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Utilisation of the results from representative and experimental basins with a view to the management of water resources by J. A. Rodier
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INTERNATIONAL SYMPOSIUM ON THE HYDROLOGICAL CHARACTERISTICS OF RIVER BASINS AND THEIR ROLE IN THE IMPROVEMENT IN THE MANAGEMENT OF WATER RESOURCES.

Utilisation of the results from representative and experimental basins with a view to the management of water resources.

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It is sometimes believed that studies on representative and experimental basins may be classified within the field of fundamental research: this is correct to a certain extent, but in actual fact they may also be directly of great service for the study of water resources management projects. It is generally not necessary to provide, if it is a question of practical application, all the sophisticated equipment indispensable for certain fundamental research. As a means of study it is, therefore, perhaps a little costly but also one which is particularly effective, as we are going to attempt to show in what follows.

The management of water resources poses two categories of problems:

1. First it is a matter of being acquainted with the spatial distribution of surface and groundwater resources and the temporal distribution at each point, including the values which may be reached in exceptional circumstances.

The spatial distribution is generally presented by the maps which, for the needs of development, one is frequently obliged to draw up well before one has at ones disposal all the elements for making an accurate map. These maps are drawn up for the diverse statistical parameters which we will be dealing with later.

The temporal distribution is represented either by the classic parameters of the statistical distribution (average, standard deviation, skewness with values corresponding to the differing frequencies) or hydrological characteristics (annual, discharge flood and low water flow), or more and more by a generated chronological series of long duration. The generation of this series is such that its temporal distribution is the same as that of the river being studied and presupposes a good knowledge of the laws of statistical distribution which are most suitable for the flow regimen of that river.

2. Secondly, it is a matter of knowing accurately the influence of man's actions on the varied characteristic defining a hydrological regime, including those concerning sediment transport and water quality. It would be advisable to fit into this type of study those which may be carried out on the influence of the modifications made by man on the balance of ecosystems. This diverges a little from the domain of hydrology, although studies of this nature are not to be neglected.

Anticipating a little of what will be said further on let us state that the first set of problems may often be solved from the results of studies made on representative basins, and the second set by data gathered on experimental basins.

I. Knowledge of the hydrological regime in stationary conditions

We prefer the expression, hydrological regime in stationary conditions to that of hydrological regime in the natural environment. Only rarely does one have dealing with a true natural environment. On a catchment there is land under cultivation, forests which are managed to a greater or lesser extent and built up areas. Occasionally, all this has been stable for centuries. Main roads are a little more impermeable than in the past but the change in the behaviour of the catchment has been small for at least a hundred years. The hydrological regimen has not changed in practice, with the result that trust may be put in the long period chronological series provided by the networks; as would be the case in a natural environment. On the other hand, in different areas evolution is so rapid, and the hydrological effects so significant, that it is impossible to consider the catchment as being in stationary conditions. We will return to this subject later.

In stationary conditions the engineer has recourse to the data from the hydrometric and rainfall network, but in many cases the network data do not allow an answer to all the questions posed by the management project.

Where large basins are concerned it frequently happens that studies may be carried out in sufficiently reliable conditions using the results from a neighbouring gauging station. However, for very rare frequencies, in

particular for the determination of the design flood, the hydrologist is often of the opinion that he is taking a serious risk in calculating it, even when using a series of readings taken over a period of 70 to 80 years.

Where small water courses are concerned the situation is much more difficult, as, even in developed countries, the series of good quality flow data over the period of several decades are few in number. Also it is rare for a network of gauging stations to provide the completely reliable data which are so essential to a management project. Of course, in developing countries the situation is worse. The reasons for this are simple :

1. The small rivers are seldom equipped with gauging stations of the national network. The choice from the few representative stations is difficult and, in practice, may rarely be made in a rational way.

2. The accuracy and precision of the results are very much inferior to those from the stations of the large rivers. The variations in flow are very rapid and special organisation is needed to take the measurements of the flood flow. It takes only very little to modify the cross-section sufficiently for the rating curve to become unusable. In short, almost everywhere in the past studies of small watercourses have been greatly neglected.

I. a) Small watercourses

It is precisely for these small rivers that representative basins are of greatest service. In general a study of a representative basin is not started for the study of a management scheme; it would often cost as much as the management of the scheme itself. A regional hydrological study is designed with the equipping of two or more representative catchments for the estimation of a value for the given region where a fair number of management schemes are envisaged. On a national scale the whole country is equipped with a certain number of representative basins. They are selected after the country has been divided up into hydrologically homogeneous zones, and from the results of these basins one may proceed to studies of syntheses. From these studies may be drawn sufficiently reliable quantitative values for most of the hydrological calculations necessary for civil engineering.

If only the resources of surface water are taken into account the three most useful characteristics to know are: - the average annual flows, the flood flows, and the minimum annual values of flows.

The average annual flow often presents a significant correlation with the depth of annual precipitation, and the correlation may be sufficiently close for one to be able to use a regression to pass from one to the other, but only when the depth of annual precipitation is much greater than the runoff deficit. The scatter is great, especially in arid and semi-arid zones for which the relation between depth of runoff in mm and depth of precipitation often varies between 0 and 15%. The runoff deficit, difference in mm between the depth of annual precipitation and runoff is nearly equal to that depth of annual precipitation. In these conditions, the knowledge of this runoff deficit and even its spatial distribution, in accordance with the varied natural conditions, will be of little help, whereas a representative basin may provide all the necessary data for the study of the average annual flows. Later we will give an example used for a general study of flows in the tropical African Sahel.

