# Application of the index-flood method to the regionalization of flood peak discharges on the Portugal mainland

M. M. Portela[1] & A. T. Dias[2]
[1]*Department of Civil Engineering and Architecture, Environment and Water Resources Division, IST, Technical University of Lisbon, Portugal*
[2]*HIDROPROJECTO Engenharia e Gestão, Lisbon, Portugal*

## Abstract

The regional analysis of flood peak discharges is an important tool that enables more reliable estimates of flood quantiles at watersheds without or with insufficient flood data.

Usually, the flood regional analysis combines two main issues concerning, first, the identification of homogenous regions in terms of flood peak discharges and, second, the establishment of, for each region previously recognized as homogenous, a flood frequency distribution model.

One of the most widespread procedures for flood regionalization is the index-flood method. As the main assumption, the method considers that the statistical distribution of the floods within a homogenous region is similar except for a scale parameter or index that reflects the specific local features.

The index-flood method was applied to the Portugal mainland, based on the records of annual maximum instantaneous discharges at 120 Portuguese stream gauging stations. As result, six homogenous regions were identified and the models applicable to each region to estimate flood quantiles established. The adopted index-flood was the mean annual flood, that is, the flood having a peak discharge with a return period of 2.33 years.

In this paper the general description of the method as well as some of the results achieved for the Portugal mainland are briefly presented.
*Keywords: flood regionalization, annual maximum instantaneous discharges, index-flood, homogeneity test, local and regional frequency distribution curves.*

## 1 General concepts

The insufficient number of years with measurements of annual maximum instantaneous discharges at Portuguese stream gauging stations often compromises the accuracy of the flood discharge estimates, especially when design floods with high return periods are envisaged. Also, many of the water resource projects requiring estimates of flood quantiles involve ungauged river sections.

One of the possible procedures to evaluate flood peak discharges under unavailability or shortage of flow data utilizes the regionalization of the information established for others watersheds.

The flood regional analysis is often accomplished in two steps. The first one relates the identification of homogenous regions, in what concerns flood peak discharges, and the establishment of a regional frequency distribution curve for each homogenous region. A region is considered to be homogenous when the watersheds belonging to it exhibit a similar behavior in terms of exceptional discharges, that is to say, when the non-dimensional local frequency distribution curves have similar shapes, obviously, within a sampling error. The second step of the regional analysis involves the development of procedures that based on the results from the previous step enables to evaluate peak discharges at rive sections without the required flow data.

Among the different approaches to identify homogenous regions the work presented herein utilized the index-flood method (Dalrymple [1], WMO [6]). According to this method, the stream gauging stations are grouped into potential homogenous regions and the local frequency distribution curve at each station is obtained and expressed in non-dimensional form (by means of an index-flood). The homogeneity of each region in then analyzed based on a homogeneity test that verifies if the dispersion exhibit by the non-dimensional local frequency curves at the stream gauging stations belonging to each potential homogenous regions is due to fortuitous causes. If so, the region is considered to be homogenous. Otherwise, the stream gauging stations are re-grouped until the "regional pattern" thus achieved proves to be homogeneous. The index-flood can be the average or other statistical location parameter of the frequency distribution curve of the annual maximum instantaneous discharges.

The method as originally conceived (Dalrymple [1]) does not required an explicit association with a given frequency distribution curve or with a specific parameter estimation method, though, in fact, it implicitly considers that the maximum instantaneous discharges approximately follow the Gumbel law.

## 2 Steps of the index-flood method

The application of the index-flood to Portugal mainland was accomplished according to the following steps (Dias [2], Dias and Portela [3]):

1) Collection of the annual maximum instantaneous discharges measured at as many stream gauging stations as possible and identification of a common recording period, that is to say, of the largest period having records

(continuous or with some faults) at the highest number as possible of stations. Only stream gauging stations under pristine conditions were selected. Based on the analysis of the available records, the common recording period of 20 years, from 1970/71 to 1989/90 (hydrologic years) was adopted. Only those stations having at least 6 years of records along the previous recording period were adopted in the analysis. It should be pointed out that this minimum number of records, though very small, exceeds the one proposed by Dalrymple [1] (5 years). The quality of the records (in terms of temporal independence and of homogeneity) was analyzed based on several statistical tests (adopted confidence level of 95%) and the missing records in the common period were fulfilled by means of regression analysis.

