Regional techniques for extreme rainfall and runoff prediction

Maria A. MIMIKOU (1), I.A. NIADAS (1), P.S. HADJISSAVVA (1), Y.S. KOUVOPOULOS (1)

ABSTRACT

A regional technique for extreme rainfall and runoff prediction is presented. The method uses five nomographs in which flood and storm characteristics are associated and by which design flood peak and volume can be derived, once the return period and storm duration and depth have been determined. Problems of basin non-linearity do not affect the method which proved to be accurate, fast and simple. These qualities render the method useful for engineering and research applications, especially in ungauged basins.

KEY WORDS: Extreme storm — Runoff prediction — Design flood — Ungauged basin — Greece.

RÉSUMÉ

TECHNIQUES RÉGIONALES POUR LES PRÉCIPITATIONS EXTRÊMES ET LA PRÉVISION DES ÉCOULEMENTS

Ce papier présente une technique régionale pour les précipitations extrêmes et la prévision des écoulements. La méthode utilise cinq abaques où sont associées les caractéristiques des crues et des averses ; ces abaques permettent de déduire la pointe de la crue de projet et son volume, une fois que la période de retour, la durée de l'averse et sa hauteur ont été déterminées. Les problèmes de non linéarité des bassins n'affectent pas la méthode qui se montre précise, rapide et simple. Ces qualités rendent la méthode utile pour les applications d'ingénierie et de recherche, spécialement dans le cas des bassins non jaugés.

MOTS CLÉS : Averse extrême — Prévision de l'écoulement — Crue de projet — Bassins non jaugés — Grèce.

INTRODUCTION

The study of extreme and flood characteristics and the subsequent prediction of design floods when designing hydraulic works constitue basic problems in engineering hydrology. The usual method of combining a statistical analysis of rainfall with the unit hydrograph, based on the assumption of basin linearity, is the best known methodology developed for such problems. However, problems are encountered with this method in ungauged drainage basins, and besides, unit hydrograph concepts may prove misleading in non-linear basins (Rogers and Zia, 1982, Mimikou, 1983). In this paper a regional method for extreme rainfall and runoff prediction is presented. The method can be easily applied in ungauged catchments and it is also helpful in avoiding problems arising from basin non-linearity.

DATA USED

The precipitation and runoff data used in the study were obtained from four drainage basins covering a considerable portion of western and nord-werstern Greece. This region is of major hydrological importance since it

(1) Department of Water Resources, Hydraulic and Maritime Engineering, Faculty of Civil Engineering, National Technical University of Athens, 5 Iroon Polytechniou, 15773 Athens, Greece.

contains four major rivers of Greece and several hydraulic works, such as dams and reservoirs, spillways, flood protection works, etc. The study basins are associated with the Acheloos, Aracthos and Aoos Rivers and vary in magnitude from 200 to 1,350 km². The criterion for the selection of these basins was their relatively good record of past flood events. A general map of the study area is shown in Fig. 1.

From the available stage recordings at the outlet of each drainage basin, several extreme flood events were identified in terms of flood peak and volume. The selected flood recordings, 65 in total, were then transformed to flood hydrographs by using appropriate stage-discharge relationships. From these, both total and net discharge peaks Q and volumes V were calculated. Base flow separation was carried out using a typical procedure commonly suggested (Wilson, 1974; Linsley *et al.*, 1975). Moreover, for each flood event the respective hydrograph and the causal storm were studied and a matrix with the following characteristics was compiled: total flood duration t_{tot}, time of rise to the peak t_p, storm duration t, total areal rainfall depth h and mean areal rainfall intensity i, baseflow at the peak Q_{bf}, baseflow volume V_{bf}, and mean rate of precipitation losses f. The areal rainfall characteristics were calculated by using the Thiessen polygon method.