In these arid regions the runoff is constituted by a series of floods without permanent flow. The correlations between rainfall/flows on the annual scale are not usable. G. Girard has perfected a simplified model which permits the determination of the depth of runoff for each individual flood from the height of precipitation for each storm, at a point situated towards the centre of the basin and from the depth of the preceeding precipitations. The depth of annual runoff (or the volume of runoff) is the sum of the depths of runoff corresponding to the various storms. It is sufficient to use as an entry into the model the daily precipitations from a raingauge station observed for several decades in order to obtain a long series of average annual flows and consequently average annual flow rates.

The model has been tested on several representative basins some of which have been carefully observed. For one of the latter drainage basins, that of Kadiel (in Mauretania), we have reproduced one of G Girard's graphs representing the depth of annual flow (E) in terms of the depth of annual precipitations (P). The basin is sufficiently impermeable and the runoff values are obtained in this instance to a fairly close approximation. In

these conditions, too, if the accuracy of the simplified model's results is acceptable for an individual flood flow then it is very good for the estimation of the total annual flow.

On this graph, established in good conditions, it may be seen that the correlation between flow (E) and precipitation (P) - if it is significant - is too loose for one to be able to establish directly a regression with the observations made over two or three years. Also it may be seen that it is a difficult matter to estimate the average value of flow (E) with observations made over two or three years.

With the use of the model, however, it is possible to reconstitute a series of around forty values of (E) with which it is simple to calculate the parameters of the statistical distribution of annual flows.

In many instances it is not necessary to profit by such good conditions as those in the representative basin of Kadiel in order to reach an evaluation of the depth of the annual water stage flow in an average year, and to arrive at an initial outline of its temporal distribution curve. We can cite the example of the Abou Goulem representative basin (in Chad) on a rocky subsoil with a majority of porous soils. The quality of observations made on this was mediocre. It was only possible to make use of a single year of rainfall and flow readings. This was enough to set up the simplified model which, let us recall, transforms the rains into flow from the storm depth. Annual flows are then determined working from daily precipitations with an accuracy acceptable for this type of basin with low flow: on which it would almost be enough to determine an order of magnitude.

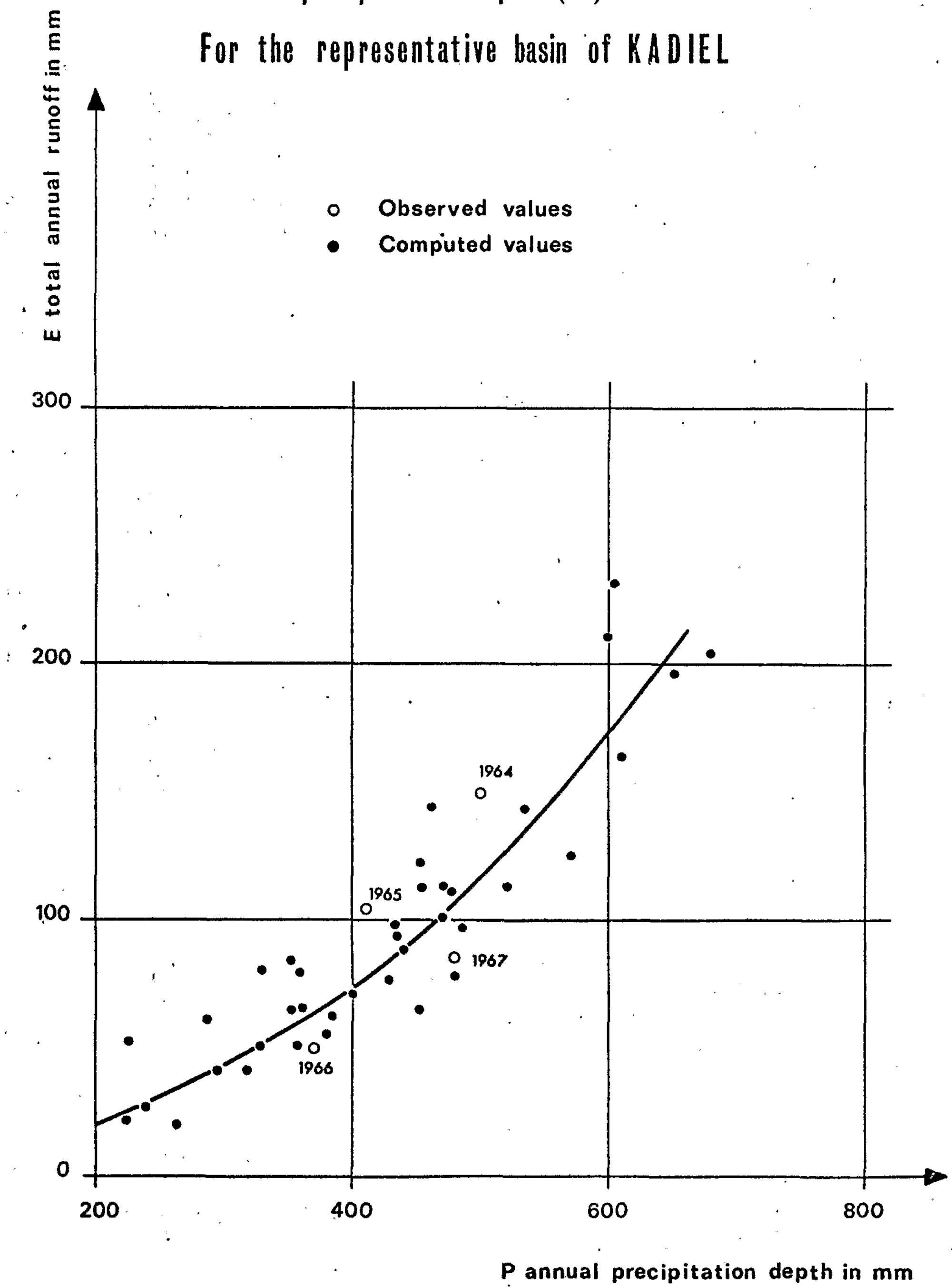
Thus it has been possible to calculate the median value of flows for most types of small catchment areas in the Sahelian zone.

