COMITE INTER-AFRICAIN D'ETUDES HYDRAULIQUES (C.I.E.H.)
INTER-AFRICAN COMMITTEE FOR WATER STUDIES (I.C.W.S.)

Bureau Technique
Technical Staff
15, Square Max-Hymans - PARIS-15e

GENERAL STUDY OF EXCEPTIONAL STORMS IN WEST AFRICA

by Y. BRUNET-MORET
Hydrological Engineer
ORSTOM

Translation by : W. E. HERRIDGE
Chief Hydrological Engineer
Public Works Department
MINISTRY OF WORKS AND HOUSING OF GHANA

JUNE 1963

Carried out by OFFICE DE LA RECHERCHE SCIENTIFIQUE ET TECHNIQUE OUTRE-MER (ORSTOM)
24, rue Bayard - PARIS-8e

with the financial support of the FRENCH FUND OF COOPERATION.

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By agreement n° 16/M/62/S of 16 th March 1962, ORSTOM undertook the systematic study of rainfall in West Africa.

This study, based on the analysis of daily records and raingauge records, has as its principal aim the determination of the amounts of daily rainfall of rare frequencies and the establishment of intensity-duration curves for various periods of recurrence, over the whole of West Africa and Tchad.

For very understandable administrative reasons, the results of this study are published country by country. Each publication thus being independent, we have considered it useful to retain in each all the considerations and justifying explanations the methods have used. But it remains that the study has been effected for the whole of West Africa, which assures a wider statistical base and also the possibility of a better understanding of the phenomena, and of better presentation of the completed results.

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A - STUDY OF THE DAILY RAINFALLS OF UPPER VOLTA

1. Observed data

The material which we have had at our disposal includes the observations of 1960, the records of 68 stations totalling about 900 complete years of daily raingauge observations. Alone, a quarter of these stations have a period of abservation of 35 years.

We can firstly make the following remarks on the value of the observations :

- It has frequently happened that a raingauge installed in one locality has had its position moved with a change of observer ; these changes can reach or exceed one kilometre and modify the position of the gauge in relation to the orography, to the dominant wind. But we do not have precise details of these old occurrences, and it has not been possible to take complete account of the changes, which we consider without real importance to the daily rainfall study, the regions studied having a little accentuated relief.

- Certain raingauges can be found in bad positions in relation to pre-existing obstacles or ones which have since been introduced ; trees, buildings ... there is no question of taking complete account of these imperfections.

- There are many errors in observations, the following for example :

  . The observer neglects tenths of millimetres, and systematically rounds off the amount to the millimetre below. This can have an influence, relatively small, on the annual total.

  . It so happens that certain observers, in the case of rains greater than 10 mm, count accurately the number of increments of 10 mm, but write in tenths of millimetres the contents of the last 10 mm. increment ; thus 50.6 mm instead of 56 mm. This can easily be verified from the wrong number of zeros showing in the unit column, and we have not taken into account the years so observed.

  . Negligence in observations is frequent : the observer neglects to measure small storms individually, and these are totalled, less evaporation, with the first storm a little stronger. The number of days of recorded rain is thus reduced, and the greater number of storms of less than 10 mm. are not shown in the records.

. Errors of measurement in relatively old observations prior to 1926 are sometimes difficult to detect if the observer has not specified the medium used. On the creation of the Meteorological Service, the raingauge "Association" and the millimetre scale were lacking. Use was made of scales graduated in cubic centimetres and any old recipient (buckets, medicine bottles), of which the surface area of the mouth was not always correctly measured. In a good number of cases the observer wrote the number of cubic centimetres collected and divided it by 40 to find the amount of rainfall, when contrary to requirements, the surface area of the recipient was not 400 cm2. Certain measurements have had to be corrected, many others have been discarded.

. A delicate point is that of the definition of the "day of rain". The Meteorological Services requires readings to be taken at fixed hours (twice a day), and counts as the day of rain all the 24 hour period (commencing with the morning reading) during which it was measured to be 0,1 mm or more. It can thus happen that a little rain can fall into the raingauge bucket and have evaporated before the following reading. It can also happen that the time of the morning reading occurs during a storm, and that the total amount of this storm will be counted over two different days. We now seek to establish the rule for distribution of rainfall over a 24 hour period, independently of the time of commencement of that period. In certain cases, with the help of original memoranda by the observer the total amount may be re-established. In many other cases this is not possible. It is true to say, that it is very rare, save in meteorological observation stations, that the observer troubles to take a reading before the end of the storm.

. We note further that certain observers are clearly counting heavy morning dew as rain.

To conclude these remarks on the value of the observations, we think meanwhile, on the whole they are good, otherwise it would not be possible to disentangle the general trends of the distribution to make them more precise later on.

2. Method of study

The number of years of observation, at the most 40 for the best stations, does not permit the estimation with sufficient precision of the value of the rainfall amount with a probability of once in 5 years, only to the extent of arranging daily raingauge records in decreasing order.

