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FLOOD HYDROLOGY SYMPOSIUM - NAIROBI

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PREDETERMINATION OF THE FLOW FOR FLOODS IN WEST AFRICA FOR SMALL CATCHMENT AREAS

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INTRODUCTION

It is generally difficult in tropical Africa to obtain information on previous flooding of small water courses by making local enquiries. There are various reasons for this, one of the more important being the low population density. In West Africa, in spite of very heavy rain storms, the flow of flood water is not very great for quite a number of locations, as a result of the slight slope of the ground and the small proportion of cultivated surface area. This is why, at the beginning of the century, railway constructors who probably relied on standards that were applicable for France, did not have much difficulty. However the construction of a number of small barrages after the second world war and the simultaneous development of the road network proceeded both in regions where flooding was not to be expected and also in certain areas where run-off was very violent. This was particularly the case in the Sahel region and adjacent areas. A large number of barrages and bridges were destroyed and the responsible authorities, that is the local Engineering Departments and the Hydraulic Services of the Public Works Departments, were obliged to make a general study of the problem. The Federal Hydraulic Service of French West Africa asked the Office de la Recherche Scientifique et Technique Outre-Mer (Office for Scientific and Technical Research Overseas) to equip and study ten groups of typical and representative catchment areas, with a view to determining the magnitude of floods occurring at ten year intervals and hence the resultant flow of water under bridges and over barrages. The Engineering Departments in the different country areas, particularly in the Sahel region, arranged for a certain number of regional studies to be made involving representative catchment areas. So far as ORSTOM (Office de la Recherche Scientifique et Technique Outre-Mer) was concerned priority was given to a study of the flooding of small catchment areas and a number of such areas were equipped for measurement at ORSTOM's expense. Altogether, nearly one hundred groups of representative catchment areas have been studied in French Africa, west of the Congo.

Each catchment area was the object of an analysis with a view to determining the characteristics of the ten year flooding. These analyses were followed by a number of regional assessments. A first assessment for West Africa, as a whole, was made and reported in 1961 by C. Auvray, General Inspector of Research at ORSTOM.

At the request of the Inter-African Committee for Hydraulic Studies, this report was revised and completed in 1965 by J Rodier. The studies for this report were based on the ten year flood characteristics for each representative catchment area as determined by the analyses made for each of those areas, many of these analyses being conducted under the direction of one of the two authors.

At this period, all the calculations were made manually and rain/flow transformation models were very simple. The form of the hydrograph was determined by the unit hydrograph procedure for rain storms producing heavy run-off, the volume of the flood water being determined by the residual method (coaxial analysis). Usually the height of the run-off water (surface run-off) was determined with reference to a principal factor, namely the height of precipitation produced by the rain storm, and a secondary factor which was normally a humidity index. For example in many cases the Kohler humidity index was used. A third factor, related to the intensity of the rain storm was sometimes used but for the first representative catchment areas considered the analyses were of a much more summary nature.

In all cases, determination of the magnitude of the ten year flooding was based on the ten year rain storm for which it was assumed that there was a distribution of intensity similar to that applying in general for very heavy rain storms and on soil saturation (humidity index) corresponding to the conditions that are generally encountered during the rainy season. Given the height of precipitation for this rain storm, the humidity index and average intensity, or another index related to the intensity diagram, the depth of run-off and hence the volume of the flood water was determined using graphs established by the residual method. The maximum flow was determined with a unit hydrograph This procedure is not correct. In fact what is really required is the use of a good rain/flow transformation model and information on a chronological series of individual rain storms over a forty year period for which it would be possible to determine the corresponding floods and with a statistical analysis the characteristics of the ten year flooding. Such a procedure could not be employed without the use of a computer.

Nevertheless, however incorrect our procedure may be, used with care it gives fairly reliable results for 98% of cases.

In order to allow a geographic extension using the results it was necessary to analyse the effects of the different factors of run-off by making the analysis such that the minimum number of factors were involved.