The representative basins in this case enable much better results to be obtained. For small reservoirs it is often asked what the annual volume is in a decennial dry year and in a decennial wet year. Now the representative drainage basins, at least in this climatic zone, allow calculations with good precision to be made of annual volumes for this frequency since flows are calculated storm by storm. For very wet years the method is less reliable because it is difficult to extrapolate from the observations made during a drier period to the effect of a much more

Total annual runoff (E), related to annual precipitations depth (P)

For the representative basin of KADIEL

Fig. 1



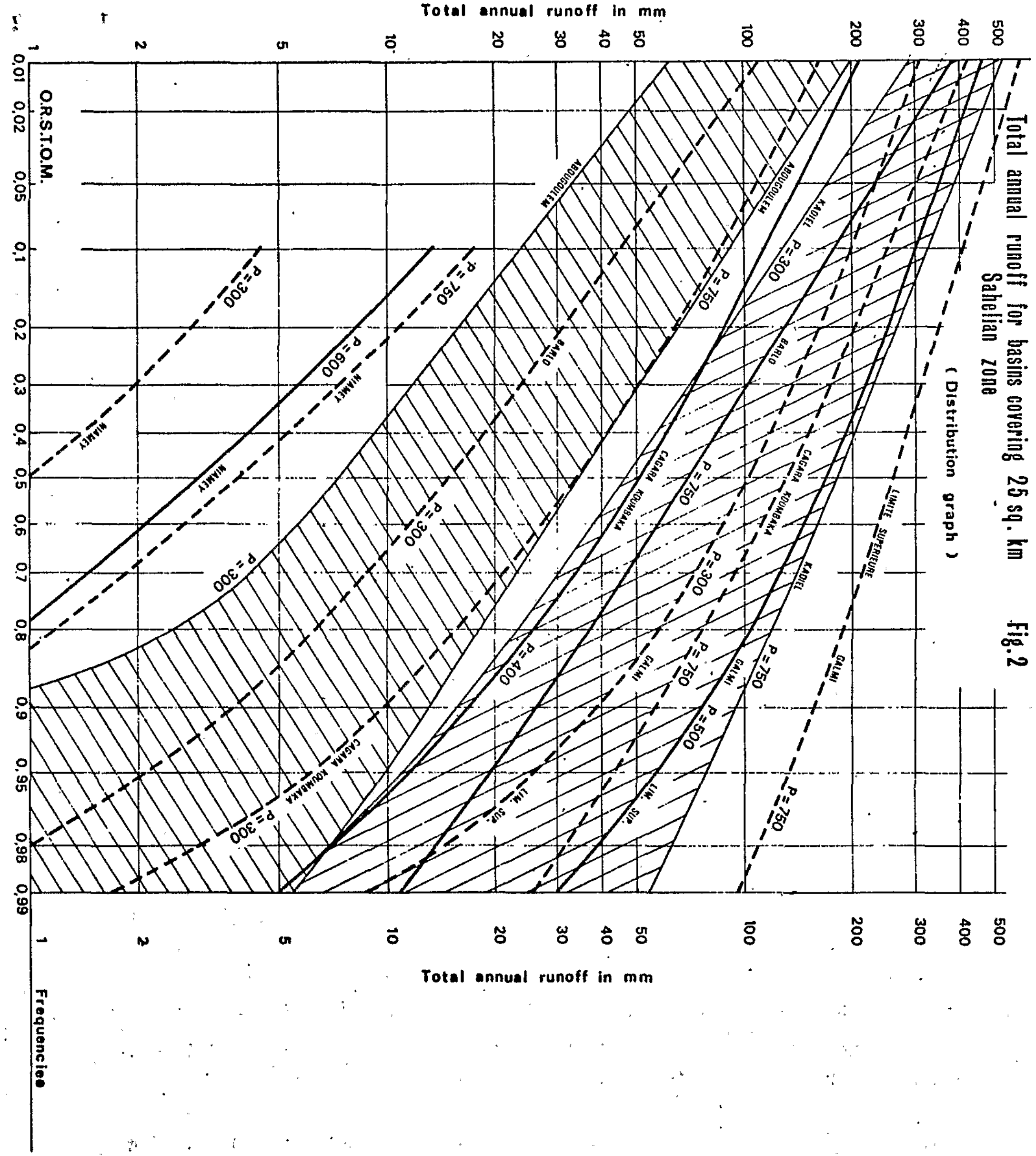
saturated terrain. In point of fact one can obtain the distribution curve. In this way it has been possible to draw diagrams like those in graph 2 on which it may be seen that for basins with an area approximately 25 km^2 distribution curves are arranged for different types of basin in the Sahel. These range from highly permeable sandy basins to basins of very low permeability. Without any representative basins it would have been impossible to achieve these results.