From an initial universe of 227 pre-selected stream gauging stations only 120 were utilized in the flood regional analysis as they: i) represented pristine conditions; ii) had records with quality; iii) had complete series during the common recording period or iv) had at least six records during that period the missing values having been estimated by means of correlation analysis.

2) For each stream gauging station establishment of the corresponding local frequency distribution curve. The local frequency distribution curve at each stream gauging station was obtained by plotting the annual maximum instantaneous discharges, $Q_T$ (yy rectangular axis), as a function of the return periods, T (xx transformed axis), and by adjusting a curve to the points (T; $Q_{2.33}$) thus achieved. The equation for the time graduation (xx axis) was (Powel [4]):

$$y = -ln\left[-ln\left(1-1/T\right)\right] \tag{1}$$

where y is the linear distance. The previous equation assumes that the distribution can be fairly described by the Gumbel law.

The return period of each observed annual maximum instantaneous discharge ("empirical" return period) was evaluated according to the Weibul formula (Rao and Hamed [5]), also adopted by Dalrymple [1].

3) Based on the contiguity between successive watersheds and on the similarity of the flow regimes, preliminary outlining of a pattern of homogenous regions by grouping stream gauging stations with contiguous watersheds.

4) Verification of the homogeneity of each region by means of a homogeneity test. The test was based on the 10-year flood as this is the longest return period for which many records will give dependable estimates (Dalrymple [1]). The value of y that corresponds to the 10-year return period is of about 2.25 – eqn (1). Taking into account that the standard deviation, σ, of the reduced variable, y, of the Gumbel distribution is given by:

$$\sigma = \frac{e^y}{\sqrt{n}}\sqrt{\frac{1}{T-1}} \tag{2}$$

where T is the return period and n, the number of years with records, and considering as amplitude of the "acceptance area" of the homogeneity hypothesis two standard deviations (in order to ensure that 95% of the estimates will lie within 2 σ of the most probable value of T), the following result is achieved, based on the 10-year return period:

$$2\,\sigma = \frac{2\,e^{2.55}}{\sqrt{n}}\sqrt{\frac{1}{10-1}} \approx \frac{6.33}{\sqrt{n}}\;\; 2\,\sigma \approx \frac{6.33}{\sqrt{n}} \tag{3}$$

The table included in Figure 1 provides the values of y in correspondence with those of T. In that table and also in the chart included in the same figure, TL and TU are the lower and upper boundaries of the “acceptance area” of the homogeneity hypothesis and were computed by solving eqn (1) in order to T, for the values of y of (y-2 σ) and (y+2 σ), respectively. The adjusted length of the recording period is the number of years of actual records plus one-half of the number of years the records were extended (missing records in the common recording period) (Dalrymple [1]).

| n (year) | y | $2\sigma \approx \frac{6.33}{\sqrt{n}}$ | Lower limit | | Upper limit | |
|---|---|---|---|---|---|---|
| | | | y - 2 σ | TL | y + 2 σ | TU |
| 5 | 2.2504 | 2.8297 | -0.5794 | 1.20 | 5.0801 | 161.29 |
| 10 | 2.2504 | 2.0009 | 0.2494 | 1.85 | 4.2513 | 70.70 |
| 20 | 2.2504 | 1.4149 | 0.8355 | 2.84 | 3.6652 | 39.57 |
| 50 | 2.2504 | 0.8948 | 1.3555 | 4.40 | 3.1452 | 23.73 |
| 100 | 2.2504 | 0.6327 | 1.6176 | 5.56 | 2.8831 | 18.37 |

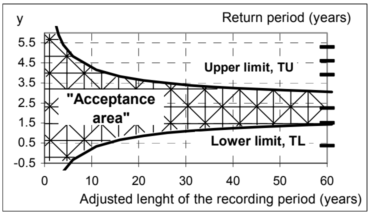


Figure 1: Homogeneity test.