The depth of the ten year precipitation is an essential factor. This factor was the subject of a general assessment requested by the CIEH. This assessment led to the production in 1965 of an initial series of maps giving the daily ten year precipitation heights for the countries of French West Africa.

For this region of Africa there is a degree of correlation between the depth of the annual yearly precipitation P and the depth of the daily ten year precipitation. Fortunately this latter varies rather slowly with the depth of the annual precipitation P. It ranges in fact from 85 mm to 130 mm when P varies from 300 mm to 1400 mm. We considered three climatic regions: the whole of the Sahel and sub-desert regions (P varying from 150 mm to 750 mm), the tropical and the tropical transition regions (P varying from 800mm to 1600 mm) and the forest regions.

In addition, in studying the volume of flood water, we considered the run-off coefficient: ratio between the volume of run-off and the volume of rain producing that run-off which does not vary very quickly with the depth of the corresponding precipitation. Thus we almost eliminated the effect of the depth of the ten year precipitation within each of the three regions as well as that of other climatic factors.

It was then necessary to examine the effect of the following factors: the surface area of the basin, the slope, the permeability of the soil, the vegetation cover, the use of the soil, the shape of the catchment area and the characteristics of the hydrographic network. The last two factors were neglected. Allowance must be made however in the case of very elongated basins or for areas where the hydrographic network consists of lakes and marsh land. In these cases the run-off time must be appreciably increased and in the second case the value of the coefficient is definitely lower than for normal conditions.

The natural vegetation cover is related to the climate and this factor is therefore implicitly accounted for by the division into three regions as described above.

With regard to the use of land, this is not relevant for most cases in West Africa once the area of the basin exceeds 10 km^2, due to the fact that generally a large proportion of the surface area is fallow land and only slight slopes are involved. It is certain however that for intensely cultivated regions the figures obtained by our method should be increased because it is alas rare that effective measures are taken to limit run-off and erosion.

Thus in studying the volume, or rather the coefficient, of run-off, it is necessary to consider in particular the surface area, the slope and the permeability of the soil, the slope being defined by the general slope index namely the average longitudinal slope excluding 10% of the upstream and 10% of the downstream water course and by the transverse slope of the valleys defined in the same manner. Thus the catchment areas were grouped into six categories of R1 to R6.

For the permeability we referred to five categories, P1 to P5 for basins with soil ranging from impermeable to very permeable (sandy or volcanic soil). For the representative catchment areas considered we were guided in this classification by the limiting depth of precipitation beyond which there is run-off. For example, if this limiting depth of precipitation amounts to 20 mm after two days without rain, then the catchment area is considered to be very permeable. However in any geographic extension of the study to other catchment areas this procedure cannot be employed and the classification into a particular category is rather subjective.

In considering the duration of run-off and the rise time for ten year rain storms, the soil being completely or nearly saturated, the permeability factor does not have much effect and consequently only the surface area and the slope have been considered for each of the three regions considered.

Thus using the data for the representative catchment areas we plotted diagrams showing the variation in the values of the run-off coefficient K_R as a function of surface area for each pair of classifications R and P.

In fact since there was not a sufficient number of catchment areas involved we plotted for each region a family of curves corresponding to a given value of P_n and all values of category R.

For the family of curves defining the duration of run-off and the rise time as a function of surface area of the basin we considered different categories R.

We finally determined the form of the hydrograph by studying the ratio K between the average run-off flow for the duration of the flood run-off and the peak flow. We studied variations of K as a function of surface area for the three regions involved.

Determining the characteristics of the ten year flood

The operations to be effected, as defined in the 1965 report are as follows:

1. Determine the physical characteristics of the catchment area: surface area, longitudinal and transverse slope, classification in one of the categories of

slope R_i and permeability P_i on aerial photographic maps and as far as possible as a result of a limited survey of the land during which attempts should be made to locate traces of heavy flooding which will allow some comparison with the results of the calculation.

2. Determine the depth of the ten year precipitation using maps established for the different countries of French West Africa.