For areas of 100 to 500 km^2 methodology is far more tricky. It is difficult for convective tropical storms to represent rainfall on the basin by means of data from a single raingauge station. It is necessary to make use of the data from representative basins and at the same time to make use of the sparse runoff data from the basins in the network.

Where estimation of high flows are concerned the decennial frequency is often taken into consideration for small drainage basins. In tropical zones the flood flows very often correspond to surface runoff, for the very high frequencies. So this is an instance when the unit hydrograph method is most easily applied. On a representative basin where observations have been made for three years, one can realiably determine three parameters from the unit hydrograph: time of rise (TR), time of surface flow (TB) and ratio (K) of the peak discharge and average value of surface flow rate during the time (TB). In the same way it is possible to predetermine the value of the volume of surface runoff or of the coefficient of surface runoff (KR) from the characteristics of the generating storm for the flood flow. This is done either by employing the residuals method taking the depth of precipitation as principal factor, together with antecedent precipitation indices representing the soil moisture and intensity of rainfall as secondary factors, or by using more elaborate models.

In any case one can in this way determine the volume of flow and the shape of the hydrograph, and thus the maximum flow for any given storm (these simplified models are often valid onlyfor heavy storms).

So it is possible to reconstruct in this way the decennial flow by working from the decennial storm and taking certain precautions. This is not without risks, for without the precautions one may calculate a flood flow with a frequency either higher or lower than the decennial frequency. It can also be done by reconstructing the whole of the flood flows from the data from a raingauge station used for several years and, by the study of the



statistical distribution of these flood flows to deduce from this the decennial flood flow or the flow of another frequency.

When one has determined the characteristics of the flood flow on a representative basin, it is then necessary to proceed to generalise on the geographical plan. This operation is carried out by using the data from several drainage basins for a region not too heterogeneous in nature if it is a case of regional study, or for a set of homogeneous regions if the study is made on the national scale. On occasion only those zones are considered which, a priori, present the most dangerous flood flows.

The different parameters of the rainfall/flow model are therefore determined in terms of the physiographic characteristics of the basin and its rainfall regime. In this way one plots graphs similar to graphs 3 and 4 which have been established for the Sahel.

The first graph provides the coefficient of surface runoff for the decennial flood flow in terms of a permeability index, an index of slope and of the area of the basin; the vegetation cover varying very little over the whole sahelian zone.

The second graph provides the time of rise as a function of the slope index and the area of the basin.

The most difficult problem consists in finding one or more quantitative indices which permit determination of the characteristics of the permeability of the whole basin.

These few examples concerning the difficult zone of the Sahel show that representative basins allow one to reach quantitative results which numerous controls have verified.

Representative basins are far less attractive when it comes to making a direct evaluation of the minimum flows, because the geographical transposition of the results is frequently difficult and presents too many risks. Fundamental research on the groundwater increment and on depletion does, it is true, facilitate this kind of study but does not bring direct solutions. On the other hand, it is often easy, within the limits of the exploitation of hydrometric networks, to proceed to systematic campaigns of measuring base flow over a good number of small catchments which allow data useful to management to be supplied.