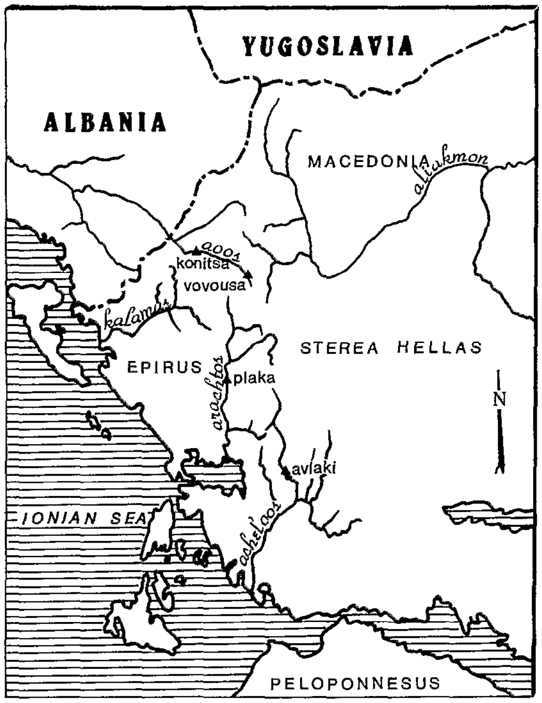

FIG. 1. — General map of the region.
Carte générale de la région.

ANALYSIS OF MAXIMUM ANNUAL FLOOD PEAKS AND VOLUMES

Samples of annual extremes of net flood peak, Q_n, and volume, V_n, were selected from each station, with the exception of the Vovousa basin at the Aoos River because of its limited record. Vovousa basin was used instead for verification purposes. The samples were then fitted with the appropriate extreme value distribution functions. Specifically, the EV1 distribution function (Gumbel) was chosen for maximum flood peaks, while the Log Pearson III distribution was chosen for maximum flood volumes. The fitting was carried out according to established methodologies (Yevjevich, 1972), using the Weibull plotting position. For the estimation of parameters of the EV1 distribution the Gumbel method was followed (Gumbel, 1958), while the parameters of the Log-pearson III distribution were derived by the method of frequency coefficients. The goodness of fit was tested for both distributions. The pairs ($Q_n(T)$, $V_n(T)$) were used in nomograph 1, shown in Fig.2, which was constructed with the reduced variables V_n/A and Q_n/A, A being the drainage basins area, as coordinates. Curves of equal return period are plotted for T =