3. Determine the value of the reduction coefficient namely the ratio between the height of the average ten year precipitation on the catchment area and that for a single point. The report gives a series of values for this coefficient for surface areas varying from 0 to 200 km^2. From these values we can determine the depth of the ten year precipitation P10.

4. Calculate for the ten year flood, the run-off coefficient K_R, using the graph for the geographic region involved, and for the indices P and R selected for basin. An example of the resulting graphs is given on the next page.

From these graphs we can determine the height of the run-off water in mm:

$$E_R = \overline{P_{10}} \times K_R$$

and the volume of run-off:

$$V_R = E_R \times S_{km2} \times 1000$$

5. Determine the duration of run-off or time base T_B using the graph for the geographical region considered and on the basis of a slope R. T_B is given in hours.

6. We then derive the average flow during the duration of run-off in m^3/s:

$$M = \frac{VR}{T_B \times 3600}$$

7. Next we select a value of K, namely the ratio between the maximum flow of the ten year flood Q and the average flow M, which varies according to the vegetation cover (that is, in this case, the value depending on the geographical region) and the surface area S in accordance with the values given in the 1965 report.

   From this we can determine Q = KM, K varying between 1.7 (tropical forest) and 4 (basin having very violent run-off and a surface area of the order of 100 km^2). The values V_R and Q are of prime importance for the Engineer.

8. For the very small catchment areas, for which the ten year flood hydrograph no longer has a unit value since the duration of the ten year rainstorm is too long, special rules apply in calculating the duration of the time base.

9. For basins having a surface area lying between 120 km^2 and 200 km^2, special rules also apply.

<u>Limitation of the procedure</u>

Estimates of the depth of the ten year rainfall at a single point are not necessarily accurate. Altitude has an effect here. Above 1 000 m there is certainly an appreciable reduction in the depth of the ten year precipitation for a given depth of annual precipitation, the reduction amounting perhaps to 20%. However there are not many large mountainous masses in West Africa so that this source of error is not often involved. Moreover there is the effect of any particular exposure, for example, the location of a point being considered with respect to a line of hills.

The value of the reduction coefficient which gives the rainfall on a given surface area in terms of the rainfall at a single point is based on insufficient data.

The method of calculating the ten year flood, for each respresentative catchment area, which is the basis for our graph, can be criticised. Certain figures are probably not sufficiently accurate and others, this is the most frequently occurring case, are affected by the reaction of the Engineer who tends to give figures which are too high in order to have a margin of safety. Finally for other figures the period of observation does not include a sufficient number of heavy floods or alternatively includes too many and this can lead to over or under estimating. The result of all this is that the experimental points on which our graphs are based give values of K_R which are too high or too low and since in addition there are not many points, the curves cannot be drawn accurately.

The choice of indices of R and in particular of P for each representative catchment area is not always very strict.

The most difficult matter however is the choice of the same indices for the catchment area where it is required to pre-determine the flood characteristics and this is by far the cause of the greatest errors! The concept of permeability refers to the overall value which is related, in some degree, to the permeability determined with soil samples, but this relationship is very indirect. The existence of a village with impacted and very impermeable soil can completely change the flood characteristics of a small catchment area which otherwise has a permeable surface.

In fact, the 1965 report is simply a guide which to a large extent can only be used with safety by hydrology specialists and where each case is considered with a great deal of common-sense as illustrated by the example quoted above.

We have attempted to improve the situation since issuing this report but at the present time we are far from being satisfied with the results of our investigations.

<u>Investigations made since 1965 with a view to improving the method of calculating ten year flood characteristics</u>

1. <u>Depth of the ten year rainfall</u>

ORSTOM, at the request of CIEH and the French Ministry of Cooperation, have undertaken a review and systematic examination of all field data concerning the depth of daily precipitation in West Africa. But firstly we have established and published an indexed list of the raw data based on the <u>original</u> measurements and observations and following corrections of the larger errors. This work is now complete and the data is being published. Secondly we are establishing a list of operational data following a systematic correction of errors (re-location of a rain gauge or an ill-timed change in taking a sample). This list will be given in another communication.