For a station observed over 40 years for example, the deviation between the 10 heaviest depositions at each station varies in much too irregular a fashion for the 4 th value which would correspond to the 10 year frequency to be chosen, a method which would very effectively give the ten year storm : a value distinctly too low can be obtained if the number of very heavy storms has been abnormally low during the 40 years considered, or a value distinctly too high if the number of very heavy storms has been abnormally high. Meanwhile the distribution of all the classified values, as has been said above, shows, for those stations studied, common factors which tend to facilitate our task.

a) First considerations on the distribution of daily rainfall

The daily rainfall figures of stations are classed in descending order, starting with the N (N number of years of observation) first values, than the others by incremental groups of 10 mm down to 0,1 mm.

If we express in semi logarithmic co-ordinates : p, the amount and log r, logarithm of the rank r, we establish that the representative points form a straight line over a certain distance - from p = 10 or 20 mm. until r = about N. It deviates for very high and very low frequencies.

To facilitate the comparison of representative diagrams of various stations, it would be interesting to define the lines which are set out on the diagrams with respect to two characteristic points. The first characteristic point of the line of agreement is the intersection with the axis of the abscissae, which has for co-ordinate $p = 0$ a value of log r which we designate by log r_o. The point r on the experimental curve corresponding to $p = 0$ is not well known but as we see later on, it is clear that it deviates distinctly from the line of agreement.

We can take as the second characteristic point of the line, that of which the abscissa is

$$\log \frac{r_o}{10}$$

This point is always situated both on the curve and on the line of agreement when in practice the stations have more than 10 storms per year,

$\frac{r}{10}$ is therefore greater than N. The ordinate corresponding to

$\log \frac{r_o}{10}$ is designated by p_1.

We establish that the product $r_0 \times P_1$, for the various stations is proportional to the product N.P. (N number of year, P average annual rainfall) :

$$r_0 \times P_2 \times K = N \times P \quad (1)$$

If we determine graphically the coefficient K for each of the 119 stations of MALI and SENEGAL (stations having 10 or more years daily observations at their disposal) it is found that K is effectively constant : its average value is 0.456.

The deviations, in relation to that value, are very low, they can be specified as follows : given K_1, one of the values of K, the average being 0.456, n the number of raingauge stations, the dispersion is defined by the deviation value :

$$s = \sqrt{\frac{\sum (k_i - 0.456)^2}{n - 1}}$$

It is found that this deviation value is equal to 0.009.

The coefficient of variation which is equal to the relationship of the deviation value to the amount of uncertainty allowed for it, being given here the value K, is equal to :

$$\frac{0.009}{0.456} \text{ , that is } 2\ \%.$$

The coefficient of variation, very small, shows that in practice one can accept that K is to all intents and purposes a constant.

The existence of this effectively invariable K shows that the whole of the daily rainfall distribution which we have studied follows a unique relationship, and we have, in the following paragraphs looked for a mathematical representation which approximates as closely as possible to that relationship, one which we cannot hope to find in the actual course of the studies.

What is the practical significance of the formula found above ? It is granted that the line of agreement coincides with the actual curve of the points representing p as a function of r, as far as the axis of the abscissae. The abscissa r_0 then becomes the total number of observations of days of rain.

$\frac{r_0}{N}$ is the number of daily precipitations per year.

If $\bar{p}$ is the average of the daily precipitations, we have :

$$P = \frac{r_0 \quad \bar{p}}{N}$$

and under these conditions relationship (1) can be written :

$$K\, r_0 \quad P_1 = r_0 \quad \bar{p}$$

$$\bar{p} = K\, p_1$$

but, the distance along the axis of the abscissae between the point $\log\ r_0$. and the point $\log\ \frac{r_0}{10}$ is constant and equal to 1.

p_1 therefore defines the slope i of the lines of agreement.

If p_1 were constant, that is to say if $\bar{p}$ were constant for all the stations, all the lines would be parallel. This is not true in reality, and, under these conditions, the slope of the lines is a linear function of $\bar{p}$ which increases slightly with P.

The greater the amount of annual precipitation, the more the slope of the line increases, which indicates that the number of days of rain increases less quickly than P (average annual rainfall). Unfortunately all this assumes that the experimental curve is identical with the line of agreement, which is not always correct. The explanations which we give therefore remain approximate. Without any excuses, the exact number of days of rain is very difficult to determine because the observers count dew as rain, do not always count small storms, etc ... so that even if the experimental curve were adjusted near the extremity of the line, it would be difficult to arrive at a precise value for $\bar{p}$ and from this, at an exact determination of the various parameters defining the group of lines.

b) <u>Choice of the relationship</u>

Having determined that there exists a unique relationship defined by an invariant between the lines of agreement of the experimental curve, we have tried to formulate a simple mathematical relationship for this group of experimental curves.

