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Hydrological computations for water resources development with inadequate data

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ABSTRACT Preliminary operations such as data checking, gap filling and field surveys, together with a thorough analysis of the physical factors controlling runoff, are all absolutely necessary. For most parts of a zone the runoff deficit is stable (exhibiting variations with precipitation, temperature and physiographical factors) permitting an estimation of annual runoff. For small basins formulae derived from representative basins give annual runoff in terms of most of its determining factors. Combined with the unit hydrograph these representative basins permit the computation of the 10 year flood for ungauged basins. For larger basins, one may derive long time series of computations by using correlations between discharge data from neighbouring stations (mean or maximum discharge). In general, the distribution curves are not far from normal, with a low coefficient of variation, but the pseudo-cycles of wet and dry years cause perturbations. Areas that are relatively dry or affected by cyclones present difficult problems.

Calculs hydrologiques pour l'aménagement des ressources en eau dans le cas de données insuffisantes

RESUME Le contrôle des données et une analyse minutieuse sur le bassin, des facteurs de l'écoulement sont absolument nécessaires. Dans la majeure partie de la zone étudiée le déficit d'écoulement stable (variations progressives avec les précipitations, la température et les facteurs physiographiques) permet l'estimation du module annuel. Pour les petits bassins des formules déduites des données de bassins représentatifs déterminent le module annuel en fonction de la plupart des facteurs conditionnels. Combinées avec l'emploi de l'hydrogramme unitaire ces données permettent le calcul de la crue décennale. Pour les grands bassins par corrélation avec les débits d'une station voisine (débit moyen ou maximum) on reconstitue une longue série temporelle pour la plupart des calculs. En général la distribution voisine de la distribution normale, le faible coefficient de variation facilitent cette tâche, mais les pseudo-cycles d'années sèches et humides apportent des perturbations. Les régions relativement sèches ou affectées par les cyclones présentent de sérieux problèmes.

INTRODUCTION

Hydrologists are not often satisfied with the information available for hydrological computations needed for the planning and design of a water resources project. This is particularly true in humid tropical areas: raingauge and flow gauging networks are generally sparse, the quality of the data is sometimes poorer than is desirable, the length of time series is often too short, and for some countries the estimation of design floods is made very difficult by catastrophic floods produced by cyclones.

On the other hand humid tropical areas may offer some hydrological characteristics which often facilitate these computations. With the exception of areas affected by cyclones, the meteorological mechanism generating rainfall is relatively simple and the characteristics of the precipitation can easily be estimated. The statistical distributions of mean annual discharges and of maximum floods are not too different from normal distributions, with low or relatively low coefficients of variation. There is often good correlation between the discharge of neighbouring rivers or between the maximum annual and the mean annual discharge. Water balance computations or the use of the concept of the runoff deficit offers better possibilities than in arid countries. Sometimes at last, for large rivers some very long time series have been provided by navigation services.

PRELIMINARY WORK

To make best use of meagre data it is necessary to have a perfect knowledge of these data. A thorough checking of rainfall and runoff data and of rating curves is essential. It is also important to improve these data. Finally, it is impossible to carry out hydrological computation without having a good knowledge of the physical characteristics of both the basin and the river. All these things do not only apply to humid tropical areas. Here, we shall only recall what is specific to these regions.

Most of the rainfall (in some countries all rainfall) corresponds to convective storms covering relatively small areas. Consequently, for small basins, the correlation between the precipitation at raingauges say more than 50-100 km apart, is bad with the exception of very wet years, when there are very many storms over a large area, or very dry years when there are very few. For large basins there is often a good correlation between mean annual discharge and corresponding maximum discharge. The correlation between the precipitation of a rainy season and the mean annual discharge may be satisfactory if there are more than two or three raingauges in the basin. During cyclonic precipitation it may happen that raingauges are over-filled and also that 75-90% of them are destroyed. All such information should be utilised when checking data and for filling gaps in a record. This last operation must be achieved as far as possible; we have often found one whole year eliminated from the records of mean annual discharge because two months of dry season record were missing for which mean discharge was less than 20% of the mean annual discharge.

