

Regional flood frequency estimation using the two-component extreme value distribution

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ABSTRACT The two-component extreme value (TCEV) distribution, suggested for modelling Italian annual flood series (AFS), is shown to account both for the presence of flow outliers and for the high variability of the skewness of historical AFSs. Using such a model, it is found that the T-year flood varies with $\log(T)$ much more rapidly for large values of T than is the case for small values of T. The presence of four parameters in the TCEV distribution introduces great uncertainty in estimating the T-year flood when the parameters are estimated from a single series. Regional analysis, which exploits basin similarities, is then needed, not only at ungauged sites but also at gauged ones. Regionalization techniques, by which all flood data over a region are combined to produce a single regional flood distribution, are described and their application to Italian data is shown.

Estimation régionale de la fréquence des crues par la distribution des valeurs extrêmes à deux composantes

RESUME La distribution des valeurs extrêmes à deux composantes suggérée pour décrire les séries italiennes des crues annuelles, tient compte de la présence des valeurs exceptionnelles et également de la grande variabilité de l'asymétrie des séries historiques. Par ce modèle, on a estimé que les valeurs de la crue de période de retour T varie avec $\log(T)$ beaucoup plus rapidement pour les grandes valeurs de T que pour les petites. La présence de quatre paramètres dans la distribution des valeurs extrêmes à deux composantes donne beaucoup d'incertitude lorsqu'il s'agit d'estimer la crue de période de retour T lorsque les paramètres estimés proviennent d'une seule série. Ensuite, une analyse régionale exploitant des similarités du bassin doit être faite aussi bien pour les stations qui ont été mesurées que pour celles qui ne l'ont pas été. On décrit des techniques de régionalisation à travers lesquelles toutes les données de la crue sur une région donnée permettent de produire une seule distribution

régionale de crue; suit l'application aux données italiennes.

NOTATION

A	basin area
C	dimensionless runoff coefficient
c	fraction of basin area formed by carboniferous rocks
$F_X(x)$	cumulative distribution function (CDF) of the variable X
G	sample skewness coefficient
g	value of G
\tilde{t}_r	mode of the annual maximum of the mean rainfall rate over a time duration equalling t_r
K'_1	characteristic parameter of the Gumbel distribution of X_1
n	series length or time interval, in years
T	return period
t_r	basin lag time
X	annual maximum of the instantaneous flood (annual flood)
X_i	annual flood in the year i ($i = 1, 2, \dots, n$)
\bar{X}	sample mean of X
$X_{(n)}$	largest flood in n years
X_1	annual maximum of the basic component
X_2	annual maximum of the outlying component
$X' = X/\varepsilon_1$	dimensionless annual flood, scaled by the index flood ε_1
$X'_{(n)}$	largest value of X' in n years
x	value of X, $X_{(n)}$, X_1 and X_2
x'	value of X' and $X'_{(n)}$
Y	$(X - \hat{\varepsilon})/\hat{\theta}$, the reduced annual flood
$Y_{(n)}$	reduced largest order statistic (largest value of Y in n years)
Y'	$(X - \hat{\varepsilon}_1)/\hat{\theta}_1$, the reduced annual flood (reduced by the basic component parameters)
y	value of Y and $Y_{(n)}$
y'	value of Y'
$\varepsilon, \varepsilon_1, \varepsilon_2$	position parameter of the distributions (1) and (5) for X, X_1 , and X_2 respectively
$\Lambda, \Lambda_1, \Lambda_2$	parameter (mean annual number of independent floods) of the distributions (1) and (5) for X, X_1 , and X_2 respectively
$\theta, \theta_1, \theta_2$	scale parameter of the distributions (1) and (5) for X, X_1 , and X_2 respectively
$\hat{\Lambda}'_1, \hat{\theta}'_1, \hat{\Lambda}'_2, \hat{\theta}'_2$	regional parameters of the TCEV distribution of Y'
$\hat{\cdot}$	estimator of the parameter

INTRODUCTION

In flood frequency analysis, whenever the return period T is large compared with the length n of the available series, the error in the T-year flood estimate is found to be greatly affected by the

flood-distribution model adopted. In many cases, furthermore, the correct design of hydraulic structures for flood control must take cognizance not only of the flood associated with the selected value of T , but also of the expected behaviour of the T -year flood as T varies. For the latter purpose, the choice of the distribution is even more critical, for any error is going to be amplified with increasing T .