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

PERMEABILITY P3

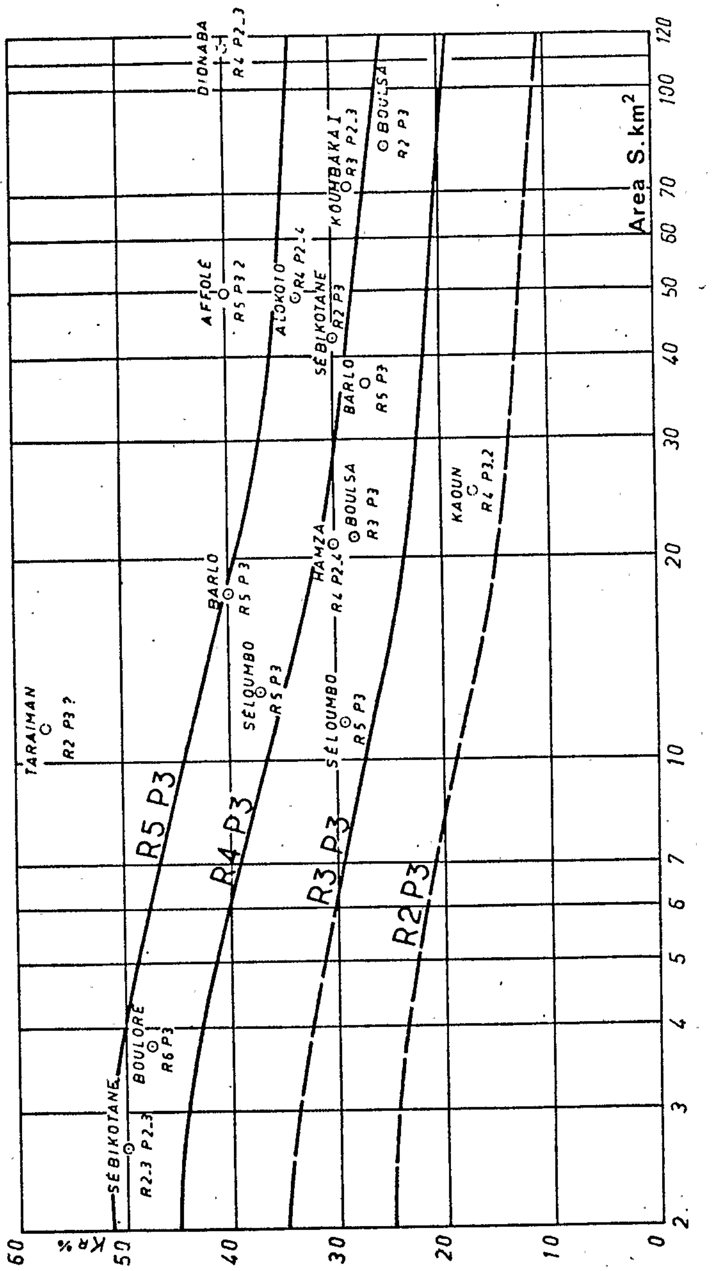
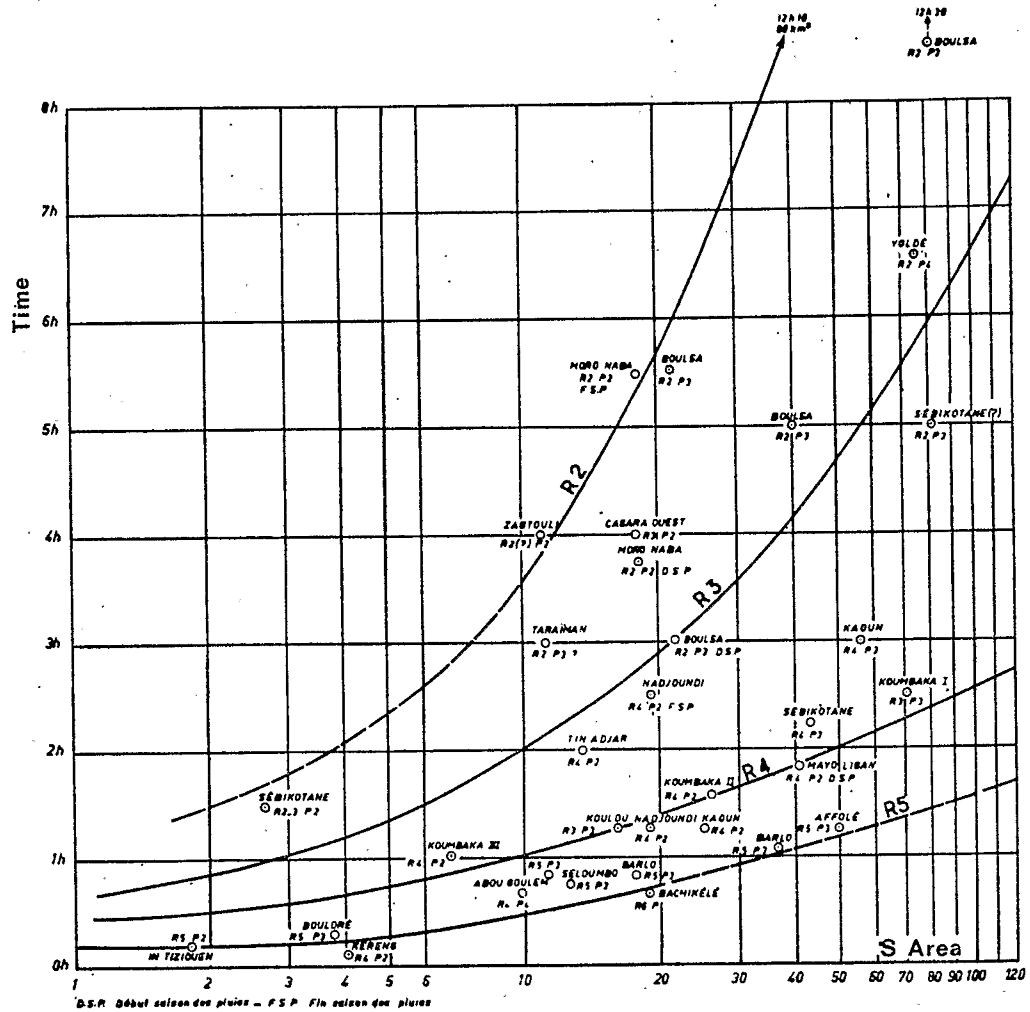


Fig:3

RISE TIME, related to R (slope index) and S (catchment area) Fig.4

Sahelian zone



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

Sediment transport in stationary conditions may be studied without too much difficulty on a representative basin, thanks to the continuing presence of the hydrometry personnel on the terrain. The results obtained may often be transposed from one catchment to another, whereas the study of sediment transport on small drainage basins, if it had been made with the stations of of their networks, would pose serious problems in developing countries.

Representative basins may provide answers to most hydrological problems posed by the management of small watercourses and, except in the case of basic networks fully equipped with automatic instruments, they are the only ones to be able to do so.