We have envisaged a relationship of exponential form and a gausso - logarithmic relationship, the analytical procedure being graphical in both cases. The agreement between the rainfall amounts of given frequency determined following the two is very good up to the probability of once in 10 years. The agreement is not so good for more rare frequencies, the gausso-logarithmic determination corresponding to heavier rains in all cases. The exponential relationship risks leading to under-estimated values, which would be dangerous. It is for this reason that we choose to work to the gausso-logarithmic relationship.

c) <u>Use of the Gausso-logarithmic law</u>

M. ROCHE has already studied the distribution of tropical daily rainfall amounts (non cyclonic) for a certain number of African stations between 4° S and 17° N. Whilst considering the amounts as a group of indeterminate independent variables, he has accepted that they follow a garbled form of gausso-logarithmic law.

Before expressing the relationship more precisely, it seems necessary to give a brief revision of the representative definitions for this type of law.

A gausso law is of the form :

$$F(x) = \frac{1}{s\sqrt{2}} \int_{-\infty}^{x} e^{-\frac{1}{2}\left(\frac{x - \bar{x}}{s}\right)^2} . dx$$

F (x) being the probability, or the number of chances in 100 for the indeterminate variable studied to be less than or equal to the value of x. For a very high value of x, F (x) will approach 1. One uses most frequently the probability of exceeding, which is equal to 1 - F (x).

$\bar{x}$ is the arithmetic mean of the indeterminate variable x.

s is its deviation of the type : $\sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}}$

The Gausso formula is most frequently written in the following form :

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-\frac{1}{2}u^2} \, du \quad \text{with} \quad u = \left(\frac{x - \bar{x}}{s} \right)$$

The values of F (x) are furnished by tables of GAUSSO integrals as a function of u, called the reduction chart.

The curve representing

$$e^{-\frac{1}{2}\left(\frac{x - \bar{x}}{s} \right)^2}$$

is symetrical, which indicates that very high and very low values of the variable, which have the same deviation in relation to $\bar{x}$, have the same probability.

In other words, if one consideres annual precipitations, if $\bar{x}$ = 1,400 mm, and if the 10 year wet rainfall is 2,000 mm, the 10 year dry year deposition accordingly of the same probability, is equal to 1,400-(2000 - 1400) = 800 mm. This in fact is not true due to a number of phenomena, for example the curve of daily storm amounts is assymetric. One then comes back to the Gausso Law and takes a reduced value equal to a linear function of the logarithm of the variable :

$$u = a + b \log x$$

We then have a gausso-logarithmic law.

In all strictness, one should for a given rainfall station, consider the collection of all the daily records, including the values $x = 0$, that is to say the days on which there is no rain. For one year (not a leap - year) one therefore should have 365 values.

However, in most applications we consider only the amounts of precipitation greater than a given limit and most frequently than the limit 0, that is to say we take into account only the values which are not zero. We are concerned, in this case, with what is called a distorted distribution.

If $F_1(x)$ is the probability for the daily amount of precipitation to be greater than or equal to x (in relating that probability to the 365 daily amounts for the year, which include the days of nil precipitation) $F_1(o)$, the probability for the amount of rain to be greater than 0 (for example, if the number of days of rain is an average of 122 days per year, $F_1(o) = \frac{1}{3}$,

$\frac{F_1(x)}{F_1(o)}$ is the distorted probability.

The being granted, the logarithmic law is written as follows :

$$\frac{F_1(x)}{F_1(0)} = \frac{1}{\sqrt{2\pi}} \int_u^{+\infty} e^{-\frac{u^2}{2}} du$$

$$\text{with} \quad u = \frac{\log x - \overline{\log x}}{s}$$

- $F_1(x)$ is the probability for x to be <u>greater than or equal</u> to x, (probability related to the <u>total number of days</u> the observations last)

- $F_1(0)$ is the probability that the amount will not be nil

- $\overline{\log x}$ is the average of all the values of log x, and takes into consideration only the number of rainy days.

- s is the deviation value of log x.

Experience shows that the fit does not hold true between the Gausso-logarithmic law and the experimental curve the former giving $F_1(o)$ little less than the experimental value. The direct determination of $\overline{\log x}$ and s would be very laborious ; a graphical procedure is used for each station.

Under these conditions the operations carried out for each rainfall station are as follows :

- arrangement of the daily rainfall amounts in descending order, and determination of their distorted frequency

$$\frac{F_1 \quad (x)}{F_1 \quad (0)}$$

For the value of F_1 (0) one can take for a trial attempt, 2/3 of the experimental value.

- placing the points on gausso-logarithmic paper and taking from the abscissae (logarithmic scale) the amount in millimetres, and from the ordinate (gausso scale) the corresponding distorted experimental frequency (see graph. 2).

In practice one takes the first 20 values, when one considers only the storms in 10 mm increments up to the amount of 10 mm.

- the points having been aligned, by virtue of the relationship indicated above, the greater part of the curve is thus traced. The alignment of the points is checked. If the alignment is not sufficiently true, a new attempt is made with another value of F_1 (o). We return later on to the choice of F_1 (o).

- once the points are aligned as well as possible, one can determine from the graph the values of $\overline{\log x}$ and s which serve the chosen value of F_1 (o), to calculate the amounts x corresponding to the given probabilities F_1 (x).