Difficulties are met in selecting a theoretical flood distribution stemming mainly from the fact that in many geographical areas some of the annual flood series (AFS) exhibit one or more values ranking much higher than the bulk of the remaining data. Such values are generally unaccounted for by the most commonly used two-parameter distributions which, for this reason, are in many cases inadequate for flood-frequency analysis purposes. Among these, reference may nevertheless be usefully made to the Gumbel distribution, for it may constitute the basis for building more refined models.

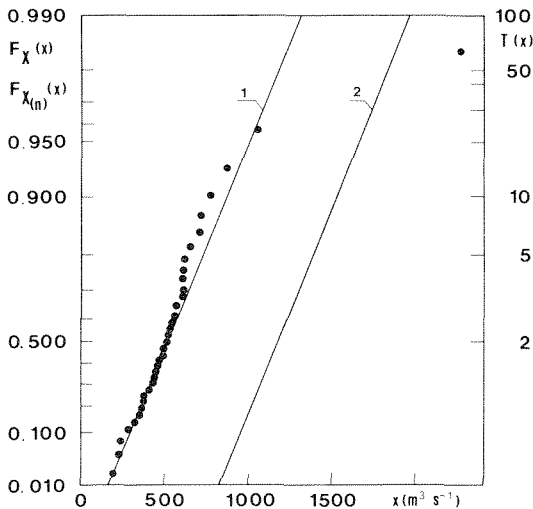


Fig. 1 Observed CDF of the annual flood X for the Arno River at Subbiano station, compared with both the Gumbel CDF of X (curve 1) and the CDF of the n -year flood $X_{(n)}$, for $n = 35$ (curve 2).

A typical example is shown in Fig.1, where the observed cumulative distribution function (CDF) calculated from the AFS (X_1, X_2, \dots, X_n) of the Arno River at Subbiano in central Italy is plotted using the Gringorten formula (Cunnane, 1978) and compared with the CDF of the Gumbel distribution:

$$F_X(x) = \exp(-\Lambda e^{-x/\theta}) = \exp[-e^{-(x-\epsilon)/\theta}] \quad (1)$$

with the parameters Λ and θ (or $\epsilon = \theta \ln \Lambda$) estimated by the maximum likelihood (ML) method. Also shown in Fig.1 is the theoretical CDF of the n -year flood $X_{(n)}$ ($n = 35$) which, if equation (1) applies, is itself a Gumbel variable:

$$F_{X_{(n)}}(x) = [F_X(x)]^n = \exp(-n\Lambda e^{-x/\theta}) \quad (2)$$

Under the Gumbel hypothesis, the largest flood, observed during the disastrous storm of 1966, corresponds to a cumulative probability 0.9979 for $X_{(n)}$ and may accordingly be reckoned an outlier.

More precisely, whether the largest observed flood $X_{(n)}$ is or is not an outlier may be tested by one of two statistics: either

(a) the sample skewness coefficient (Ferguson, 1961):

$$G = n^{1/2} \frac{\sum_{i=1}^n (X_i - \bar{X})^3}{[\sum_{i=1}^n (X_i - \bar{X})^2]^{3/2}} \quad (3)$$

where \bar{X} is the sample mean; or

(b) the reduced largest order statistic:

$$Y_{(n)} = (X_{(n)} - \hat{\varepsilon})/\hat{\theta} \quad (4)$$

where $\hat{\varepsilon}$ and $\hat{\theta}$ are ML estimators of ε and θ .

For both tests the critical region is defined only by large values. By sampling experiments, critical values at the 5% significance level have been determined for both statistics as a function of n (Rossi *et al.*, 1984). In particular, for $n = 35$ (the length of the Arno River AFS) $G_{0.95} = 1.87$ and $Y_{(n)0.95} = 6.40$, both smaller than the values of these statistics for this river ($g = 3.48$ and $y = 9.73$). Thus the largest observed flood must be classed as an outlier under the Gumbel distribution.