5) For each region previously recognized as homogenous, establishment of the corresponding regional frequency curve based on the local frequency curves at the stream gauging stations belonging to the region. For that purpose several sets of values of discharge versus return period – (T; $Q_T$) – were obtained from each local frequency distribution curve. The previous discharges were next expressed in a non-dimensional form, by division by the 2.33-year flood, $Q_{2.33}$, at the stream gauging station, $Q_{2.33}$ being the index-flood. For each return period, the values of the non-dimensional discharges $Q_T/Q_{2.33}$ thus achieved for the set of stream gauging stations belonging to the region were next characterized in terms of their median.

   The regional frequency curve at a given homogenous regions was obtained by plotting the medians of the non-dimensional discharges (yy rectangular axis) as a function of the return periods (xx transformed axis according to eqn (1)) and by adjusting a curve to the points thus achieved. It should be stressed that the regional frequency curve is more and more worth meaning as higher is the number of local frequency distribution curves considered in its establishment.
6) Based on the stream gauging stations belonging to a same homogenous region, establishment of a relationship between the $Q_{2.33}$ indexes and one or more features (as physical or climatic features) of the station watersheds. In the analysis carried out the following relationship was adopted:

$$Q_{2.33} = \alpha\, A^{\beta} \tag{4}$$

where $Q_{2.33}$ is the index-flood and A is the watershed area. The parameters α and β were estimated based on linear regression analysis applied to the logarithmic transformed of $Q_{2.33}$ and of A. To verify if the correlation coefficients of the regression analysis were statistically significant the test presented by Yevjevich [7] based on the Fisher transformation was applied.

The first four steps resulted in the identification of the homogenous regions in terms of flood peak discharges and the two last steps in the establishment, for each homogenous region, of the models applicable to flood quantile evaluation at river sections without flow records or with insufficient flow records.

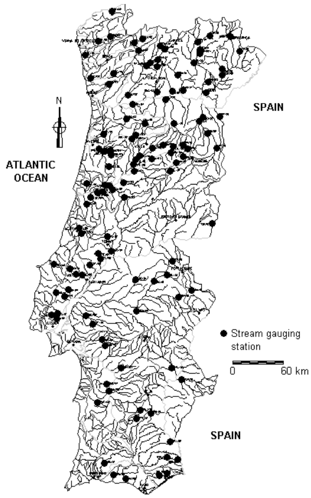


Figure 2: Schematic location of the 120 stream gauging stations utilized in the flood regional analysis.

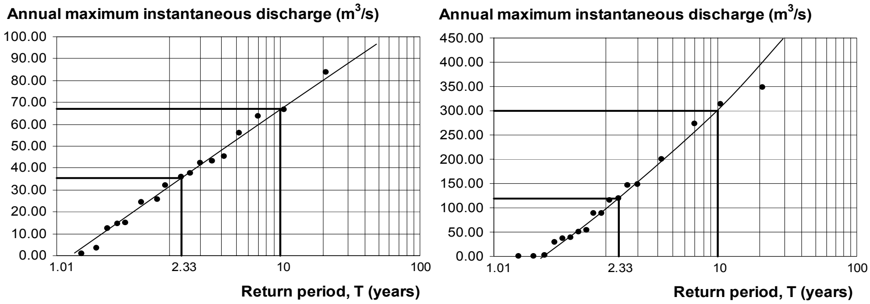


Figure 3: Local frequency distribution curves at Pai Diz (left) and Monforte (right) stream gauging stations.

# 3 Results

## 3.1 Delimitation of homogeneous regions

As mentioned, the regionalization analysis was based on the records of instantaneous maximum discharges at 120 stream gauging stations (Figure 2) distributed over Portugal though with a higher concentration in the North of the country where water is far beyond more abundant and, consequently, where the main water resources systems, such as hydropower plants, are located. Figure 3 exemplifies two of the 120 local frequency distribution curves thus established.

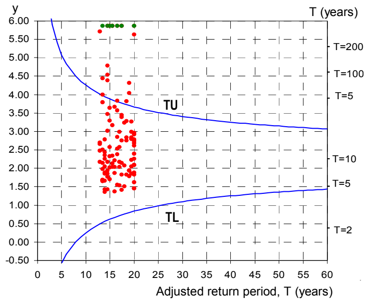


Figure 4: Homogeneity test considering Portugal as only one homogenous region.