2. <u>Study of the reduction coefficient</u>

This coefficient was defined above. It is in this field that the greatest progress has been made. The principles for analysing the raw data with a view to determining the value of this coefficient had been rigorously defined by Y. BRUNET-MORET, but there remained a need for a series of studies involving representative catchment areas and including necessary investigations concerning factors likely to have a sensible effect on the value of the coefficient. This latter work was in fact carried out by G. VUILLAME and completed in 1974.

It should be understood that this concept of a reduction coefficient is only directly significant for regions <u>where there is little relief</u> and this is the case for a large part of West Africa. In such conditions, the parameters of the law for the statistical distribution of the daily precipitations varies only with the depth of the annual precipitation with the exception of the coastal region of MAURITANIA and SENEGAL and in the case of particular local conditions which will be considered later.

It will be recalled that the law involved is a truncated PEARSON equation

$$F_1(x) = F_1(0)\frac{1}{\Gamma(\gamma)}\int_x^{\infty}(dx)^{\gamma-1}\,e^{-ax}\,a\,dx$$

The parameter γ is constant, bearing in mind the reservations mentioned above and has a value of 0.7. The parameter a varies with the height of the average precipitation. Certain local geographical conditions can however affect the value of γ: isolated relief, forest, areas of water near to the station. Altitude also has an important effect for heights greater than 1000 m, which is rather rare in West Africa.

The investigations concerning the reduction coefficient require the collection of data from a rain gauge station over a long period and this station should not be subjected to the influence of any local perturbations. Thus it is necessary to base the study on a fictitious law of distribution corresponding to rain measuring stations which do not suffer from any of the singular conditions mentioned above and for which the results can be represented by curves on ten year precipitation maps with $\gamma = 0.7$.

A complete investigation was made with a representative basin having a surface area of 126 km^2 namely the catchment area of RISSO (Cameroons) that was divided into a number of sub-basins of different surface areas in order to study the influence of different physio-graphic factors on the reduction coefficient. The same type of investigation was made in a more extensive manner with three other basins (and their sub-basins): those of GHORFA (Mauritania) 1125 km^2, of BAM BAM (Chad) 1200 km^2 and of AMITORO (Ivory Coast) 170 km^2. Each basin was associated with a rain gauge station where observations were made over a long period, the coefficient γ in the Pearson equation being returned to its initial value of 0.70 as necessary.

The results for the four basins are in agreement. Providing we eliminate the affect of relief, the reduction coefficient varies inversely with:

- the logarithm of the surface area of the basin
- the logarithm of the recurrence period for the daily rain-fall for a given surface
- the scale parameter for the law of distribution for the daily precipitation

Conversely the value of the coefficient varies directly with:

- the height of the annual precipitation

If we simplify the equation, taking account of particular conditions in West Africa, then K is given by the following relation:

$$K = 1 - (9 \log r - 42\ 10^{-3}\ P + 152)\ 10^{-3}\ \log S$$

where

r = recurrence period for the exceptional rain storm in years

P = height of the annual precipitation in mm

S = surface area of the basin in km^2

With this equation we can plot the graph given on the next page.

For the 1000 mm annual isohyete, the reduction coefficient for a ten year rain storm has the following values:

S = 3 km^2	K = 0.95
S = 10 km^2	K = 0.9
S = 25 km^2	K = 0.83
S = 50 km^2	K = 0.80
S = 100 km^2	K = 0.76
S = 150 km^2	K = 0.74
S = 200 km^2	K = 0.72

It will be recalled that in the 1965 report we assumed a value of K = 0.95 for $25 < S < 50$ km^2, a value which is clearly pessimistic. It should of course be understood that a further study in determining the value of this coefficient would be necessary for higher altitude regions and where there is a fair amount of relief.