In effect : $\log x = \overline{\log x}$ corresponds to $u = 0$ and for

$$u = 0 , \frac{F_1 \quad (x)}{F_1 . \quad (0)}$$

distorted frequency is equal to $\frac{1}{2}$. It is sufficient to take on the graph the abscissa corresponding to that value of ordinate.

Moroever it is the slope of the line in relation to the axis of ordinates. It can be determined practically by considering the ordinate point

$$\frac{F_1 \ (x)}{F_1 \ (o)} = 0{,}001 .$$

It seems that the determination of $\overline{\log x}$ and of s will be of no help, since it is sufficient, to find x corresponding to the given value of F_1 (x), to take

$$\frac{F_1 \ (x)}{F_1 \ (o)}$$

as ordinate on the representative line of the general relationship, which is determined graphically. But in the research which preceeded the placing of daily precipitations of low frequencies as points on the plan, it was very important to verify if the parameters F_1 (o), S and $\overline{\log x}$ formed simple relationships with the average amount of precipitation or with the latitude. It will be seen later on that this research has not given very satisfactory results.

If the graphical determination of $\overline{\log x}$ and of s does not present any difficulty,it is not the same for F_1 (o); in fact for a considerable variation of that value, the points remain aligned. But fortunately, as can be seen by the following example, a bad determination of F_1 (o) does not have a big influence on $\overline{\log x}$ and s, and even less on the values obtained for the amounts of precipitation of rare probability.

Take the case of a station for which the gausso-logarithmic relation can be defined exactly by :

$$F_1 \ (0) = 0{,}100 \qquad s = 0{,}300 \qquad \log x = \overline{1{,}173}$$

Suppose that, instead of taking F_1 (0) = 0.100, it has been taken as 0.080 or 0.125. Set out graphically the representative points obtained, and divide the experimental F_1 (x) by F_1 (o) and take the x abscissa corresponding to the values of x varying by increments of 5 mm. It is seen that on the two new diagrams the points remain perceptibly aligned for the values of x between 25 and 100 mm. Determine $\overline{\log x}$ and s graphically for the two new lines, similarly the daily amounts of low probability ; the table here under is obtained :

F_1 (0)	0.080	0.100	0.125
log x	1.230	1.173	1.114
S	0.286	0.300	0.315
Daily amounts of annual probability	56.4 mm	56.2 mm	56.1 mm
Once in 2 years	68,4 -	68.4 -	68.4 -
- 5 -	86.1 -	86.4 -	87.1 -
- 10 -	101 -	101,5 -	102 -
- 20 -	116.5 -	118 -	120 -
- 50 -	140 -	142 -	145 -
- 100 -	159 -	162 -	167 -

Notwithstanding a big variation of F_1 (o), the extreme values of the amount of 10 year rain, 101 and 102 mm are very close, and similarly for the 100 year precipitation the variation is quite acceptable.

The uncertainty in the choice of F_1 (o) therefore has no serious effect on the result. On the other hand, it introduces a certain dispersion in the comparison of values from the same parameter for various stations.

3 - Results of the analysis

The following table summarizes the results obtained by analysing by a gausso-logarithmic law, the records of 30 stations in Upper-Volta for which we have 10 years or more of daily records.

We give by stations :

- the average annual amount of rainfall in millimetres

- the number of years of observation

- the values obtained graphically for F (o), $\overline{\log x}$ and s which determine the law of distribution. From them are deduced in each case the amounts of precipitation corresponding to various frequencies

- the values in millimetres of daily amounts of annual probability and of probabilities once in 2 years, 5 years, 10 years, 20 years, 50 years and 100 years.

We have added, beside the calculated values, the experimental values in millimetres of the daily amounts of annual probability and probabilities once in 2 years and once in 5 years taken directly from the daily rainfall records.

The agreement between the calculated values and experimental values is good for annual probabilities and for once in 2 years, less good for the probability of once in 5 years, which is normal when the stations have periods of observation covering generally less than 35 years. The gauging is then insufficient to determine a precise value of the 5 year storm, and the extrapolated value taken from the adjusted line is more reliable.