Another improvement may be brought in the field by supplementary gauging to give some idea of the magnitude of the rating curve for high discharge or for low flows. The last case is the more frequent because surveys generally take place in the dry season. Even without a gauging station one may obtain an indication of the value of low flows particularly for very permeable basins where the low flow discharge does not vary too much throughout the low flow period and from one year to another year. A field survey is necessary in order to obtain a good knowledge of the basin, especially for small basins; even for large basins the hydrologist should know exactly the nature of the soil, vegetal cover, slope and aspect of the river beds belonging to the different zones of the basin. Not all important information can be found from maps, even those obtained by remote sensing. For instance, the grass of the savannah might or might not be a good protection against runoff and erosion; in forest areas on clay soils some of the small basins with the same climate, area and slope index may have 10 year flood peaks of 500 or of 3200 $l\ s^{-1}\ km^2$. The last case does not often occur but is possible whenever there is a compact layer 30 cm to 1 m under the soil surface. A quick survey of river beds or rivulets might give some idea of the runoff; but in forests, with the exception of mountainous areas, it is difficult to derive the annual flood magnitude from the inspection of river beds for small basins. This is much more difficult in such an area than in an arid zone. It is not possible to present here all that could be observed in the field but many indications might be obtained by a skilled field hydrologist and this might significantly supplement the available data.

HYDROLOGICAL PARAMETERS NEEDED FOR WATER MANAGEMENT

The following parameters are generally used: the mean annual runoff; its statistical distribution; sometimes autocorrelation characteristics, seasonal variations; flood for the period of construction; design flood; possibilities of silting of the reservoir; water quality (deleterious effects on turbines or for irrigation water or water supply). These parameters and the approach to their estimation vary broadly with the nature of the project, the basin area, the available data and the financial constraints on the study. In the following we shall consider only the case of both small basins and large basins, the former generally correspond to small structures, few data and small financial resources.

For hydrological computations no magic formulae or procedures exist. The hydrologist must rely heavily on his judgement and experience and has to deduce the maximum from the available data and from his knowledge of the river and of the basin characteristics.

COMPUTATION OF ANNUAL RUNOFF FOR SMALL BASINS

Here, commonly no discharge data are available, and there is no raingauge in or near the basin. In a homogeneous area it may be possible to find a raingauge for the same precipitation regime. If not, the precipitation can be deduced from vegetation indices but this is not easy in the humid tropics. To choose the specific mean discharge of a larger reference basin and to consider only the basin area is dangerous if the annual precipitation is less than 1400 mm on an impervious basin with steep slopes. With these exceptions, it is sometimes possible to use the formula $Q_x = Q_o (A_x/A_o)$ as a first approximation, with Q_o and A_o corresponding to the reference basin (Basso, 1973).

Some formulae may be used which take into account an approximate value of the yearly or monthly precipitation depths. They start from the ratio runoff/precipitation, R/D = runoff coefficient K_{ry} or from their difference, rainfall minus runoff = deficit. Both vary with climatic and physiographical conditions. The old Strange's table used in India (Banerji & Lal, 1973) considered (for each given precipitation depth) three categories: "good, average and bad basin" with three different runoff coefficients. In other parts of the world other regional values of K_{ry} are given. For average conditions of slope, soil and vegetal cover, Smith (1973) gave a curve presenting variation of K_{ry} with the basin climatic index (BCI) combining monthly precipitation and temperatures, but unfortunately the influence of the other factors was neglected and important errors may result from this.

Other formulae mostly use the runoff annual deficit D_y which is relatively stable in the humid tropical zone. It varies between 700-800 and 1500 mm. In Africa, at a lower altitude, it increases from 1000 mm year^{-1} for P_y = 1100 mm to 1150-1250 mm for P_y = 1500-1600 mm. At this stage it is practically constant as precipitation increases from 1500 up to 2200 mm. But in South America with precipitation between 2400 and 3700 mm in the forest, it reaches 1500 mm (Roche, 1982). The runoff deficit decreases with altitude: at 1000 m, for instance, in Central Africa, D_y is 900-1000 mm instead of 1100-1200 mm (P_y = 1500 mm). All these variations are similar to those applied for computing K_{ry} by Smith (1973). But if the slope or the permeability greatly varies from the average conditions, D_y is significantly different from the values computed with climatic parameters only. Steep slopes or impervious soils may correspond to a runoff deficit of 900 mm or even less instead of 1150 mm. This also applies to mountains affected by cyclonic precipitation; very few accurate data are available for this last case. As regards very small basins, high permeability increases the losses and consequently D_y.