As to accepting or rejecting a theoretical distribution, however, a reliable decision can only be reached on the basis of tests applied to a large number of AFSs. Thirty-nine AFSs of stations in central and southern Italy, for n ranging from 34 to 49 with an average of 40 years, were selected among those operated by Servizio Idrografico Italiano. The observed CDF of the corresponding values

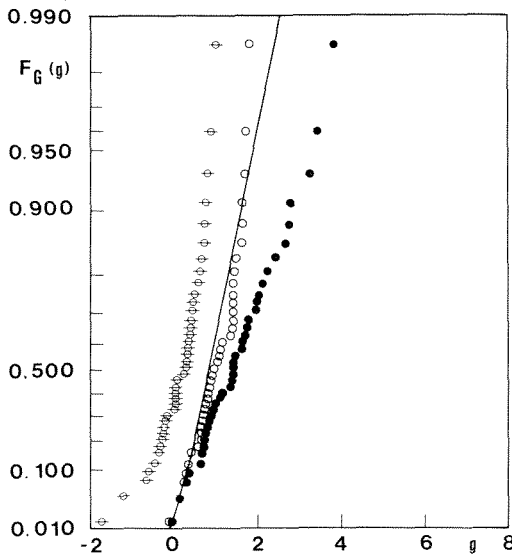


Fig. 2 Observed CDF of the skewness G for 39 Italian AFSs: of X with outliers (●); of X without outliers (○); of $\log X$ (⊕). Sampling-experiment derived CDF of G for the Gumbel distribution and for $n = 40$.

of G is compared in Fig.2 with the sampling-experiment derived CDF of G for the Gumbel distribution for $n = 40$ (Rossi *et al.*, 1984). The two CDFs tend to separate more and more sharply as g increases. Referred to as condition of separation (Matalas *et al.*, 1975), this behaviour of the observed skewness vis-à-vis that expected for a Gumbel distribution is closely connected with the presence of outliers in some AFSs. In fact, the condition of separation is no longer observed if a similar comparison is carried out on data from which the outliers have been discarded. The elimination of extreme observations was implemented using an iterative procedure, the largest annual flood in each AFS being taken out until the outlier-test statistic (whether G or $Y_{(n)}$) yielded a nonsignificant value at the 5% level. Altogether 18 outliers were identified in 12 of the 39 AFSs.

RATIONALE FOR A SUITABLE FLOOD DISTRIBUTION: THE TCEV DISTRIBUTION

The inadequacy of the Gumbel distribution for deriving a suitable T -year flood estimator has prompted many suggestions for alternative models. It is a fact, however, that the condition of separation remains unresolved by the most common two- or three-parameter empirical distributions (Matalas *et al.*, 1975; Landwehr *et al.*, 1978). Not even classical extreme value theory is of much help in the choice of a flood distribution since its basic assumptions, namely the annual number of independent floods sufficiently large and flood-peak magnitudes identically distributed, are too restrictive. In Fig.2, the Italian historical data are compared with the extreme value Type-2 or Fréchet distribution. To this end, considering that the Fréchet distribution may be obtained from the Gumbel distribution by a logarithmic transformation, the sample skewness coefficient G was calculated for each of the 39 AFSs from the transformed data $\log(X)$. The observed CDF for $\log(X)$ is found systematically to the left of the theoretical CDF. Thus, whereas the Gumbel distribution generates samples less skewed than the historical data and will, on the average, underestimate the T -year flood, on the contrary the Fréchet distribution generates samples more skewed and will tend to overestimate the T -year flood.

The presence of outliers in AFSs rather prompts the hypothesis that flood peaks do not all arise from one and the same distribution, some being generated by a mechanism different from that responsible for the other data. In the case of the Italian rivers considered, flood outliers generally correspond to similarly disastrous rainfall storms. In the example quoted of the Arno River, during the storm, rainfall stations operating in the basin recorded a daily rainfall much higher than the rest of the annual maximum values (Evangelisti, 1968). Similar results were also found for various sites in southern Italy by Penta *et al.* (1980).