It must be remembered that the determination of the ten year flood is based, at least for West Africa, not on the real law for the distribution of daily precipitation but on a fictitious law with γ = 0.70 or values of ten year precipitation taken from maps. This however is not the case for coastal regions or at high altitudes where it is best to assume a real distribution law.

The best conditions for these investigations are with basins provided with at least fifteen rain measuring stations with good quality measurements being made for a period of at least four years.

3. Methods for analysing the rain/flow relationship for a given basin

There has been a great deal of progress in this field since 1965. For most of the representative catchment areas at present under observation, the raw data referring to precipitations and flows are the subject of computer processing. This in effect eliminates data processing errors and satisfactory models have been established for transforming rainfall into flood data. Thus it is possible to use as inputs, the rainfall data from a measuring station obtained over a long period, to make assumptions based on an average diagram and rainfall intensity and hence to determine the corresponding flood data, the ten year flood information being derived as a result of a proper statistical study. This procedure is relatively straightforward for representative catchment areas at present under observation but the processing of data from old representative basins gives rise to difficult problems. A considerable amount of work is involved in preparing the raw data for going on to punched cards and in the preparation of the punched cards themselves. In addition, automatic processing requires that the rainfall data be of good quality and that there should be few omissions. An appreciable number of old representative basins do not meet this requirement and data can only be analysed manually. For these reasons it has not been possible up to the present time to revise the ten year flood data which served as a base for the 1965 report.

4. Study of the rain/flow relationship as a function of the conditioning factors

These conditioning factors are the surface area of the basin, the slope, the permeability of the soil, the characteristics of the hydro-graphic network and the percentage and type of culture.

a) Effects of slope

A systematic geomorphologic study, which will be considered further below, allowed a classification of relief for the representative basins considered in the 1965 report. It was noted however that the slope index does not represent all the relief characteristics. There are some important exceptions. For example in the case of a basin in the Sahel region, if the upstream part has a steep slope with the flow from this uneven relief concentrated in a single course of water at the foot of the hills then the flow can be sufficiently vigorous for the water to arrive at the downstream extremity of the basin without much loss. On the other hand if the flows do not come together except at the downstream extremity having a slight slope then a large proportion of the flood water will be absorbed. In both cases the slope index is affected, the slight slope of the downstream part of the basin being compensated by the steep slope of the upstream part. In the first instance the run-off coefficient is high, in the second it is much lower.

A general study of the annual flow for representative basins by P. DUBREUIL and G. VUILLAUME, referred to the effect 'specific unevenness' namely the product of the index for the overall slope by the surface area of the basin. Use of such an index would perhaps give better results than the index of overall slope.

It is unlikely that we will find a slope index that is easy to determine and that gives satisfactory results for all cases.

b) Effect of soil permeability

We had hoped to be able to determine an index of permeability directly based on the data given by pedologic maps, a large number of which are available for West Africa and we made a series of measurements, for an initial group of representative catchment areas, relative to the characteristics associated with movement of water in the soil which is usually determined by Pedology specialists. There has been a great deal of work in the field and laboratory but it has not progressed sufficiently for us to draw useful conclusions. It should be noted that in the case of pedology maps for East Africa, established in accordance with a classification based on pedogenesis, it seems to be very difficult to make use of these maps in determining the physical characteristics of the soils. Tests involved here have however led to improvements in the equipment and procedures for making Müntz permeability tests which can give a first indication regarding the permeability of a given site.

In any case, discussions between pedology and hydrology specialists have shown clearly that in the strict sense of the word a catchment area is very rarely homogeneous. A catchment area involves at least three types of soil corresponding to the plateau, the slopes and the floor of the valleys and these three types of soil generally have different permeabilities. This lack of homogenity is already evident for catchment areas having a surface area of one or two km^2.