It is often possible to obtain a first approximation of R_y by the simple formula $R_y = P_y - D_y$, D_y being the mean value for a small or medium basin under the same conditions. Rule of thumb corrections are made by taking into account the altitude, slope and permeability of the soil. The Khosla formula (1949) used in India gives the monthly runoff: $R_m = P_m - D_m$ with $D_m = 5T_m$ (T_m = monthly temperature). The annual runoff is $R_y = P_y - k\,(45\,.T_y + 800)$ where T_y is the annual average temperature, and k is a constant corresponding to the physiographical factors of D_y. Some maps of D_y exist, for instance for Central America (Basso, 1973). The main difficulty is obtaining a good estimation of P_y: for instance in mountains with significant variations of P_y (if P_y exceeds 2000 mm).

More elaborate formulae may be used for very small basins: Dubreuil & Vuillaume (1975), using data from 65 representative basins in Africa and in French Guyana, established two formulae taking into account most of the significant runoff factors. They considered the index P_r:

$$P_r = 12\ (P_m - \frac{1}{36} E_{TB})$$

where P_m is monthly precipitation, and E_{TB} is the annual evaporation from a sunken pan of 1 m^2. For savannah with trees R_y is defined as follows: $R_y = 0.47P_r + 1.5C + (aD_s + b) + B$, where D_s is $I_g \times \sqrt{A}$, with A the area of the basin; I_g is global index of slope (Dubreuil, 1966); C is percentage of cultivated land; a = 1.78, b = 50 for relatively sparse vegetation; a = 1.20, b = 1.75 for dense bush or very permeable soil; B = +175, +50, -70 respectively for $A < 5\ km^2$, $5\ km^2 < A < 25\ km^2$, $A > 25\ km^2$. For forest areas $R_y = 1.05P_r + 0.92\ D_s - 960$. In East Africa Balek (1973) presented characteristic curves for the estimation of R_y for $1000 < P_y < 1700$ mm and for four general cases corresponding to various slopes, altitudes, and vegetal covers.

SEASONAL DISTRIBUTION OF RUNOFF FOR SMALL BASINS

The seasonal distribution of runoff for small basins is generally deduced empirically from the mean annual discharge and from the variations of monthly precipitation with the help of at least one annual hydrograph of a similar river having a basin area of the same magnitude. If such a basin is not available the use of data from compilation of representative basins results such as those of Dubreuil (1972) may give an idea of how to transform a plot of the mean monthly precipitation into a plot of mean monthly discharges.

STATISTICAL DISTRIBUTION OF MEAN ANNUAL RUNOFF

This is less frequently used than for larger basins, which present lower coefficients of variation. Nevertheless it is sometimes useful to know the 10 year low (annual) flow. If a representative basin for the same regime was observed, a good rainfall/runoff model permits a long time series of annual discharges to be derived from rainfall series,from which their distribution can be studied. However, this situation does not often occur.

There are many formulae for estimating mean annual runoff but it would be unwise to use them for the establishment of a series of annual runoff since the coefficient of variation would be completely wrong. Only the Khosla formula can be used on a monthly basis. This takes into account the altitude, but neither the slope nor the nature of the soil are considered. It certainly underestimates the variation.

For some small basins in equatorial or tropical areas of transition regimes, no runoff may occur during a year of a drought if the mean annual precipitation is near 1100 mm. In 1958 this was the case for drought with a return period 10-20 years in the two representative basins of Lhoto (Benin) and Ifou (Ivory Coast) (Rodier, 1964). In a normal year the mean annual discharges are 2.5 and 0.3 $l\ s^{-1}\ km^{-2}$; the coefficients of variation are perhaps 0.80 and 0.40. For basins with a higher precipitation of 1400-1700 mm $year^{-1}$ the situation is much better, but even in large homogeneous basins with a coefficient of variation of 0.16 for R_y it is possible to find small basins with values of 0.25 for the same coefficient. It is not easy to estimate this coefficient starting from large basins and this also applies to variation coefficient deduced from precipitation series because the discharges are often more irregular than rainfall.