Proceeding from the assumption that outliers are generated by a different meteorological mechanism than is the case for the other floods, the two-component extreme value (TCEV) distribution suggested by the authors (Rossi & Versace, 1982; Versace *et al.*, 1982; Rossi *et al.*, 1984) treats the annual flood as the maximum of a Poissonian number of flood peaks, generated by a mixture of two exponential distributions. In this model, the CDF of X is given by:

$$\begin{aligned}
F_X(x) &= \exp(-\Lambda_1 e^{-x/\theta_1} - \Lambda_2 e^{-x/\theta_2}) \\
&= \exp[-e^{-(x-\varepsilon_1)/\theta_1}] \exp[-e^{-(x-\varepsilon_2)/\theta_2}] \\
&= F_{X_1}(x) F_{X_2}(x); \quad X \geq 0
\end{aligned} \tag{5}$$

$$\text{with } \varepsilon_j = \theta_j \ln \Lambda_j \quad j = 1, 2 \tag{6}$$

Λ_j is the mean number of independent peaks, and θ_j the mean peak magnitude, of the "basic" ($j = 1$) and the "outlying" ($j = 2$) component. The TCEV distribution has a finite probability, $\exp(-\Lambda_1 + \Lambda_2)$, that the value is exactly zero. Since such a probability is generally negligible, the TCEV distribution is in practice indistinguishable from a continuous one also allowing for negative values. Then the CDF of equation (5) is also interpretable as the CDF of the larger of the two independent Gumbel-distributed variables X_1 and X_2 , which are the annual maximum of the respective component. In the absence of an outlying component, the TCEV distribution reduces to the Gumbel distribution.

The four parameters of the CDF of equation (5) can be estimated by the ML method by simultaneously solving the four equations obtained by equating to zero the first partial derivatives of the logarithm of the likelihood function with respect to the parameters (Rossi *et al.*, 1984). Using this method, TCEV-distribution fits were obtained for the 12 AFSs of those analysed that exhibited outliers under the simple Gumbel hypothesis. All seemed to fit by eye the data adequately. The Hazen plotting formula was used because of the high skewness of the TCEV distribution (Cunnane, 1978). In particular, as is shown in Fig.3 in the case of the Arno River and two other representative examples, the exceptionally large values no longer qualified as outliers.

The TCEV model was also shown to fit well the annual maximum values of the daily rainfalls at many sites in southern Italy where data classifying as outliers under the Gumbel model are present. In this case, the analysis was based on the partial duration series (Penta *et al.*, 1980).

REGIONAL ANALYSIS FOR THE OUTLYING COMPONENT

Because of the limited data for each site, the choice of the distribution cannot be based exclusively on a single series. Prior knowledge about the form of the distribution must also be used.

Accordingly theoretical considerations supported by statistical analysis of 39 Italian AFSs suggest that the TCEV distribution can be adopted as a suitable flood distribution. In applying the TCEV distribution to a single AFS, the comparative rarity of the outlying component introduces large errors in the estimation of the parameters.

In the light of this, regionalization techniques (by which the uncertainty is reduced by virtue of the large number of data used) become of interest. They can give us empirical, more precise, prior knowledge of the distribution and thus enable us to obtain a reliable estimator for the T-year flood, not only for ungauged but also for gauged sites. The key idea is that the meteorological