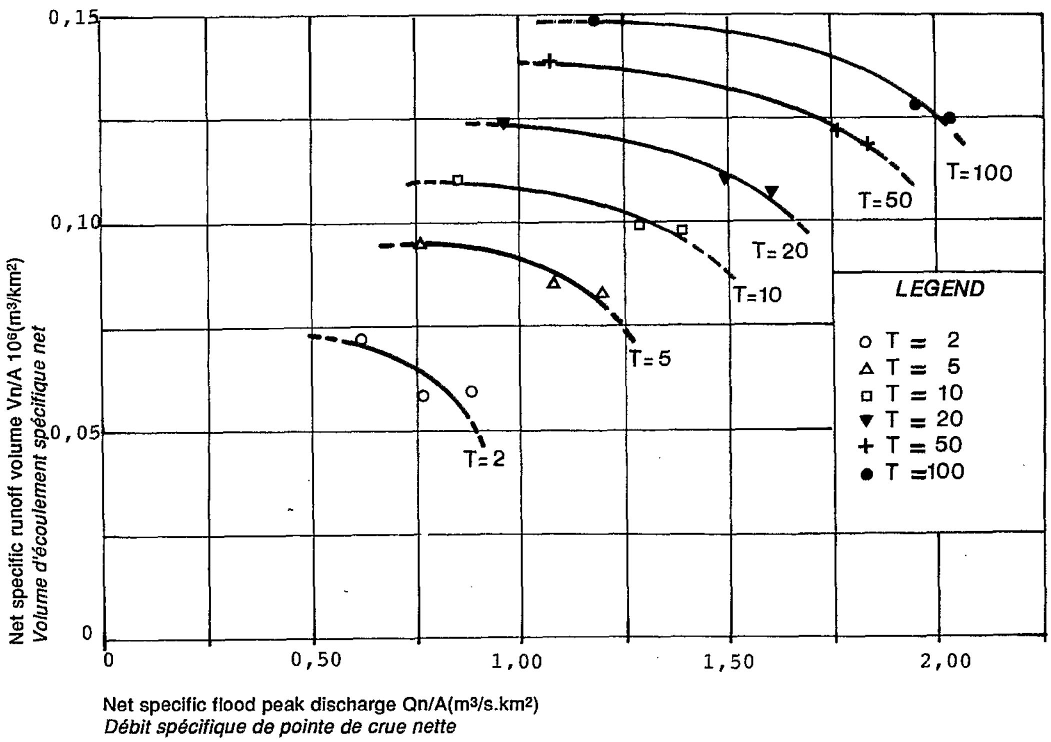

FIG. 2. — Flood peak — volume — return period envelope curves - Nomograph 1 -
Courbes enveloppes pointe de crue-volume-période de retour.

(2,5,10,20,50,100). From this nomograph one can obtain for any given pair of variables (e.g.V_n,T), the third (e.g.Q_n).

For a design flood to be described, the base flow discharge at the time of the peak, Q_{bf} and the total baseflow volume V_{bf}, are also required. Therefore a relation was sought between Q_n and Q_{bf}, and correspondingly between V_n and V_{bf}. For the relations sought, the dimensionless ratios Q_{bf}/Q_n and V_{bf}/V_n were defined as dependent variables and, to remove the effect of basin area A, the specific values Q_n/A and V_n/A were used as independent variables. A semi-logarithmic regression for the discharge resulted in the relation:

$$\frac{Qbf}{Qn} = 0.1146 \exp\left(-0.8837\, Q_n/A\right) \quad (r = -0.865) \tag{1}$$

while a semi-logarithmic regression for the volumes resulted in the relation:

$$\frac{Vbf}{Vn} = 0.4807 \exp\left(-6.0817\, V_n/A\right) \quad (r = -0.887) \tag{2}$$

Eq. (1) has been plotted as nomograph 2 in Fig. 3 and Eq. (2) has been plotted as nomograph 3 in Fig. 4. For given net values and the basin area, the respective base flow estimate can be instantly deduced from these graphs.

ANALYSIS OF EXTREMES STORM EVENTS

For each maximum flood event examined, information on the respective storm was collected as previously described. This information specifically included: Areal rainfall depth, h (mm); Total rainfall volumes, $V_{R,tot}$ = h A, ($10^6 m^3$); Storm duration, t (hr); Mean rainfall intensity, i = h/t, ($mmhr^{-1}$); Rainfall losses, $V_{R,f} = V_{R,tot} - V_n$, ($10^6 m^3$), and Mean rate of rainfall losses, f = $V_{R,f}$/A t, ($mmhr^{-1}$).