FLOODS FOR SMALL BASINS

Often for small structures (small weirs, very small bridges), the flood of interest is the 10 years flood. In this case the corresponding rainfall produces surface runoff and the unit hydrograph may be used. General studies made on this basis for West and Central Africa (Rodier & Auvray, 1965) provide guidance for the computation of the peak and the volume of the 10-year flood starting with the 10-year precipitation and using an intensity diagram and the antecedent soil moisture conditions corresponding to the average for heavy storms. The runoff coefficient K_r is given by a set of curves of K_r *vs.* A (area of the basin) for various categories of permeability Pe_1 to Pe_6 and slope S_1 to S_5. The 10-year point precipitation is reduced to the 10-year areal precipitation by a reduction coefficient k_p varying from 1 to 0.80 for areas varying from 0 to 200 km^2. A diagram gives the base time of surface runoff T_B in relation to A and S. It is easy to compute the flood volume knowing P_{10} year, k_p and K_r. The coefficient k varying with the vegetal cover, the basin area and to some extent with the slope, defines the ratio between the 10-year peak discharge Q_P and Q_M (mean flood discharge during T_B), $k = Q_P/Q_M$ which is near 2.5 for savanna.

For forested areas, a more recent study (Rodier, 1976) classified forested basins in six categories determined by slope and permeability, the runoff coefficient K_r being computed for a precipitation of 120 mm which is not far from the 10-year precipitation. The K_r values differentiate into six ranges: 3-5%, 7-10%, 10-16%, 20-30%, 30-40%, 58-62%. The highest values (very impermeable soils and significant slopes) are less frequent. The determination of the category of an ungauged basin is often delicate. By the use of small sprinklers (range: 1 m^2) such as those used by ORSTOM followed by a quick pedological survey it is possible to find the classification range of the basin and even to determine K_r for 120 mm. This coefficient is correlated with the runoff from various types of soils computed from the sprinkler experiments. K_r may also be determined by studying the structure and texture of the soil but this is not operational at the present time (Casenave *et al.*, 1983). The base time is taken from graphs and the coefficient $k = Q_P/Q_M$ varies between 1.9 and 2.3 on plains for A varying between 1 and 25 km^2 and between 2 and 2.4 in mountain regions. Some hydrologists use a triangular hydrograph corresponding exactly to a K value of 2. This procedure is valid for West and Central Africa and it could be used with care elsewhere. The important points are the necessity for data on the 10-year precipitation and for the intensity diagram to be comparable from one area to another.

Sometimes the formula $Q = K_r(P_i)\ A$ is used where Q is flood maximum discharge of frequency F; P_i is precipitation mean intensity during the concentration time for a storm of frequency F; A is basin area and K_r is runoff coefficient. This formula may be improved by taking into account the slope S, $Q = K_r P_i A (S/A)^{1/5}$ (Mac Math formula). This formula has often been improved but the problems of determining K_r in relation to the soil permeability remains as difficult as is described in the methodology above.

COMPUTATION OF ANNUAL RUNOFF FOR BASINS OF LARGE OR MODERATE SIZE

For basins of this category there is some compensation between subbasins with varying physiographical characteristics and, therefore, the formulae based on the runoff coefficient or the runoff deficit (such as the Khosla formula describing small basins) sometimes give better results for large basins than for small basins. If sufficient data on precipitation and runoff factors are available, computerized data banks and regression analyses may afford a first estimation of precipitation and runoff (Basso *et al.*, 1979).