A characteristic feature of a homogeneous region is a well defined association of the different types of soils. According to the relative proportions of the different types of soils involved in the association, a representative basin can be classified as either average or a limiting case. Consider a typical example namely the catchment areas of ADER DOUTCHI of the Niger. The plateaus are made up of sandstone and a certain number of faults with argillaceous cements - a very permeable mixture, the slopes consist of argillaceous colluvion and areas of impermeable lime marl while in the case of basins of less than 100 km^2 the soils of the valley floors only involve a small surface area and therefore have negligible effect. In a case like this the concept of an overall permeability is not a simple one.

In studying the basins of ADER DOUTCHI we consider an extreme case namely the basins of GALMI where the proportion of soils covering the plateau is very low, of the order of 10%, and a more normal case namely the basins of MAGGIA (HAMZA and ALOKOTO) where plateaus of sandstone cover 90 to 95% of the total surface area. In calculating the flood conditions we are obliged to consider simply the surface area of the slopes which must be classified in category P1 or P2.

In the case of the Sahel basins with a crystalline subsoil we are also obliged to consider the association of different types of soils but here the association is much more complex. In calculating the annual flow we have defined typical basins corresponding to a given association of different soils with approximate proportions of each type. It is possible that this technique of considering typical basins will result in the best way of classifying representative catchment areas with regard to permeability and lead to the establishment of simple rules for determining the classification of any particular basin being considered. It can be seen that pedology and geomorphology play a role here which is important but difficult to explain.

During the course of the geomorphologic study mentioned above it was noted that there was a rather good correlation between the drainage density $\frac{\Sigma L_i}{A}$ and the likelihood of run-off but again there are a large number of exceptions to this correlation.

It appears that the systematic use of a rain simulator will give a good idea regarding the permeability of different types of soils making up a basin but the use of such a simulator in the field, covering a sufficient surface area, is still time consuming and costly. It will be necessary to compare the simulator results both for known representative basins and those that are to be studied.

c) Form of the hydrograph

A simple procedure for determining the three characteristics of the standard hydrograph where the influence of the operator had been completely eliminated, has been established by M.ROCHE. The rising part of the hydrograph is assumed to be a straight line and its intersection with the absorption curve, also drawn as a straight line, corresponds to the start of run-off. The falling part of the hydrograph is assumed to be a hyperbola which again intersects with the latter part of the absorption curve, drawn with respect to logarithmic coordinates and this latter intersection corresponds to the end of run-off. Thus we obtain a precise definition for the duration of run-off or time base.

However there has been no attempt in West Africa to make a new and systematic study which would allow determination of each of the different characteristics of the hydrograph rise time, time base, etc, in accordance with the physical data of the catchment area and leading to the establishment of equations such as those developed by SNYDER.

CONCLUSIONS

The results obtained, which concern West Africa, can certainly be applied to other tropical regions but great care must be exercised in any such extrapolation. In particular given the very marked relief and the great differences in climate over short distances, the procedures for West Africa are probably inapplicable for extensive areas of East Africa.

Much remains to be done in improving the procedures for determining the flood characteristics of small catchment areas. The most difficult matter is still the classification of basins that are to be studied in a given category of overall permeability as a result of a simple field inspection and some quick measurements.

The influence of hydrographic degradation, as soon as it becomes appreciable, in the Sahel region, is also difficult to assess. It is unlikely that we will ever be able to make calculations giving reliable results using simply a collection of maps or topographic plans. Even after appreciable progress as a result of research a minimum experience of hydrology and a critical attitude will always be necessary.

A problem which has a much less scientific character, but which should not be neglected, is that of transferring the knowledge of the Hydrology Specialist to the Engineers. The Specialist should make an effort first of all in avoiding terminology which cannot be understood by the Engineers and secondly in distributing the results of their work. This is in fact one of the objectives of this present meeting.