I. Large rivers

Calculations are made from the network data, but, in the case of large management projects, the hydrological characteristics must be determined accurately and the frequencies which are to be taken into account for the design flood are very low. In these conditions it is essential to be thoroughly conversant with the regime of the river, not only at the barrage, but over the whole basin. If the hydrometric network is not of high density, and if it is has only been set up for a short time, some well sited representative basins provide precious information.

In the instance of the dam project of Sounda on the Kouilou in the Congo (catchment of 55,000 km^2) the stations in the network had only been set up for five years. The two main stations had been managed and operated very carefully but the determination of the design flood, whose return period in theory exceed one thousand years, posed some difficult problems. An idea of the response of the various parts of the basin for a period of exceptional rainfall was wanted. The basin comprised four parts: a zone of limestone, a zone of sand and sandstone which was extremely unfavourable to surface runoff, a forest zone on rocks and a zone of savannah on limestone-schist which had a very bad reputation as far as flood flows were concerned. Two representative basins had been studied as a whole, one in the forest zone - that of the Leyou - the other in the limestone-schist zone - that of the Comba. They allowed an estimation to be made of the limiting value of the drainage ratio in the case of a season of exceptional rainfall,

and this provided a far more sound basis for the study of the volume of the exceptional flood flow.

From the foregoing it may be established that the use of representative basins must not be limited to the study of the problems of fundamental research. As a matter of fact, if at the start of their planning and equipping one had provided for these basins the elements for forecasting the most common hydrological characteristics (average annual discharge, total hydrological balance, decennial flood flows and low water flow) then these may directly contribute some solutions to practical problems.

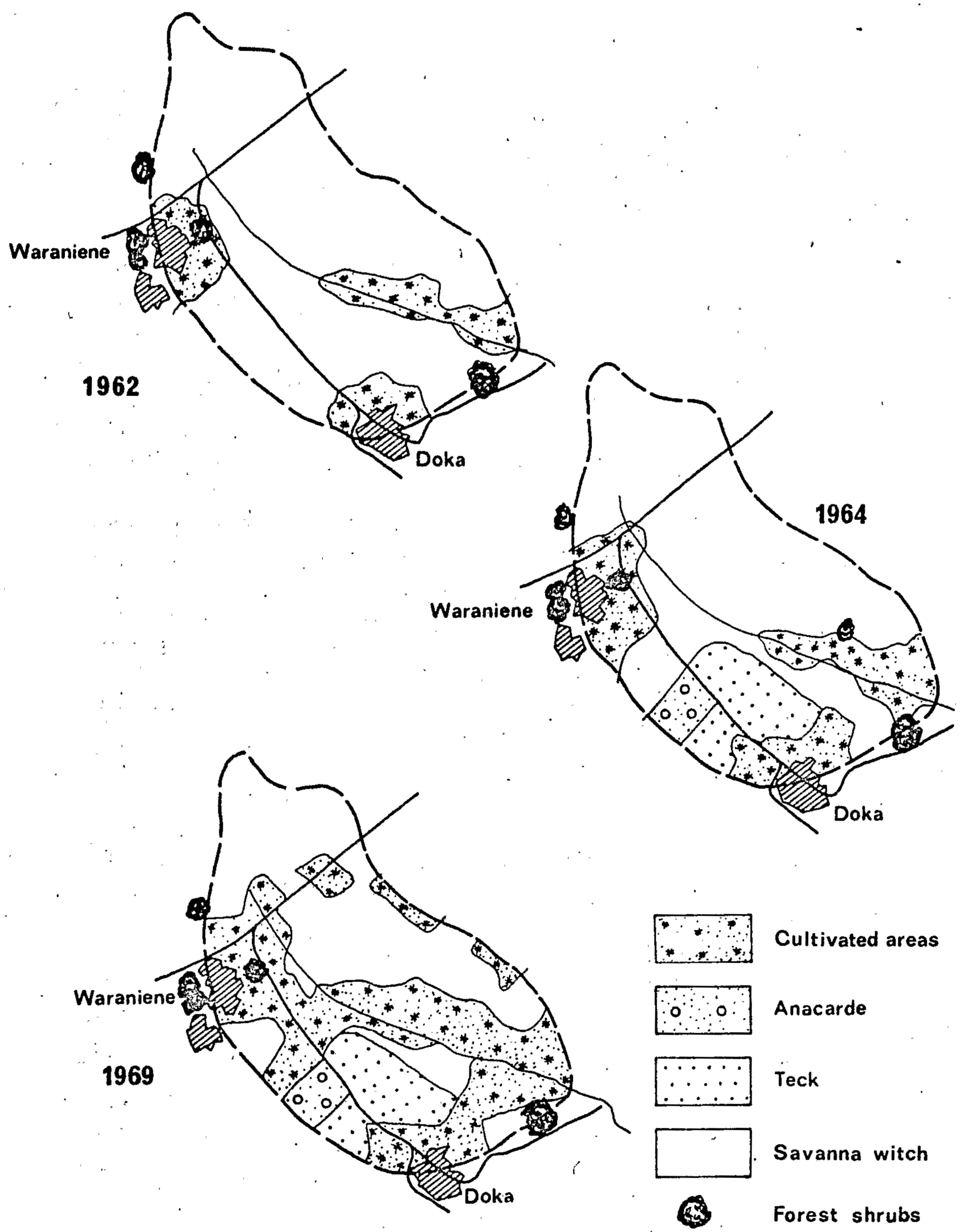
II. Study of man's influence on the hydrological cycle

It is hard to find a catchment in a natural state, even in countries with a low population density and still being developed. It is a frequent occurrence in these countries to find a small basin in the middle of a catchment area which is very well suited for a study of the representative basin type. It is still more difficult to find a basin from 5 to 10 km^2 in size in a dense tropical forest area, which may neither be managed nor plundered in the five years to come.