For this case it is possible to use a more elaborate method. With the development of hydrometric networks there is often a gauging station and, therefore, at least one short record of recharge not far from the station to be studied. The first step is to determine its hydrological regime, using precipitation, basin characteristics, latitude, altitude, the few hydrological data available etc. in order to choose a reference gauging station. The hydrologist must construct time series of discharges as long as possible for the basin studied by correlating the discharges (observed for a short period at the site or near the site to be studied) with the discharges at the reference station. This last station may be situated on a neighbouring river or on the same river; in the latter case the correlation is better. The correlation with annual precipitation depth or with annual precipitation for the rainy season may also give good results particularly for an annual precipitation exceeding 1600 mm. For less than 1600 mm it is necessary to use the data of four or five raingauges in the basin and this is not always possible. Multiple regressions at the monthly level should be used. For the correlation with discharge, if the observation period at the station to be studied is very short, i.e. less than three or four years, it is advisable to study also the correlation between the monthly values keeping in mind the fact that the regression can be different during high and low flows. The improvement cannot be related to the multiplication of plotted points by the factor of 12 but, nevertheless, is significant. If the coefficient of correlation is high and the length of reconstructed records is less than 30-40 years, another correlation with a station having a longer record is necessary even if this new correlation is relatively poor. In humid tropical basins series of dry and wet years are not necessarily of the same length. They are called pseudo-cycles and this may induce important sampling errors. In order to reduce these errors, it is necessary that the record length of the second reference station includes at least part of a dry period and part of a wet period. This improves the value of mean annual runoff and information on very low and very high values of this runoff. Fortunately, the correlations are better for very wet and very dry years. As regards large basins it is also often possible to use the correlation with maximum annual discharge instead of the mean annual discharge.

If no cyclones occur and if the mean annual precipitation exceeds 1400 mm it is generally possible to obtain an acceptable estimation of the mean annual discharge from 10 years of observations, but due to the pseudo-cycles, a sampling error of 5-10% is possible.

DISTRIBUTION OF ANNUAL DISCHARGE

In the case defined above the distribution of the mean annual discharge is often normal or very close to normal. When fitting the distribution it is not sufficient to accept the normal distribution as given by the computer; it is necessary then to check the plots on the curve in order to avoid systematic bias. If the record is not long enough corrections should be made in order to take the fluctuations resulting from the pseudo-cycles into account. In such a case the coefficient of variation is often of the order of 0.16-0.25. For very large basins the lack of homogeneity may involve complex distribution curves (see the case of the Zaïre River in the following section).

For the case of $P_y < 1400$ mm the distribution is more irregular, the coefficient of variation higher and if only 10 years of records are available the mean error may be 30% or more. The situation is not quite so difficult but very similar for areas affected by cyclones. In both cases long time series are necessary to obtain a first approximation of the statistical distribution which is no longer normal.

FLOODS IN LARGE BASINS

Here the distinction between areas with and without cyclones is extremely important. As regards the first case, in large basins a flood of very low frequency results from an exceptional cyclonic rainfall or an exceptional series of such rainfalls. In the second case a flood of the same frequency results from a very wet rainy season or from an exceptional series of convective storms.

The second case is relatively simple when P_y exceeds 1400 mm. The distribution is not far from the normal distribution often with low coefficient of variation; sometimes the skewness coefficient is negative (the influence of flood plains). Much of what has been written concerning the mean annual runoff is valid including the possibility of getting an idea of the flood distribution with a 10-year record and the necessity of taking account of the pseudo-cycles. For very large basins such as that of the Zaïre River some parts of the basin with very low runoff generally have no influence on the yearly maximum but when the exceptional flood occurred in an area of deficit as happened in 1961, the representative plot was relatively far above the distribution curve, with negative skewness coefficient established before 1961. The situation for the 1953 flood on the Amazon River was similar. The distribution was very complex.

With these reservations, this part of the tropical region is a rare example where the design flood can be safely estimated by statistical analyses of long time series of discharges obtained by regression.

We have left aside the problems of some of the rivers in the Himalayas and Andes where the construction followed by the destruction of natural dams is responsible for catastrophical floods.

If no discharge data are available many empirical formulae can be applied for the calculation of a discharge of frequency F. Most have the form: $Q_F = k\ A^n$, k and n being coefficients which must be determined for each homogeneous area; often in the humid tropical zone $0.7 < n < 0.9$ (forest with low slopes), but k varies considerably. For 5000 km^2 in Central Africa for instance Q_{10} varies between 100 and 1250 m^{3}s^{-1}. Some formulae give the ratio between Q_F and Q_{10}. These empirical formulae are only valid for a given hydrological homogeneous area and their validity must be checked before use.