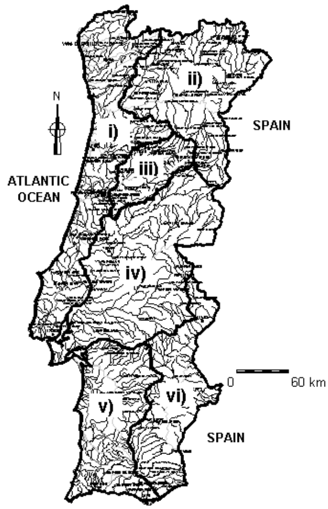


Figure 5: Portugal mainland. Proposal of homogenous regions in what concerns flood peak discharges: i) Northern coastal region; ii) Douro River watershed; iii) Mondego River watershed; iv) Tejo River watershed; v) Southern coastal region; and vi) Southern inland region.

Based on the local frequency distribution curves different patterns of homogeneous regions were built up and subjected to the homogeneity test. Figure 4 exemplifies the results of that test considering the whole country as a homogenous region. In that figure the curves TU and TL represent the upper and the lower boundaries that, simultaneously with the primary yy axis, set the limit of the area where the points representing watersheds consentaneous with the homogeneity hypothesis should lay. The secondary vertical allows establishing the correspondence between the y variable (primary vertical axis) and the return period. The set of points with the highest value of y represents those watersheds that are quite outside from the limits of the homogeneity “acceptance area” of the chart. Figures 4 denotes that Portugal as a whole cannot be considered a homogenous region in what concerns flood peak discharges.

After several trails of different homogeneous patterns the following six homogenous regions were achieved (between brackets: number of stream gauging stations, from the total of 120, located in each region): i) Northern coastal region (38); ii) Douro River watershed (30); iii) Mondego River watershed (17); iv) Tejo River watershed (15); v) Southern coastal region (9); and vi) Southern inland region (11) – Figure 5. The results of the homogeneity test that supported the previous homogenous pattern are presented in Figure 6.

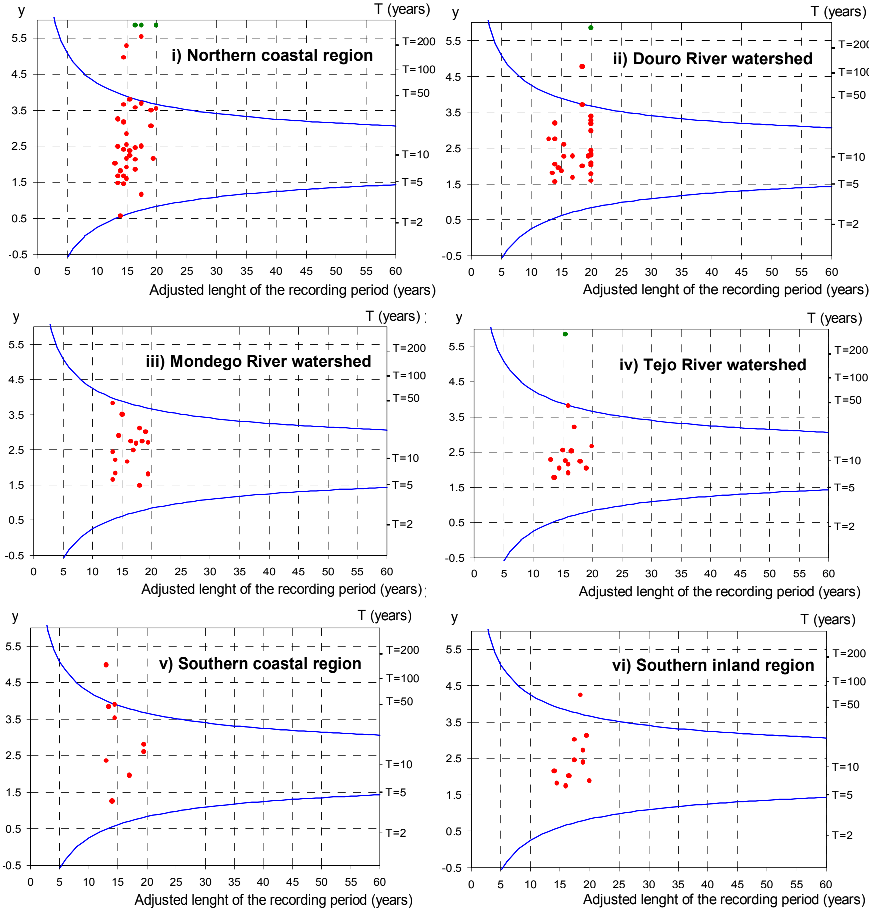


Figure 6: Regions of Figure 5. Homogeneity test.