AMOUNTS OF EXCEPTIONAL DAILY PRECIPITATIONS

AT VARIOUS OBSERVATION POINTS IN MM

UPPER-VOLTA I

Stations	$F_1(0)$	$\overline{\log x}$	s	N°. of year	Average annuel	PROBABILITIES annual		1/2 years		1/5 years		1/10	1/20	1/50	1/100
DORI	0,0548	1.307	0,238	25	546	49,9	50,0	59,3	56,7	72,4	71,0	83,2	94,4	110,2	123,0
DJIBO	0,0645	1,278	0,288	10	609	59,4	60,2	72,8	66,7	92,3	70.2	108,6	126,2	152,1	173,4
TOURCOING-BAM	0,1467	1,006	0,351	14	653	54,6	60,0	67,9	68,8	88,1	97;1	105,7	125.3	154.9	179.9
KAYA	0,0782	1,257	0,257	35	706	52,8	55,0	63,0	65,0	77,4	76,0	89,1	101,6	119,7	134,3
BOGANDE	0,0727	1,257	0,292	13	711	59,7	58,7	73,1	72,3	91,6	83,7	108,9	126,8	152,8	172,5
OUAHIGOUYA	0,0877	1,217	0,288	25	725	56,6	54,3	68,7	66,2	86,3	82,9	101,2	117,0	140,0	159,2
KANTCHARI	0,0761	1,305	0,264	18	782	60,3	54,2	72,3	70,5	89,3	85,8	103,5	118,6	140,0	157,8
TOUGAN	0,0922	1,225	0,285	27	791	58,3	59,0	70,6	67,9	88,5	85,8	103,5	119,7	142,9	162,6
YAKO	0,0952	1,243	0,281	18	813	59,8	55,0	71,9	69,4	99,7	73,8	104,5	120,2	143,2	162,2
KOUPELA	0,0896	1,242	0,300	34	821	63,7	62,3	77,8	79,0	98,6	92,7	115,9	134,9	162,9	186,2
DUAOAGA	0,0958	1,258	0,272	22	841	59,6	58,5	71,3	72,4	88,3	83,0	102,3	117,2	139,0	156,7
NOUNA	0,0967	1,253	0,271	21	845	58,7	59,0	70,3	68,7	86,9	94,0	100,7	115,3	136,5	153,8
OUAGA-V	0,0951	1,257	0,280	32	868	61,5	58,7	74,0	74,0	92,0	94,9	107,2	123,3	146,9	166,3
SARA	0,0922	1,280	0,263	17	871	59,7	59,8	71,1	69,6	87,3	84,3	100,7	115,1	135,5	152,4
KOUDOUGOU	0,1042	1,222	0,311	35	881	66,8	65,0	81,8	73,3	104,2	83,0	123,0	143,9	174,2	199,5

UPPER-VOLTA II

AMOUNTS OF EXCEPTIONAL DAILY PRECIPITATIONS
AT VARIOUS OSBERVATION POINTS IN MM

Stations	F_1 (0)	$\overline{\log x}$	s	No of year	Average annual	PROBABILITIES annual		1/2 years		1/5 years		1/10	1/20	1/50	1/100
OUAGA A	0,1096	1,207	0,307	10	901	64,4	57,2	78,5	77,1	99,5	109,7	117,2	136,5	164,8	188,8
GARANGO	0,0979	1,270	0,276	14	903	62,7	61,0	75,2	76,0	93,3	103,2	108,4	124,5	147,6	166,7
FADA'N GOURMA	0,0870	1,293	0,284	21	908	66,2	63,0	80,2	80,4	100,5	100,3	117,2	135,5	161,8	183,7
MANGA	0,0952	1,296	0,278	12	941	66,7	65,6	80,2	87,0	99,5	96, 3	115,9	133,0	158,5	179,1
TENKODOGO	0;0947	1,295	0,294	34	967	71,4	71;4	86,5	86,5	108,9	109,7	127,6	148,3	177,8	202,8
DEDOUGOU	0,1042	1,270	0,292	35	969	68,5	67,0	83,0	80,2	104,0	110,2	121,6	140,6	168,7	191,9
BOROMO	0,1039	1,270	0,281	31	990	65,2	65,0	78,3	72,7	97,5	91,8	113,2	130,3	154,9	175,4
LEO	0,1118	1,242	0,296	35	990	66,8	67,0	80,9	72,6	101,6	91,3	119,1	137,7	164,4	187,9
PO	0,1088	1,268	0,287	18	1013	67,6	68,0	81,3	82,0	101,4	100,0	118,2	136,5	162,9	184,5
PAMA	0,1039	1,290	0,282	12	1020	68,6	65,8	82,4	78,4	102,6	101,7	119,4	137,4	163,7	184,9
HOUNDE	0,1074	1,271	0,294	30	1045	70,0	64,9	84,7	77,8	106,2	109,5	124,7	143,9	172,6	196,3
GAOUA	0,1217	1,277	0,277	30	1158	67,9	68,2	81,1	77,6	100,2	90,0	115,9	132,7	157,4	177,4
BOBO-DIOULASSO	0,1014	1,323	0,269	27	1169	69,3	69,4	82,8	81,1	102,1	102,1	117,8	134,9	159,2	179,5
BADIE	0,1267	1,266	0,311	16	1170	78,5	72,4	95,5	91,1	121,1	102,5	142,6	166,0	200,4	229,6
BANFORA	0,1303	1,260	0,302	25	1181	74,8	73,0	90,6	82,8	113,8	95,0	133,4	154,5	185,4	211,3

4 - Discussion of the results of the analysis

The stations have been classified in table n° 1, by region and by increasing amount of annual precipitation. It is thus made easy to separate firstly the general tendencies which may exist in the variations of the different parameters.