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RUNOFF COEFFICIENT K_R SAHEL AND SUBDESERT AREA (P. YEARLY BETWEEN 150 TO 800 mm)
PERMEABILITY P3

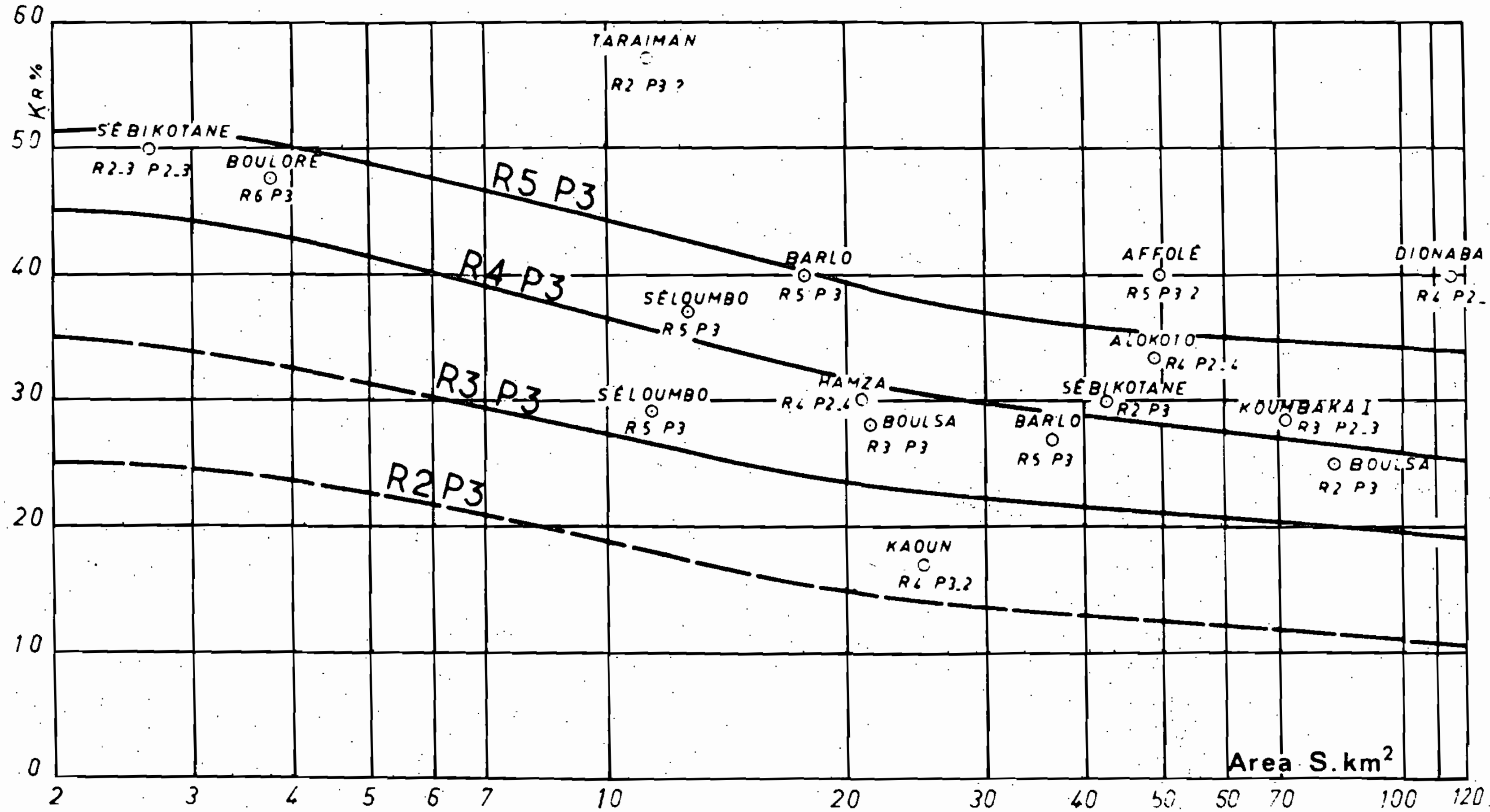

Fig:1

RELATION BETWEEN REDUCTION COEFFICIENT ($K = \frac{P.AREA}{P.POINT}$) AND AREA S. OF THE CATCHMENT FOR VARIOUS ANNUAL PRECIPITATION DEPTHS. Pmm.