The stationary state, as far as soil management is concerned, tends to become an exception. We are about to show this by means of the following example. In 1962 our service had equipped a representative basin at Korhogo on the Ivory Coast in a savannah zone, and as we had a difficult research programme ahead of us the basin was observed for ten years. After several summary interim reports made every two or three years we wanted to bring out a general report on the characteristics of the area runoff. It was then established that the conditions of vegetation and soil could not be accepted as stationary. Figure 5 shows a sequence of three maps of the basin which give the evolution which has taken place. The cultivated surfaces of the slopes show a large proportional increase, the growing has developed at the bottom of the valley, one section of the basin, after deep digging, has been transformed into plantations of anarcardiums and teak, and, of course, the hydrological characteristics have been modified. Chaperon, P., Girard, G., Camus, H. have shown that, even when simplifying the study of the evolution of this basin, the period over which observations are made must be divided in two parts: 1962-1967 and 1968-1971. Figure 6 shows the differences in the hydrological behaviour

REPRESENTATIVE BASIN OF KORHOGO Fig:5

Map of land use



with regard to one simple element: the depth of annual runoff (H). H was determined as a function of depth of annual precipitation, with a correction to take into account the depth of the previous year's precipitation. Two successive regression curves are altered significantly. The development of land comprising the teak planatations carried considerable modifications to the soil profile. This clearly increased infiltration and consequently the losses by differing evapotranspiration.

These transformations were brought about without any importance being attached to the use of modern means, since everything was done by hand and, originally, it was a question of a cultivated savannah and not a forest.

This example was given to demonstrate clearly that most hydrologists the world over must often work on drainage basins in full evolution without realising it, and this evolution is all the more dangerous because it is progressive. Cut down a forest and replace it with grass land and the hydrologist will be on his guard. He will be a good deal less vigilant for progressive changes; more especially as hydrology has progressed there are available, all over the place, long statistical series. These series have been analysed and after impassioned discussion values have been reached for one hundred year floods or even one thousand year floods. These values are considered valid and it is supposed that they will even be improved by the pursuit of better quality observations. Now very often this is a mistake: the basin is no longer the same as before and the long statistical series which is looked for will not be homogeneous. What is more serious, this will not even be suspected.

That is not to say that, in regions where Man's influence on the hydrological regime is significant, observations on the basic hydrometric network may be neglected. On the contrary, they are more necessary than ever, because the safety margin between the water resources and requirements will continually diminish. It is therefore more and more urgent to try and acquire quantitative data on the modifications to the hydrological regime.

Most of the time the study is to be undertaken from the start of important management projects on drainage basins, or, preferably, beforehand. In these two cases the data from the base hydrometeorological networks cannot be used. Two methods can be employed: studies made on experimental plots and studies on experimental basins. In this case the sense of the word

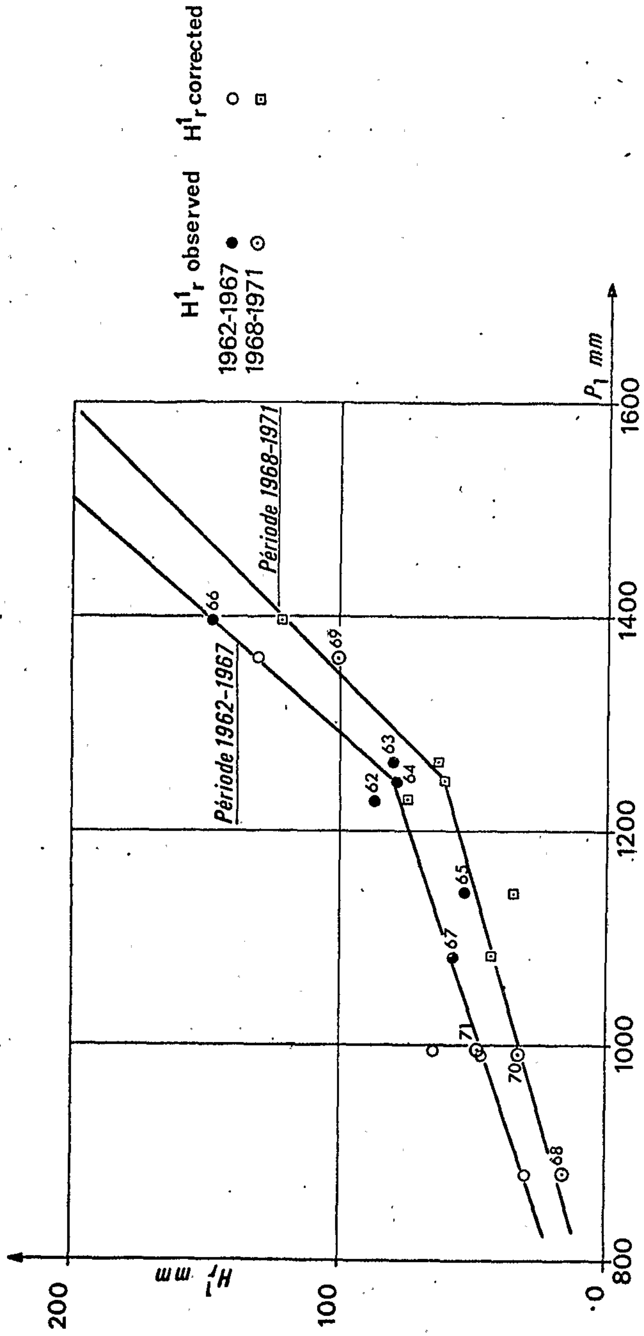
Fig.6

Representative basin of KORHOGO

Correlation between total annual runoff H^1_r in mm and precipitations P_1 in mm

(rainy season)