It is found that F_1 (o) clearly increases with the amount of annual precipitation and changes from 0.05 to 0.13 when the latter rises from 550 to 1150 mm, apart from some deviating points (such as TOURCOINGBAM with P = 653 mm and F_1 (o) = 0.1467). The low maximum variation of the amount of annual precipitation in Upper-Volta hides the variation of $\overline{\log x}$ of which the various values are grouped between 1.20 and 1.30.

The deviation - value S varies between 0.257 and 0.311 without taking account of the annual precipitation (graph 3) ; the dispersion is large (0.238 and 0.351 constitute extreme values recorded at DORI and TOURCOINGBAM). For all the 30 stations of Upper-Volta, totalling 706 years of observations, the weighted average of the deviation - values is 0.286, with a coefficient of variation of 6 %.

It is evident that a certain number of non conforming points correspond to the non-conforming values of F_1 (o). One can attempt after what has been said earlier to choose F_1 (o) so that it varies regularly from top to bottom of table 1. But we see later that the dispersion in the values of F_1 (o), s and $\overline{\log x}$ is certainly due, for several stations, to physical causes independent of the small quantity of gauging statistics and of the errors which can be introduced in consequence of the arbitrariness which enters into the adjustment procedures. Under these conditions to choose F_1 (o) in such a way that it varies very regularly with the amount of annual precipitation would react to distort the basic data available, which must be avoided at all costs, at least during the actual course of the studies.

Notwithstanding effective research in several directions we have not linked individually the constants of the distribution F_1 (o), $\overline{\log x}$ and s with the annual amount of precipitation. Contrary to what has been osberved in MALI and SENEGAL, the raingauging regime in UPPER-VOLTA is relatively homogeneous, so it is necessary to look for an explanation of the dispersion of the results both in the sometimes doubtful character of certain records and under the influence of local climatic conditions (microclimates).

Several studies relating to the influence of microclimates, such for example as that of the catchment of KOUILOU have been carried out at certain stations, frequently subject to violent storms, and at others which, on the contrary, rarely have such occurrences.

The stations are generally very distant one from another, so that a systematic study of these peculiar localities is impossible. Meanwhile, in the region of DAKAR (Republic of Senegal), well known for the irregular distribution of tempestuous storms, there are five stations fairly close to one another (they are at spacings of less than 6 km) from which can be obtained an idea of the effects of this heterogenity on the amounts of exceptional storms.

The study of rainfall records for these 5 stations on Cape Verde shows a hetrogenity both in annual amounts of precipitation and in amounts of 24 hours storms, most particularly from the 5 year frequencies upward. It is true that the same study, by close analysis of the variation of each gauging with the help of various tests by SNEDECOR and BARTLETT, shows that this heterogenity cab be put down solely to an insufficiency of gauging records (20 years, as it happens).

We are not even sure that a series of 40 years would be sufficiently long to furnish a precise result after processing in a gausso-logarithmic manner.

All this shows that there is no reason to be alarmed at the non-conforming values of table 1, and that there is not much hope of eliminating them completely.

But it would not be necessary to deduce more than, that by reason of the existence of this fairly high number of non conforming points, full generalization and full interpolation are impossible . The situation near the island of Cape Verde, without being exceptional, does not correspond to the general situation for West Africa, where a fairly flat relief ensures a certain homogenity. One simply remembers, whilst using the maps of exceptional precipitations, some particular localities exist which it would not be advisable to ignore.

With regard to knowledge of exceptional precipitations in its general sense, we note that the data of Table 1 can be reproduced on a map, which will automatically eliminate the non-conforming points.

5 - Exploitation of results

The values which we appear to have determined with the greatest precision are those of daily rainfall with annual probability. For this reason, we have related the amounts of lower frequency to those of annual frequency. We have therefore placed on the graphs, the relationships station by station, of the amounts of probability once in 2 years, in 5 years, in 20 years, to this amount of annual probability as a function of the average annual rainfall (graph 5).

The dispersion of the points on the graphs increases as the probability decreases (we give in an annex graphs corresponding to 1/2 and 1/10, (graph 4) but it does not seem that the relationship can be a function of the longitude. Wehave traced on each graph an average curve representing the variation of this relationship with the average annual amounts. These curves are reproduced on the graph (4) hereafter.

We have traced on the attached maps, the network of average annual isohyets at 100 mm intervals (graph 6) and the networks of lines of equal amounts (at 5 mm intervals) of daily rainfalls of annual probability (graph 7).

This map is less precise than the preceeding one ; to trace the lines we have used the different determined results despite their dispersion, taking into account the number of years of observations.

Both the two maps and the preceeding graph allow the determination, but with what precision it is difficult to determine, of the amounts of daily rainfall at a point up to the probability of once in 20 years. We have not dared to go beyond there. Next is found the map of 10 year precipitations (graph 8).

The lines of equal amounts of daily precipitation of annual and 10 year probability remain essentially parallel to the isohyets at least up to the 900 mm line, as has already been observed in the extreme north of Mali.