(Scale parameter s = 20)

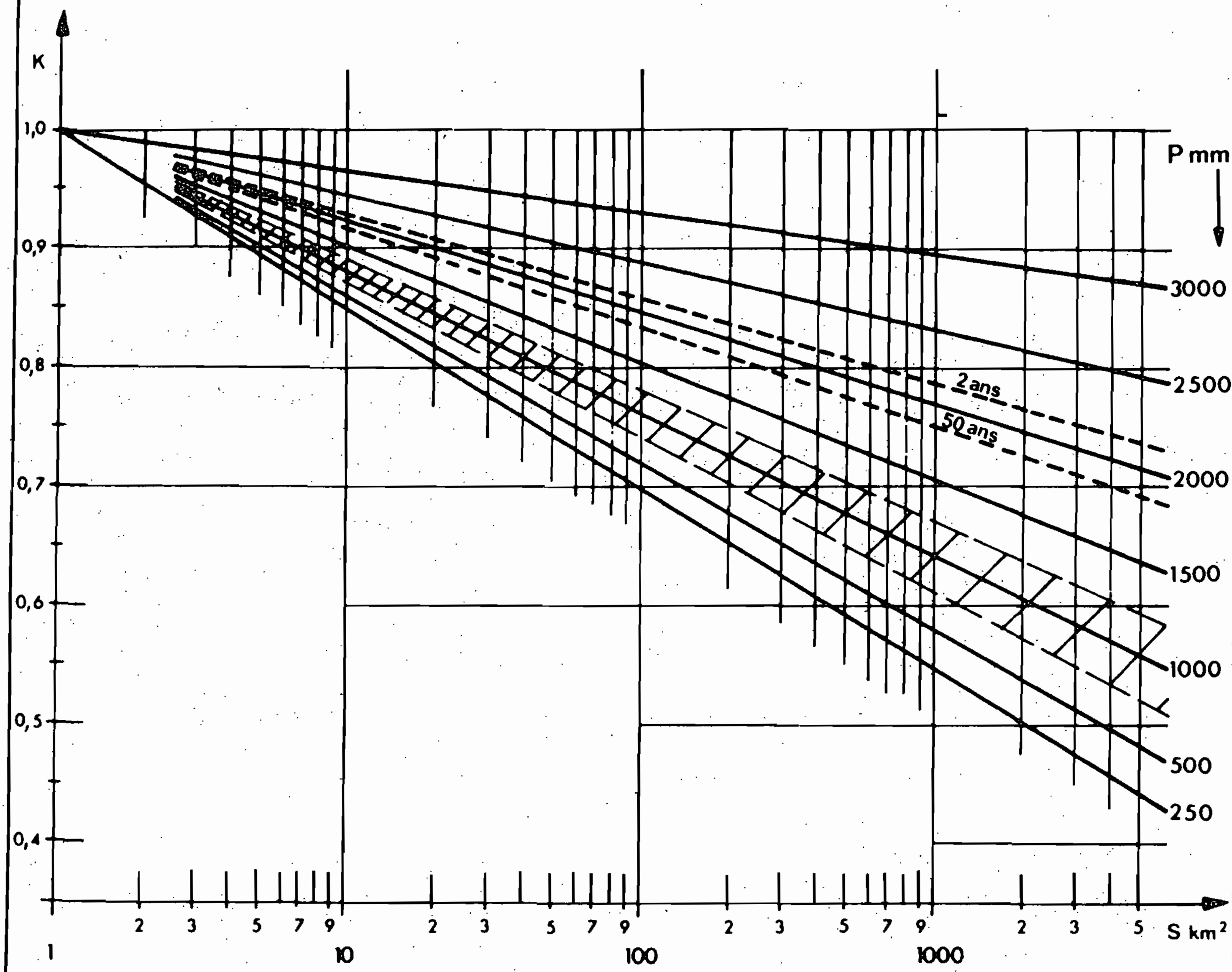

Fig: 2