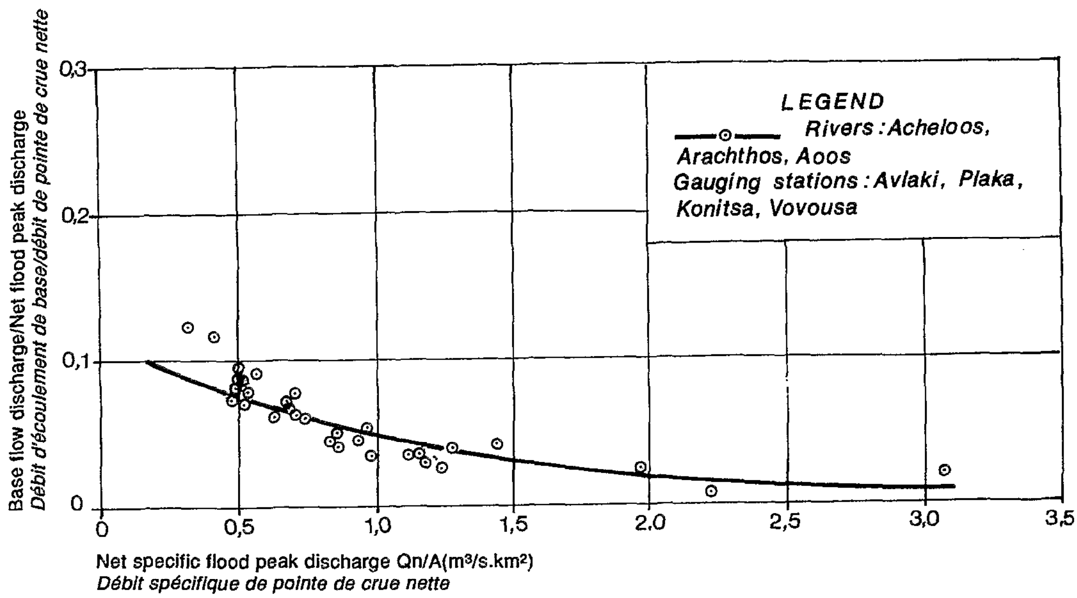

FIG. 3. — Relation between net flood peak and baseflow - Nomograph 2 -
Relation entre la pointe de crue nette et l'écoulement de base.

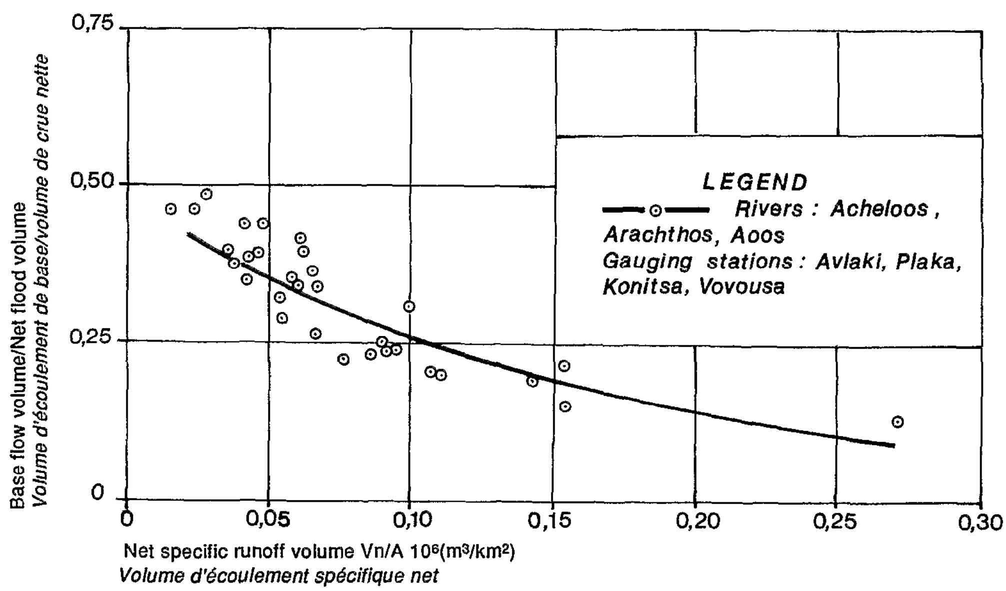

FIG. 4. — Relation between net flood and base flow volume - Nomograph 3 -
Relation entre volume net de crue et volume d'écoulement de base.