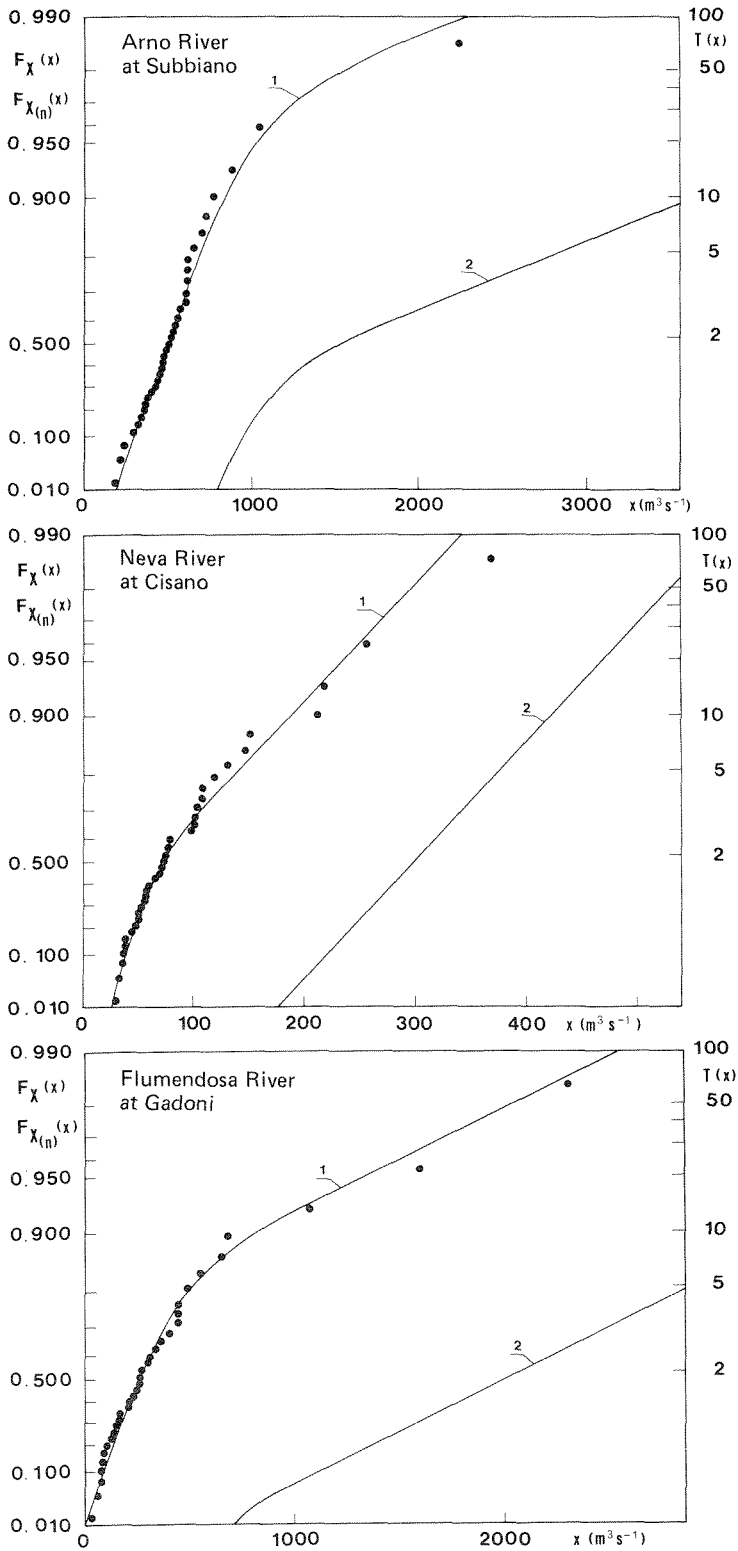


Fig. 3 TCEV distribution (curve 1) fits to three Italian AFSs. Theoretical CDFs of the n -year flood $X_{(n)}$ (curve 2) are also represented.

mechanism that causes the outlying component of a flood series is "similar" within a homogeneous region. By exploiting this similarity, a regionalization model using all the 39 Italian AFSs was inferred.

To compare data from different rivers, a dimensionless variable, the reduced annual flood, was introduced:

$$Y' = (X - \hat{\varepsilon}_1) / \hat{\theta}_1 = X / \hat{\theta}_1 - \ln \hat{\Lambda}_1 \tag{7}$$

$\hat{\theta}_1$ and $\hat{\varepsilon}_1$ (or $\hat{\Lambda}_1$) being estimates of the basic component parameters. The estimation procedure adopted consisted in rejecting outliers by the method mentioned in the Introduction, and estimating the parameters from the remaining data by the ML method for the simple Gumbel distribution.

It was then assumed that Y is everywhere distributed according to one and the same TCEV variable having a CDF:

$$F_{Y'}(y') = \exp(-\Lambda_1' e^{-y'/\theta_1'} - \Lambda_2' e^{-y'/\theta_2'}) \tag{8}$$

Λ_1' , θ_1' , Λ_2' , and θ_2' being distribution parameters typical of the region ("regional parameters"). Spatial-correlation effects were not taken into account, since they leave regional parameter estimates uninfluenced, though they do affect their variance. The 39 reduced AFSs were pooled together to form a single series of 1525 data. The ML estimation of the four parameters gave $\hat{\Lambda}_1' = 0.811$, $\hat{\theta}_1' = 0.867$, $\hat{\Lambda}_2' = 0.161$, and $\hat{\theta}_2' = 2.606$. In Fig.4 the theoretical CDF obtained for Y' is compared with the observed CDF and appears to fit the data reasonably well. Regionally estimated parameter values of the outlying component are less uncertain as well, since the maxima