For areas affected by cyclones the problem is completely different. There, rainstorms generate the most heavy floods in the world. The maximum observed at this time is 31.53 m^{3}s^{-1}km^{-2} for a basin of 330 km^2 in New Caledonia. Fortunately, these cyclones are not frequent. Consequently, the long time series of maxima directly observed or obtained by correlation is a sample which can be divided into two statistical populations: one with numerous values of a relatively moderate discharge, the other with a few values having high coefficients of variation and skewness. Unfortunately, the number of plots is not sufficient for studying the distribution by a direct analysis of discharges. If for some reason a hydrologist wants a time series of floods he may use correlations with rainfall or with discharges but he must be very careful because the tracks of the cyclones vary and the zones affected are not always the same. This operation is only sound for extrapolating the data from one gauging station to another not too far away on the same river.

All attempts to determine the design flood by direct statistical analysis are risky. Three approaches are possible: the world or the regional envelope curves do not provide a methodology for computation. They provide a general idea of all maximum observed floods so as to be able to take the differences of basin area into account. In areas being observed (at least qualitatively) for two centuries or more the general envelope curve did not significantly move upwards between 1961 and 1981 (last general world review for the IAHS *Catalogue of Large Floods*) but for areas observed for less than 60 years the envelope curve is not the same as that 20 years ago. Unfortunately many tropical areas affected by cyclones come in this category and here the envelope curve represents an average return period not exceeding 50-100 years. Francou & Rodier (1967) defined straight lines characterized by a factor K (K = 6 approximately corresponding to the maximum values). Since K may characterize the more dangerous river of a homogeneous area, it is an interesting element to be considered for regionalization purposes. For the very low frequency part of the distribution curve the hydrologist must choose a value for the design flood whose K value significantly exceeds the regional K value of the envelope curve. But what is a reasonable value for the difference between the two K's?

Due to the lack of meteorological data it is very difficult to adapt the probable maximum precipitation method to the conventional procedure. Hershfield (1965, 1981) presented a simple formula to compute PMP: $PMP = P_{max} + kS$, where P_{max} is daily maximum precipitation, and S is standard error of P_{max}. k is determined by regional studies of precipitation records. The PMP method often overestimates precipitation values. Afterwards one must transform this PMP into corresponding flood values; the runoff coefficient should be very high, i.e. 90% for very small basins.

The Gradex method (Guillot, 1979) gives some guidance for the extrapolation of frequency curves of discharges for that which are too short. To use it correctly three essential conditions must be considered: (a) the daily rainfall frequency presents an exponential decrease exp(-p/a) corresponding to a straight line of slope a (a is the Gradex) on Gumbel paper; (b) the upper layers of soil are saturated at a very low frequency of discharges; (c) the basin is not too large (less than 10 000 km^2). Under such conditions, for return periods exceeding 50 years, the distribution curve of runoff in mm on Gumbel paper is parallel to the distribution of precipitation with a duration equal to the time base of the hydrograph. For areas affected by cyclones the second condition is often satisfied and the Gradex method might be very useful for basins of moderate size.

The best way to compute Gradex is to consider the distribution of the means of the precipitation for all the raingauges used in the study and to estimate its Gradex. Given the two populations of rainfalls, the cyclonic precipitation should be considered separately and all cyclonic precipitation should be taken into consideration even if there are several such rainfall events during the same year. Once the runoff volume is estimated only that shape of the hydrograph must be chosen which is similar to the most frequent or the most dangerous shape, taking the characteristics of the basin into account.

MINIMUM FLOWS

Minimum flows are often significant but sometimes small streams may dry up in areas of low precipitation. It is very difficult to extrapolate minimum annual flows in both space and time, due to the heterogeneity of geological conditions, and because only on a few rivers is it possible to observe several successive recession curves. Nevertheless, relatively similar specific low flow discharges can be observed for rivers in homogeneous areas. The study of low flows must always be based on a sound knowledge of the geological conditions. Gaps in low flow data can be filled by deriving the missing data from information on precipitation and recession curves; however, in humid areas small floods often perturb the recession. Roche (1962) used the following method: the beginning of the recession is given an arbitrary fixed date (for east Madagascar this is taken as 1 July); the discharge on this date is correlated with the precipitation of the preceding months of the rainy season; the theoretical recession curve is drawn and the following discharges taking into account the secondary floods of each month are computed by multiple regression using the precipitation data of the preceding months.