Using these data, a relationship between the mean rainfall intensity, the mean loss rate and rainfall duration was sought across the study region. For this purpose, the events were classified by duration in classes of 12,24,36,48 and 60 hours. For each class a linear relation was found between mean rainfall intensity i and mean loss rate f, in the form:

$$f = \Lambda_t i \qquad (3)$$

where Λ_t is a proportionality coefficient depending on duration. The values of Λ_t in Eq. (3) obtained for each class were further correlated with duration t and a linear relationship gave the best fit in the form:

$$\Lambda_t = a + bt \qquad (4)$$

Substituting in Eq.(3) for Λ_t, the required relationship was derived:

$$f = (a + bt)\, i \qquad (5)$$

The estimated values of the coefficients Λ_t, a and b in Eqs (3) and (5), with the corresponding determination coefficients, are shown in table I. Obviously, this relation is empirical and no physical justification is attempted, and its validity has not been checked outside the range of storm durations in the sample. Based on Eq. (5) the nomograph 4 in Fig. 5 was constructed with f and i as coordinates, and various storm durations represented by straight lines. For a given mean intensity of rainfall, one can obtain the corresponding mean loss rate for various storm durations. Apparently, this nomograph is valid within the study region and most importantly for given rainfall intensity and duration it produces a mean loss rate which may be interpreted as an average over the range of return per-

TABLE I
Parameters of the mean rate of losses — mean intensity — storm duration relationship
Paramètres de la relation taux moyen de pertes — intensité moyenne — durée d'averse

Storm duration t (hr)	λt	Coeff. of determination r^2
12	0.7165	0.976
24	0.5760	0.865
36	0.5070	0.850
48	0.4436	0.700
60	0.2380	0.658

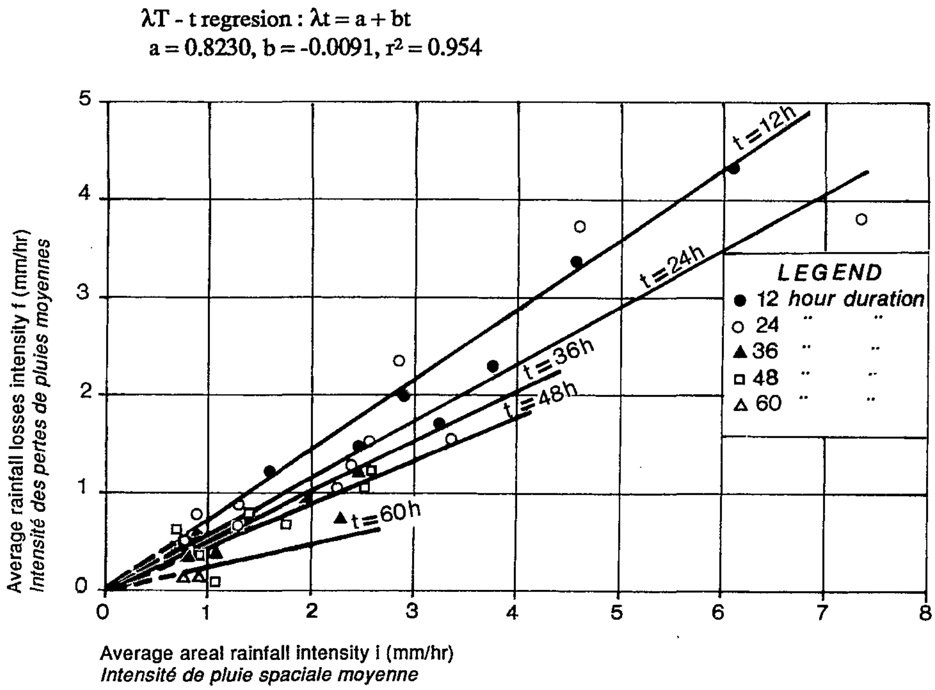

FIG. 5. — Mean loss rate — rainfall intensity — duration relationships - Nomograph 4 -
Taux moyen des relations pertes-intensités de précipitation-durée.