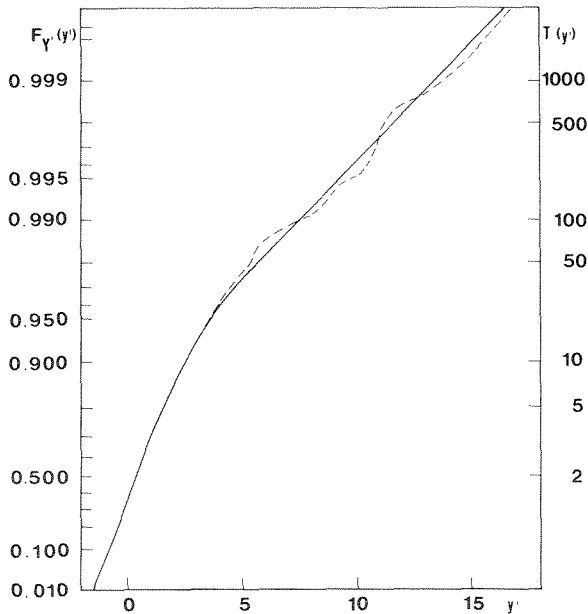


Fig. 4 TCEV distribution fit to 1525 station-years Italian data for the reduced annual flood, Y' .

originating from this component, and involved in the estimating procedure, are obviously much more numerous than those present in a single AFS. Note furthermore that such maxima are more numerous than the values identified as outliers under the Gumbel hypothesis. Nevertheless there remains the problem of evaluating the sampling properties of the suggested regional estimation procedures as could be assessed by Monte Carlo techniques, taking interstation correlation also into account.

This regionalized TCEV distribution also reproduces well such statistical characteristics of the historical AFSs as the observed distribution of the skewness coefficient G . By sampling experiment techniques, 25 000 series of length $n = 40$ were independently generated from the regionalized TCEV distribution for Y' . For each series the skewness coefficient G was calculated. The CDF of these values of G is shown in Fig.5 and it is seen to reproduce closely the observed CDF of G . Thus, in addition to accounting for data otherwise qualifying as outliers, the TCEV distribution also eliminates the condition of separation.

One further conclusion may also be drawn. The hypothesis that the whole region considered may be deemed homogeneous with respect to the distribution of Y' , i.e. that reduced floods come from a single distribution, cannot be rejected. This result may be due to the fact that the information to be extracted from regional analysis concerning the outlying component far outweighs site-specific information. Further information, such as regards, for example, meteorological processes, will be needed to ascertain whether distinct smaller areas within a region are characterized by significantly different sub-regional flood distributions.

REGIONAL ANALYSIS FOR THE BASIC COMPONENT

Gumbel characteristic parameter K'_1

The regionalized reduced flood CDF of equation (8) (or the curve of Fig.4) can be used for predicting the T -year flood for any river of southern or central Italy for which estimates of the basic-component parameters θ_1 and Λ_1 (or ε_1) are available.

In obtaining these parameter estimates, regional information is also usefully resorted to and indeed is needed either to improve upon site-specific estimates based on limited site data or to make inferences at ungauged sites. As regards Λ_1 (the mean annual number of independent floods of the basic component), invoking basin similarity relies on the fact that this mean number tends to be constant over wide regions.

To ascertain whether the observed variation in Λ_1 among different stations of a region is significantly larger than that due to random sampling, the analysis is usefully carried out in terms of Gumbel's characteristic parameter K'_1 for the basic component:

$$K'_1 = 1/\log\Lambda_1 = \theta_1/(0.4343\varepsilon_1) \quad (9)$$

whose control intervals for homogeneity tests have been evaluated (Rossi & Versace, 1982).

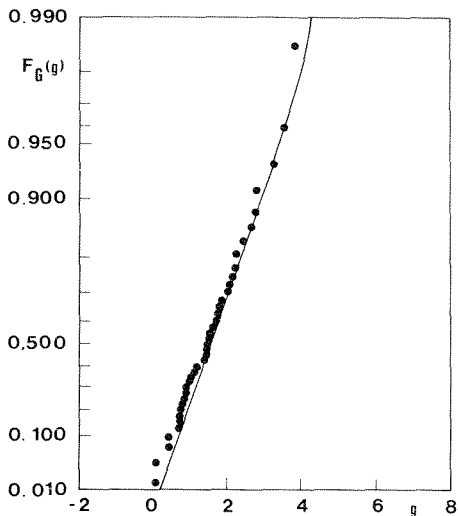


Fig. 5 Observed CDF of the skewness G for 39 Italian AFSs (\bullet), compared with the sampling-experiment derived CDF of G for the regional TCEV distribution of Y' .