Figure 6 shows that 11 stream gauging stations, from the 120 utilized in the analysis, are not consentaneous with the regional pattern of Figure 5 (points of the charts outside the boundaries of the "acceptance areas"). Taking into account: i) the small number of stations under those conditions; ii) that the watersheds of those stations are geographically disperse and could not be re-arranged in a new homogenous region; and iii) specially, that, from the huge number of scenarios of homogenous regions analyzed in the study, the one of Figure 5 led to the smallest number of stations "adverse" to the homogeneity hypothesis, it was decided to pursuit the studies with the regional pattern of Figure 5. The corresponding regional frequency curves are presented in Figure 7.

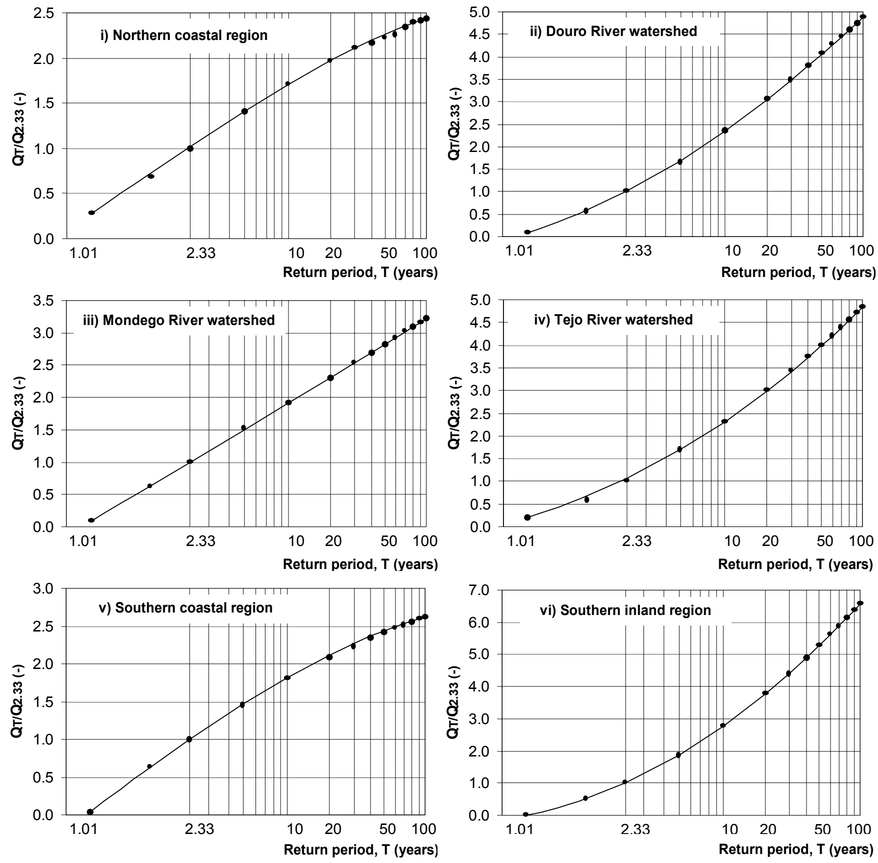


Figure 7: Regions of Figure 5. Regional frequency distribution curves.

## 3.2 Relations between the index Q2.33 and the watersheds area

The regional frequency distribution curves of Figure 7 provide flood quantiles once the indexes $Q_{2.33}$ are known. To allow estimates of the index-flood at ungauged watersheds a relationship between that index and the watershed area, A, was established for each homogenous region based on eqn (4).