iods implicity existing in the sample, since the extreme storm events considered for the derivation of Eq. (5) were used regardless of their return periods. One would expect the mean loss rate to decrease as the return period increases. Therefore, for the nomograph to be applicable beyond the return period limit of the sample size, a reduction coefficient should be defined in terms of the return period. Thus, a subset of events was selected, representative of the complete range of return periods of the samples, regardless of storm duration. For each of these events the actual mean loss rate (computed directly from rainfall and flow data) was compared with the value (from now on denoted as f) estimated by means of Eq. (5) for the given rainfall intensity and duration, and a correction coefficient was derived. A logarithmic regression (r = – 0.473) between these correction coefficients and the respective return periods revealed a weak tendency described by the following equation:

$$a = 113{,}33\ T^{-0.0919} \quad (6)$$

where $a = \dfrac{f\,(i, t, T)}{f\,(i, t)}$ in % and f(i,t) is an average within the sample size with respect to T. Eq. (6) is plotted in Fig. 6 as nomograph 5. It can be seen that for small return periods the correction coefficient is a magnification coefficient whereas for larger return periods it becomes a reduction coefficient, decreasing with increasing T. The limiting value of T (a = 100%) is within the interval determined by the sample size as expected, since f(T) is monotonic and f is an average with respect to T within the sample. For practical reasons the assumption was made that this pattern of decrease of the rate of losses is valid for larger return periods and the plot in Fig. 6 was drawn by extrapolation up to T = 100.

By combined use of the two nomographs 4 and 5, the rate of rainfall losses of any event in the region with given intensity, duration and return period (within the specified limits) can be estimated. In doing so, for return periods within the sample limits the correction for T might be omitted, but for larger return periods it should be accounted for according to Eq.(6) or nomograph 5.

ESTIMATION OF DESIGN FLOOD CHARACTERISTICS

For the estimation of design flood characteristics, the return period T and the storm duration t have to be decided and with these as inputs, mean rainfall intensity i and rainfall depth h can be derived by using the available

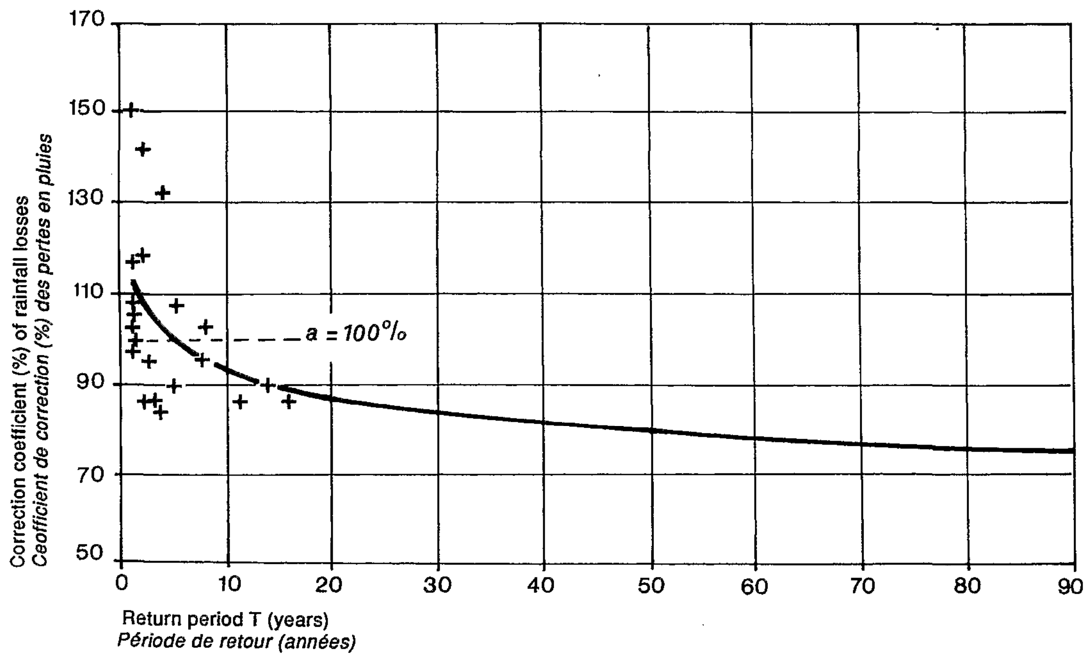

FIG. 6. — Loss rate correction coefficient in terms of return period - Nomograph 5 -
Taux du coefficient de correction de pertes en fonction de la période de retour.