$H^1_r = f\ (P_1)$



"experimental" is clear, the plot or drainage basin is the object of the trials made: the physiographical conditions are modified deliberately. One cannot keep the passive attitude that one had towards a representative basin where, on the contrary, the basin cannot be made the object of experiment.

However, the equipment of the basin or the plot entails considerable expense, and this leads one to restrict as far as possible the area to be studied. In addition, in order to ascertain the influence of the different factors as accurately as possible, one must preferably consider a homogeneous medium: another consideration which directs research policy in the same sense. That is why this kind of study is often limited to observations and measurements made over experimental plots with or without replications.

However, a plot, or even a lysimeter, does not in many cases permit the study of a hydrologic balance which is comparable to that of a drainage basin on the scale of some km^2, or even 1 or 2 km^2. The plot is an open system and the lysimeter is not, as it is almost always too restricted in size. Whereas if the substratum of the basin is impermeable, and the lateral changes insignificant in the zone of change, then the experimental basin permits a complete hydrologic balance. The drainage basin allows consideration not only of the conditions of runoff from the interfluves but also within the hydrographic network. The plot gives no information on the form of the flood flow hydrograph and its evolution. This type of study is made possible on the experimental basin by means of the extended timing of hydrological events linked with the increased area. Here there is also the possibility of intervention in that very often the bottom of the valleys are the object of management schemes.

For sediment transport the experimental plot accounts for sheet erosion and not for erosion in gullies and it is seldom that it is able to provide details about the colluvium at the bottom of slopes. The representative basin gives a more comprehensive idea of the balance of sediment transport. On the other hand it gives rather poor pointers on the erosion of interfluves, except if it is extremely small. This is the reason why on an experimental basin it is useful to see some erosion plots or micro-basins (of a few hectares in size).

A drainage basin, by the very nature of its own characteristics, imposes constraints on analysis. Studies on plots of land escape these constraints to the extent that the selected site is chosen in terms of the proposed experiment, and consequently, the results obtained are more satisfying from a theoretical standpoint because they are more systematic and of a more analytical nature. This is a further reason for equipping one or more plots on an experimental basin.

In brief, the experimental basin, whatever its size, is a small complete valley which frequently comprises all the morphological elements of a far more important valley. Thus it constitutes a sort of reduced model of a vastly greater ensemble, and permits an easy regional extension of the results. This is particularly important in the case of complex regional management schemes where the drainage basin comprises, at the same time, zones of diversified agricultural development, industrial establishments and modern built up areas.

To conclude, the experimental plot is most useful, often indispensable, but it is not in itself enough, and one is led therefore to set up experimental basins which, for the reasons given earlier, one chooses as small as possible.

The best known of these experimental basins (and probably the oldest) are those which have been set up by foresters in order to study the effects of deforestation, or forest management on the various characteristics of water resources; annual runoff, flood flows, minimum flow. However, experimental basins are used for many other modifications to the natural milieu, and in them not only the variations in discharge are studied but also the problems of water quality.

Whatever the type of experimental basin, one is induced in the analysis to eliminate the influence on the hydrological characteristics of the singularities affecting the climatological elements during the observation period. The comparison of the hydrological characteristics, before and after treatment of the catchment, will be effected when considering either the averages of one of the characteristics corresponding to a very long observation period (for example, the average of the mean annual flow), or a value of given frequency (for example, the flow rate of the decennial flood flow), or else an element from the transformation model from rainfall to flow (for example, the regression line as shown in diagram No 6).

Equipped with these elements, one may then pass on to the complete study of the repercussions of the proposed modifications on the water resources of a larger zone. At this stage of the study one must not lose sight of the problems of scale. It is not always possible to extrapolate to infinity, and this, as we have already said, often prescribes the complementing of the experimental plot with an experimental basin.

It is not within the scope of this account to present the various types of experimental basins, nor the results which each of them permit one to obtain. One is content to stress the following four points:-

1. The experimental basins constitute an irreplaceable tool for the study of Man's influence on water resources, and for this reason it is necessary to dwell on their usefulness.

2. The number of these basins is almost always insufficient in relation to the importance and urgency of the problems posed by the changes to which we are subjecting our unfortunate planet.

3. The selection of basins and their management, like the analysis of the runoff factors, pose difficult problems, and by taking great precautions it is possible to transpose the results from one country to another, and so one cannot encourage enough the exchanges of information in the field of experimental basins.

4. The research workers who are working on these basins are generally most enthusiastic about their researches but do not always apply themselves sufficiently to the swift extraction of the practical recommendations derived from their labours.

In a perpetually changing world it appears that studies on experimental basins, despite their high cost, have a brilliant future, especially if, as should be the case, one takes into account both the influence of Man's actions on water resources and on the environment.