For the 39 Italian AFSs considered, the K_1' values, estimated by the rejection-of-outliers procedure, range from 0.6 to 1.7 with an average close to 1.0. This range is significantly larger than that due to random sampling. Therefore, the region of interest will have to be subdivided into smaller areas where the observed variations of K_1' do not exceed those expected owing to sampling errors, so that the parameter may be assumed constant within each area.

By way of illustration, let us consider the case of a small region in southern Italy, the Campania. Using the gauging stations of Campania with $n \geq 30$, the corresponding K_1' values were found to be practically constant and equal to the average for central and southern Italy ($K_1' \cong 1$). As is shown in Fig.6, the K_1' values lie within the 95% control interval, so Campania may be treated as a

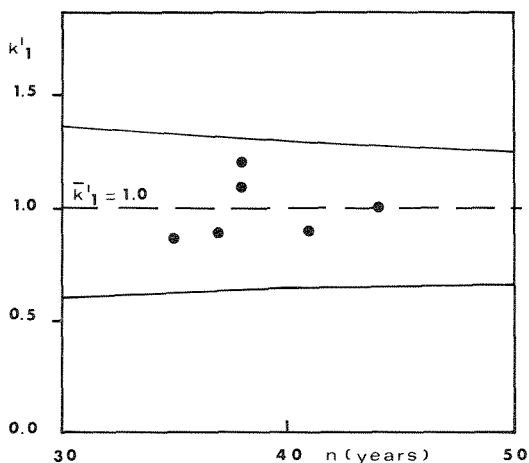


Fig. 6 Homogeneity test for the characteristic parameter K_1' in Campania (Italy).

homogeneous area with respect to the parameter K'_1 .

For larger areas, homogeneous regions can be identified using univariate cluster analysis, the space distribution of K'_1 being assumed to have the character of spatial clusters.

Having ascertained the constancy of K'_1 over the area, the dimensionless variable $X' = X/\epsilon_1$ will obey one and the same distribution for all stations in the area. From equations (7) and (9) the relation connecting X' with the reduced annual flood Y' is:

$$X' = X/\epsilon_1 = 1 + 0.4343 K'_1 Y' \tag{10}$$

From the distribution of equation (8) for Y' we obtain the CDF of X' for the area, which in the case of Campania ($K'_1 = 1$) yields:

$$F_{X'}(x') = \exp(-11.55e^{-2.66x'} - 0.39e^{-0.88x'}) \tag{11}$$

The distribution of equation (11) is plotted in Fig.7, together with (and of more direct interest for the design of hydraulic structures) CDFs of the n-year flood $X'_{(n)}$ for various values of n.

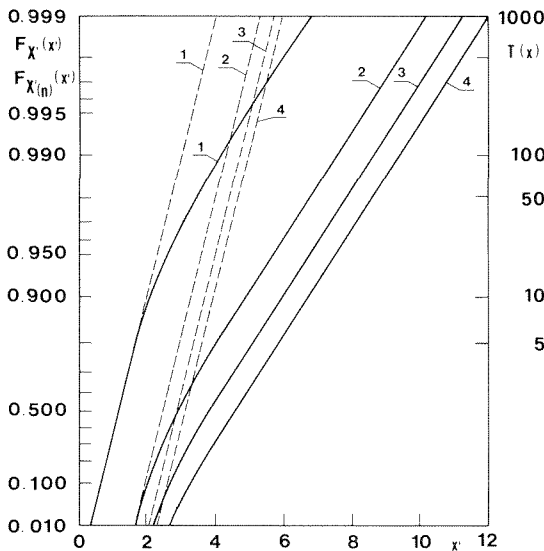


Fig. 7 Regional CDF of $X' = X/\epsilon_1$ (curve 1) and of $X'_{(n)}$ for $n = 20, 50$ and 100 (respectively curves 2, 3 and 4) in Campania (Italy) for both Gumbel (-----) and TCEV (——) distributions.