CONCLUSIONS

There is no sure and accurate formula or methodology suitable for all cases. If possible it is prudent to use several methods for each computation and to compare the results. The progress in hydrology from the use of remote sensing, multiple regression analyses, generation of stochastic series and various models, is very useful but if only inadequate data are available the weakness of the basis of these combined procedures must be borne in mind; the validity of each procedure must be checked taking into consideration the basin characteristics; a careful comparison of the computed results must be made with the observed results. If these precautions are neglected large errors may occur.

REFERENCES

Balek, J. (1973) Use for representative and experimental catchments for the assessment of hydrological data of African tropical basins. In: *Design of Water Resources Projects with Inadequate Data* (Proc. Madrid Symp., June 1973). IAHS Publ. no.108.

Banerji, S. & Lal, V.B. (1973) Design of water resources projects with inadequate data in India. General and particular cases studies. In: *Design of Water Resources Projects with Inadequate Data* (Proc. Madrid Symp., June 1973). IAHS Publ. no.108.

Basso, E. (1973) General report. Methodology for assessing hydrological characteristics in data scarce areas. In: *Design of Water Resources Projects with Inadequate Data* (Proc. Madrid Symp., June 1973). IAHS Publ. no.108.

Basso, E., Cadou, C., Osorio, C., Solomon, S.T. & Soulis, E. (1979) Estudo piloto da aplicação da technica da malha quadrada na bacia do Rio Amazonas-Brasil (III Symposio Brasileiro do Hidrologia). Brasilia Anais vol. I.

Casenave, A., Guiguen, N. & Simon, J.M. (1983) Etudes des crues décennales des petits bassins versants forestiers en Afrique tropicale. *Cah. ORSTOM Sér. Hydrol.* XX (1). Dubreuil, P. (1966)

Dubreuil, P. (1966) Les caractères physiques et morphologiques des bassins versants: leur détermination avec une précision acceptable. *Cah. ORSTOM Sér. Hydrol. no.5.*

Dubreuil, P. (1972) *Recueil des Données de Base des Bassins Representatifs et Expérimentaux de l'ORSTOM Années 1951-1959.* ORSTOM, Paris.

Dubreuil, P. & Vuillaume, G. (1975) Influence du milieu physico-climatique sur l'écoulement de petits bassins intertropicaux. In: *Hydrological Characteristics of River Basins* (Proc. Tokyo Symp., December 1975). IAHS Publ. no.117.

Francou, J. & Rodier, J. (1967) Essai de classification des crues maximales observées dans le monde. *Cah. ORSTOM Sér. Hydrol.* IV (3).

Guillot, P. (1979) Evaluation des crues extrêmes dans les régions de faibles précipitations. In: *Hydrology of Area of Low Precipitation* (Proc. Canberra Symp., Decembre 1979). IAHS Publ. no.128.

Herschfield, D.M. (1965) Method for estimating probable maximum rainfall. *Amer. Wat. Wks Ass. J.* 75.

Herschfield, D.M. (1981) The magnitude of the hydrological frequency factor in maximum rainfall estimation. *Hydrol. Sci. Bull.* 26 (2).

Khosla, A.N. (1949) Analysis and appraisal of data for the appraisal of water resources. *Central Board of Irrigation J., India.*

Roche, M. (1962) *Hydrologie de Surface*. ORSTOM. Gauthier-Villars, Paris.

Roche, M.A. (1982) Evapotranspiration réelle de la forêt amazonienne en Guyane. *Cah. ORSTOM Sér. Hydrol.* XIX (1).

Rodier, J. (1964) *Régimes Hydrologiques de l'Afrique Noire à l'Ouest du Congo.* ORSTOM, Paris.

Rodier, J. (1976) Estimations des débits de crues décennales pour les petits bassins forestiers en Afrique tropicale. Etude préliminaire CIEH-ORSTOM. *Cah. ORSTOM Ser. Hydrol.* (4).

Rodier, J. & Auvray, C. (1965) Estimation des débits de crues décennales pour les bassins versants de superficie inférieure à 200 km^2 en Afrique Occidentale. CIEH-ORSTOM, Service Hydrologique, Paris.

Smith, R.L. (1973) Utilizing climatic data to appraise potential water yields. In: *Design of Water Resources Projects with Inadequate Data* (Proc. Madrid Symp. June 1973). IAHS Publ. no.108.