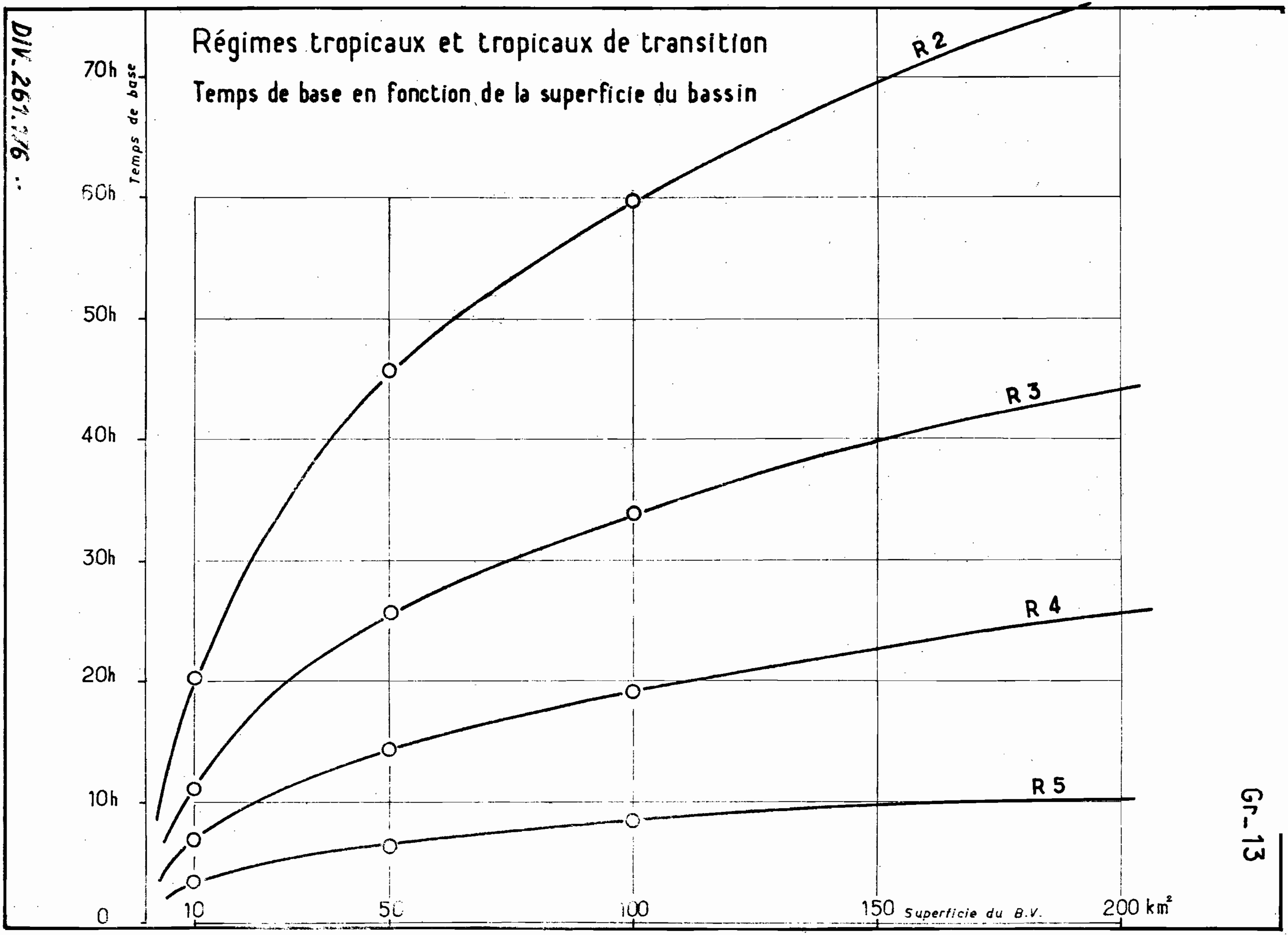
Régimes tropicaux et tropicaux de transition
Temps de base en fonction de la superficie du bassin
Temps de base
70h
60h
50h
40h
30h
20h
10h
0
10
50
100
150
200 km²
Superficie du B.V.
R 2
R 3
R 4
R 5
Gr-13

The relationship $\frac{Q}{M}$ will be taken as 3.2 except for catchments R4 P2 for which it will be taken as 3.5.

Consider a catchment of 150 km2, R4 P4, 10 year point precipitation 130 mm.

The coefficient of area reduction is 0.85. The average precipitation over the catchment is 110 mm. The coefficient of run-off is 28 %.

The volume of run-off will be

$$110 \times 0.28 \times 150 \times 10^3 = 4,610,000 \text{ m3}$$

The base time from graph 13 is 23 hours

$$M = \frac{4,610,000}{23 \times 3,600} = 55 \text{ m3/sec.}$$

$$K = 3.1$$

$$Q = 55 \times 3.1 = 170 \text{ m}^3\text{/sec.}$$

The base flow will be taken as 5 m3/sec.

Q 10= 175 $m^3$/sec. that is 1150 l/sec/sq. km.

c) For forest areas we have only two examples one for a catchment of 92 km2 and the other for a catchment of 150 km2 (the specific 10 year run-offs are 1600 l/sec/km2 and 250 l/sec/km2 respectively). It is impossible to give true rules for these. Meanwhile the indications are that in a sahelien zone the maximum 10 year runoff will emanate from a smaller tributary in the lower part of the catchment.

## CONCLUSIONS

The methods set out in this note for the use of engineers are more reliable than those given in the previous note : important research has been carried out between the time of the two notes, on 10 year precipitations, the coefficient of area reduction, the coefficient of run-off and the base time, but there is still more to be done to make the methods of calculation precise.

It now remains to take into account the disposition of the drainage network of which the effect on the base time is very important, and of thickly forested areas.

It would be of help to trace the network of different curves for tropical and equatorialsavanah regimes, and also for the various classes of annual precipitation : 800 - 1000 mm., 1000 - 1200 mm., 1200 - 1400 mm etc.. because, for the same RP index and the same annual depth of precipitation KR increases slightly as the annual depth of precipitation increases.

But above all, the principal source of imprecision rests in the classification of catchments in the categories R and P. This classification is not sufficiently fine, and moreover there is no means of saying whether a catchment is P4 or P5 when no discharge measurement has been made there. It is hard to rely on laboratory measurements of permeability, or on the overall data of the catchment ; similarly the limiting precipitation for runoff to occur is very imperfectly defined.

We indicate simply that a very impermeable clay or slatelike rocks not too fractured correspond to P2.

Very fissured non-calcareous rocks correspond to P3 and sometimes P4.

Lateritic formations with their crusts more or less weathered correspond to P4, or P3 if the crust is in good condition.

Ferralitic soils with granitic sands can be classed as P4 and P5.

Gravels/sands often correspond to P5 or P6, when they are particularly permeable.

In forest areas P must be overestimated as we have seen earlier, to take into account the role of the vegetal cover.

The examples which have been given in this present note must be applied with considerable judgement, and a careful examination of the ground, and in particular of the drainage network, to provide acceptable results.

Finally, these rules for calculation are valid for Africa south of the Sahara and West of the Congo (omitting the coastal areas, and areas having more than 2200 mm of precipitation annually). It is not impossible that they will be of value in other regions in particular in tropical areas with neither typhoons nor cyclones, but it would be very imprudent to apply them in such cases without adequately verifying their validity in these countries.