For the sake of comparison, the same Figure also shows the CDFs of X' and $X'_{(n)}$ for the Gumbel distribution with the same value of the characteristic parameter.

It may be seen that the T-year flood for the CDF of equation (11) varies with $\log(T)$ slowly for small values of T and much more rapidly for large values of T. Only for T values smaller than 20 years do the TCEV and Gumbel distributions give similar results. Thereafter they sharply separate as T increases.

The index flood ε_1

We need lastly to estimate the index flood in equation (10), namely, the mode ε_1 of the basic-component annual flood. When no flow records are available at the site, an estimate may be made from physiographic and meteorological characteristics of the basin. In Italian experience, a probability-based expression of the type of the rational formula was shown to be well suited for the purpose, viz:

$$\varepsilon_1 = C \tilde{i}_{t_r} (1 - c)A \quad (12)$$

where A is the basin area, c is the fraction of this area formed by carboniferous rocks (and accordingly, $A(1 - c)$ has the role of a reduced basin area), t_r is the lag time, \tilde{i}_{t_r} is the mode of the annual maximum of the average rainfall rate over a time duration t_r , and C is a dimensionless runoff coefficient. In Fig.8 the observed values of ε_1 for the gauged sites of Campania with $n > 10$ are plotted against the corresponding values of \tilde{i}_{t_r} . It may be seen that there is good agreement with equation (12) for $C = 0.32$.

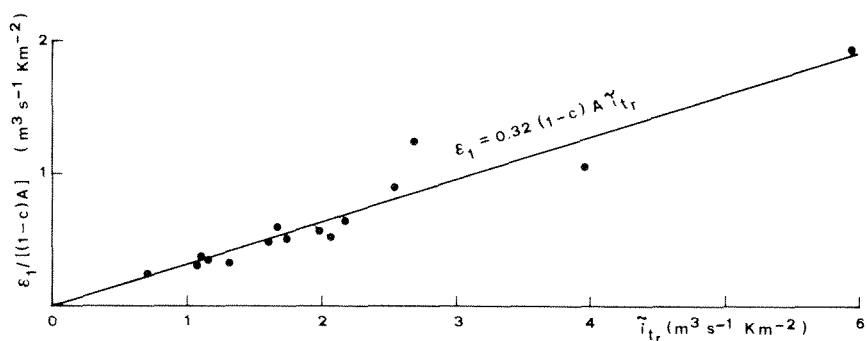


Fig. 8 Regional regression of $\varepsilon_1/[(1 - c)A]$ on \tilde{i}_{t_r} in Campania (Italy).

CONCLUSIONS

Theoretical considerations, supported by statistical analysis of 39 Italian annual flood series (AFSs), suggest that the two-component extreme value (TCEV) distribution is consistent with the presence of flow outliers, i.e. values exceptionally larger than the rest, and it is thus able to give accurate estimates of the T-year flood also for large values of T . The TCEV distribution emerges as the distribution of the larger of two independent random variables, characterizing the annual maximum of distinct components referred to as the basic component (the more frequent and the less intense) and the outlying component (the less frequent and the more intense).

The TCEV distribution has four parameters, two for each component. As the information contained in an AFS about the outlying component is comparatively much less than that about the basic one, the uncertainty in estimating the parameters, especially of the outlying

component, is great when using a single AFS and leads to gross errors in estimating a design flood. For this reason, regionalization techniques are needed not only when dealing with ungauged sites but also for obtaining a reliable estimator of the T-year flood with gauged sites.

To combine data of the various rivers within a region, the annual floods were reduced to dimensionless form no longer dependent on parameters of the basic component of individual AFSs, and were pooled together to give a single regional flood distribution of the TCEV type. It was ascertained that the hypothesis that all reduced annual floods come from a single distribution applying to the whole region considered cannot be rejected.

Within this region, however, it is possible to identify and single out smaller areas (sub-regions) such that the characteristic parameter K'_1 of the basic component remains constant within a sub-region but with different values from one sub-region to another. For each such sub-region it is also possible to define a single distribution applying to the annual floods, scaled by the basic component parameter (the index flood) ε_1 .

To determine the index flood of a gauged site, the single-station data provided reliable information. For ungauged sites an estimate for ε_1 may be obtained from physiographic and meteorological basin characteristics.

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Received 10 November 1983; accepted 23 July 1984.