To calculate for any point the amount of precipitation corresponding to a frequency which is neither annual nor 10 year, one looks on the chart (graph 6) for the average amount of annual precipitation, on the chart (graph 7) for the daily precipitation of annual probability. Then on graph 5 one finds the value of the relationship between the precipitation of annual frequency and that of the given frequency once, in 5 or 20 years, as a function of the amount of annual precipitation as already found from graph 6.

It is then sufficient to multiply the amount of annual frequency found on graph 8 by this relationship to obtain the amount corresponding to the frequency sought. The frequency most used currently is the 10 year frequency, therefore we have decided to use this procedure and to establish the map corresponding to that frequency (graph 8).

The data furnished by these maps cannot be taken as valid for individual localities ; it corresponds to average situations. For a zone of small extent which, for known reasons, would be particularly exposed to violent storms, it would be necessary to overestimate the values on the map by 10 to 20 %. For a fairly extensive area, for example between 10 and 25 km2, similar local peculiarities would on average cause a reduction in effects .

B - STUDY OF THE INTENSITIES - INTENSITY-DURATION CURVES

The study of the daily rainfall can be considered as a study of the 24 hour intensities, but can be done starting from the daily rainfall records. The intensity study is a matter concerning the occurrences of shortest duration, and the only background documents can be the charts of recording raingauges or pluviographs.

The ideal would be to be able to separate the records covering definite periods of time (for example 5, 10, 15, 20, 30 minutes, etc ...) from these classes we have already prepared for the daily rainfalls, and attempt to draw up a law of distribution.

This method unfortunately is not applicable : not only is the number of years records too small for each station, but moreover, no year is complete, one or more important record is always lacking because the throat or the raingauge is easily blocked (dead insects, vegetable debris, and above all dust and sand blown up by the wind which precedes every tornado).

Old syphon type instruments records are not of great value, breakdowns in their working having been very frequent. We have separated out all those records which were usable in the sphere of precipitations greater than 40 mm/day.

Rocking trough type recorder records have been examined for precipitations greater than 10 or 15 mm/day. No corrections have been made to the original documents, it is probable that certain of them were not useable because not all the instruments would have been regulated before being set to work, and we allow that this type of recorder can perhaps be in error by 10 % before regulation.

The rainfall records have been systematically separated into periods of 5 minutes, starting from the period of highest intensity. For each storm, we have determined the intensity - duration curve. This curve is established as follows : we consider the period of 5 minutes which encloses the maximum (intensity), and calculate its average intensity, then we take a longer period of 10 minutes and calculate its average intensity ; we continue taking a series of increasing values of time interval enclosing the maximum intensity : 10', 15', 20', 30', 45', 60', 90', 120', 150', 300', the average intensity decreasing, of course, gradually, and proportional to the time interval t, or with increasing duration. The diminishing curve of the average intensity as a function of the duration t is the intensity-duration curve.

In the course of this operation, the curve of intensities of precipitation remains just as it is. The intensities are not classed by decreasing values ; that would result, if such were done, in artificial curves which would give rise to errors in their application. The only condition is the choice of the maximum intensity as the starting point for the operation.

Tracing of the intensity-duration curves corresponding to storms of varying frequencies : annual frequency or 10 year frenquency, for example, can be agreed. These curves are determined at the outset from the analysis of the intensity-duration curves for all the storms, or more strictly, for all heavy storms for which records are available.

We have made use of what was available in the sahelien and Soudan zone, between the average annual isohyetals 200 and 1300 mm, from the Atlantic Ocean to ABECHE : a total of 145 station years (incomplete years) for 58 stations. Forty of these stations correspond to raingauges grouped for experimental catchment studies by ORSTOM. Of all the records we have obtainedonly 16 complete records of rainfall of more than 100 mm in 24 hours.

This quantity of rainfall records is menifestly insufficient, as much by reason of the low spatial density of the recorders as by the too short period of their operation, to obtain precise results.

We have grouped the records by zones : 12 zones corresponding to the amount of annual precipitation varying by 100 mm increments, 150 to 250 mm, 250 to 350 mm, etc ... We have established for each zone, intensity-duration curves for daily precipitations of 20, 40, 60, 80 mm, and taken the averages of the intensity durations of the precipitations between 20 mm - 20 % and 20 mm + 20 % etc ...

If we plot the results to logarithmic co-ordinates (durations in minutes, intensities in mm/hr), we see that there is a break in the alignment of the points. This peculiarity is easily explained when one considers the typical form or pattern of tornados ; these in their most simple form have a very short period of fairly weak (rainfall) intensity, the preliminary storm, a period of heavy or very heavy intensity called the "body", and Jurally a period during which the intensity reduces and can continue for a fairly long time at a fairly weak leval ; this last part of the storm is called the tail. The tail can form a virtual second storm in relation to the body. There are moreover, tornados other than these following the classical form ; tornados without a tail, tornados with two or three almost equal peaks, etc ... The break point in the intensity-duration curves separates the body of the storm shown on its left from the tail and the preliminary storm, shown on its right.

The parallelism of the lines representing what we have come to call the tail is good, not only between the different daily amounts in a zone, but equally between the zones. The abscissa, to the point of the break in alignment, remains, for a given amount, perceptibly the same for different zones, and we can accept the parallelism of the representative lines to the left of the break point.