depth-duration-frequency relation for the region. The procedure proposed for the calculation of the respective flood characteristics is as follows:

— step 1 — With i and t known, the average loss rate f is calculated from the nomograph 4. This value is then corrected for the return period by applying the correction coefficient from nomograph 5 and a rate of losses f is estimated;

— step 2 — From the losses rate f, the given duration t and the drainage basin area A, the losses are computed as

$$V_{R,f} = A\, ft \tag{7}$$

The total rainfall volume is given by

$$V_{R,tot} = A\, h \tag{8}$$

From Eqs (7) and (8), the net flood volume V_n is calculated

$$V_n = V_{R,tot} - V_{R,f}\,; \tag{9}$$

— step 3 — With given return period, area and net volume, the net peak discharge Q_n is calculated using nomograph 1;

— step 4 — with net values Q_n and V_n already estimated, the respective base flow values Q_{bf} and V_{bf} are deduced from the nomographs 2 and 3;

— step 5 — The required flood peak and volume for the given storm duration, area and return period are estimated as:

$$V_{tot} = V_{bf} + V_n \text{ and } Q_{tot} = Q_{bf} + Q_n \tag{10}$$

APPLICATION-VERIFICATION

For verification purposes two flood events, not previously included, in the Vovousa basin of Aoos River were selected. This basin, according to the criterion of non linearity suggested by Rogers and Zia (1982) was found to be strongly non-linear (slope of the logarithmic peak discharge distribution m = 0.646 as compared to m = 1 for linear basins).

The verification data and results are shown in Table II. The prediction error (percentage deviation of the estimated from the observed value) was sufficiently small to render the proposed method promising.

TABLE II
Verification data and results
Vérification des données et résultats

	Input data			Observed		Predicted		Error (%)	
Event	h (mm)	t (hr)	T (yr)	Q (m^3s^{-1})	V (10^6m^3)	Q	V	Q	V
10-12/1/84	90.4	34	2	183	16.4	193	12.3	5	25
30/10-3/11/74	123.3	59	5	270	26.5	230	23	15	13

CONCLUSIONS

There is a need for developing regional methods for the estimation of design flood characteristics in ungauged basins, regardless of their non-linearity. The proposed methodology is relatively precise, fast and easy to use and therefore it appears to be promising for design or research applications in the region, whithin the limits imposed by the historical record regarding flood rarity.

ACKNOWLEDGEMENTS

The authors wish to thank the Public Power Corporation of Greece for the hydrological data made available to them and for its technical support in data treatment.

Manuscrit accepté par le comité de rédaction le 26 août 1994

REFERENCES

GUMBEL (E.J.), 1958 — *Statistics of Extremes.* Columbia University Press, New York, N.Y.

LINSLEY (R.K.), KOHLER (M.A.) et PAULHUS (J.L.H.), 1975 — *Hydrology for Engineers.* Mc Graw-Hill, New York, N.Y. 482 p.

MIMIKOU (M.A.), 1983 — A study of drainage basin linearity and non-linearity. *J. Hydrol.* 64: 113-134.

ROGERS (W.F.) et ZIA (H.A.), 1982 — Linear and non-linear runoff from large drainage basins. *J. Hydrol.*, 55: 267-278.

WILSON (E.M.), 1974 — *Engineering Hydrology.* Macmillan, London 232 p.

YEVJEVICH (V.), 1972 — *Probability and Statistics in Hydrology.* Water Resources Publications, Fort Collins, Colo. 302 p.