The final diagram corresponding to the BAMAKO zone, one of the best known, is represented on graph N° 9, on which the average intensity-duration curves corresponding to all the daily precipitations of 20, 40, 600 mm are well defined, the curves 80 to 100 mm are less reliable, the curve 120, 140 and 160 are extrapolations.

The different zones studied in fact have boundaries slightly different from those given earlier, the practical limits corresponding to the different groups of raingauges. But as yet it has not been possible to reform the groups to correspond to the same number of stations and station-years. The networks of curves so traced are therefore unequal in value. Their comparison even so allows it to be stated that for daily amounts of equal duration, the intensities increase when the amount of annual precipitation diminishes, at least for the greatest intensities, it will be necessary in relation to the curves of our type graph (graph n° 9) to multiply the ordinates by a factor which is a function of the average amount of annual precipitation.

For an average annual amount of :

200 mm	multiply	the	intensities	by	1.19
300 mm	"	"	"		1.18
400 mm	"	"	"		1.16
500 mm	"	"	"		1.14
600 mm	"	"	"		1.12
700 mm	"	"	"		1.10
800 mm	"	"	"		1.08
900 mm	"	"	"		1.05
1000 mm	"	"	"		1.02
1100 mm	"	"	"		0.99
1200 mm	"	"	"		0.95
1300 mm	"	"	"		0.91

These coefficients are of use in the Sahelien and Soudan zone between the meridians 0° and 12° West. We have insufficient data to ensure their reliability to the west or east of that zone. It appears that they will diminish a little going towards the east.

Too much importance should not be attached to the accuracy of the coefficients given earlier, we do not pretend that their value will be accurate to within about 1 %. Moreover, the zones studied can be, as we have seen earlier, slightly out of position in relation to the zones of the table, this is why graph n° 10 does not correspond exactly to the 1100 mm mark, for which a coefficient of 0.99 is taken in place of 1.00.

We now have available all the data for the determination of the intensity-duration curve corresponding to any point and to any frequency.

One notes for the given point the amount of annual precipitation, from which one calculates the value of the coefficient, then, using the procedure given in the first part of this paper, one determines the exceptional 24 hour storm of the frequency sought. On graph 9 one chooses the intensity duration curve corresponding to the amount of the 24 hour exceptional storm found earlier and multiplies the ordinates of that curve by the coefficient.

Let us consider for example a station situated exactly halfway between DORI and KAYA, and look for the intensity over 45 minutes for the 10 year storm at this place. From graph 6 the annual precipitation is found to be 620 mm, for which the correction coefficient can be taken as 1.12.

It is seen from graph 8 that the 10 years storm at this place will be 98 mm. For such a storm, graph 9 gives us an average intensity of 65 mm/hr. over 45 minutes. For the station under consideration this 45 minutes intensity would be 65 x 1.12 = 73 mm/hour.

To reduce the number of operations of this type, we have for Upper-Volta, as for each other country, drawn intensity duration curves corresponding to the various frequencies. These curves have been established as follows : for any one frequency, 10 years for example, graphs 6 and 8 are superimposed to give the average annual rainfall corresponding to each storm of the same frequency (in this example the 10 year frequency). This matching up does not introduce any difficulty for Upper-Volta, and is carried out with good precision, by virtue of the parallelism of the lines on the two graphs.

This having been done, the ordinates of the basic diagram graph 9 are multiplied, for each frequency, by the correction coefficient corresponding to the amount of average annual precipitation linked to the 24 hour precipitation of the same frequency.

5 graphs (10 to 14) are thus established, for annual frequencies, and for frequencies of one in 2, 5, 10 and 20 years, giving directly the intensity-duration curves for a given frequency.

Suppose, for example, that it is wished to obtain the intensity duration curve for a 10 year storm at OUAGADOUGOU, it is found from graph 8 that the 24 hour storm occurring there once in 10 years is 110 mm ; graph 13 gives directly the intensity-duration curve for such a 10 year storm of 110 mm in 24 hours.

It must not be thought that this procedure gives absolute precision, for there are always exceptions for particular localities. On the other hand, the intensity-duration curves have been established principally on the basis of raingauges installed to the north of the 1200 mm isohyet, in a region where simple tornados with a main body and sometimes a preliminary shower and a fairly long tail of low intensity dominate (example given in graph n° 15).

Multiple storms do not occur north of the 1200 mm isohyet and in the middle of the cool season, but they are mostly encountered in the wettest regions (to the south of BOBO-DIOULASSO) where they become almost as numerous as simple storms during August and September. An example of a multiple storm of duration 4 to 10 hours, sometimes more, with several peaks separated by periods of low intensity is given in graph 16.

The shortage of observations as yet allows neither differentiation of the intensity-duration curves relative to different types of storms, nor their reciprocal probability of appearance. By all means, simple tornados tend to provide the greatest intensities, which tends to act as a safety factor (for estimation purposes).