The equations thus achieved for the six homogeneous regions of Figure 6 as well as the pair of values ($Q_{2.33}$; A) utilized in their establishment are displayed in Figure 8. In those equations $Q_{2.33}$ is expressed in $m^3/s$ and A in $km^2$, and r is the correlation coefficient of the linear regression analysis between logarithms of the index-flood and of the watershed area.

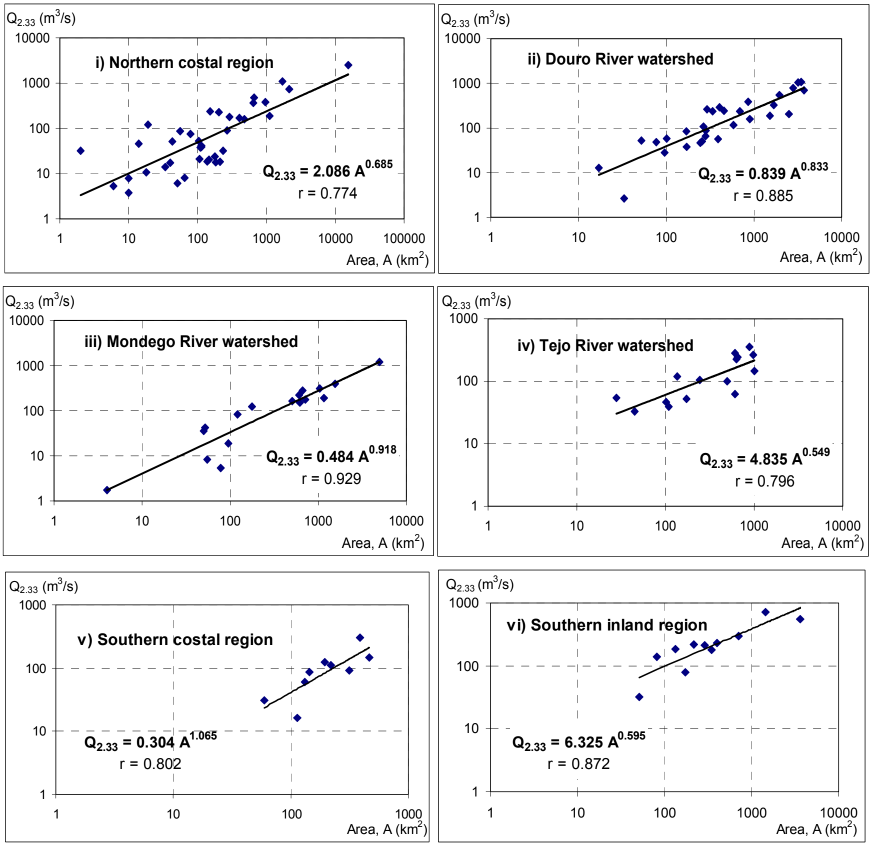


Figure 8: Relationships between the index-flood, Q2.33, and the watershed area, A.

## 4 Summary and conclusions

As result of the index-flood method six homogenous regions, in terms of peak flood discharges, were delimited for Portugal mainland. For each homogenous region two fundamental models were established: one allowing estimates of flood quantiles based on the index-flood $Q_{2.33}$ – regional frequency distribution curves, Figure 7 – and the other allowing evaluating this index as a function of the watershed area – Figure 8.

Based on the models of Figures 7 and 8, the steps that enables to estimate the peak flood discharge with the return period of T years at an ungauged watershed are the following ones, as schematically represented in Figure 9: i) measurement of the watershed area; ii) identification of the homogenous region to which the watershed belongs; iii) as a function of T, evaluation of the value of the ratio $Q_T/Q_{2.33}$ by utilizing the corresponding regional frequency curve; iv) based on the watershed area, evaluation of the index-food, $Q_{2.33}$; v) and taking into account the previous values of $Q_T/Q_{2.33}$ and of $Q_{2.33}$ evaluation of $Q_T$.

To ensure the reliability of the estimates of flood peak discharges continuous updating of the models, especially those of Figures 7 and 8, should be carried out as more records of annual maximum instantaneous discharges become available. Also the validation of those models in watersheds that, though having records, were not utilized in the regional analysis (as they did not fulfilled the requirements mentioned in section 2) should be accomplished.

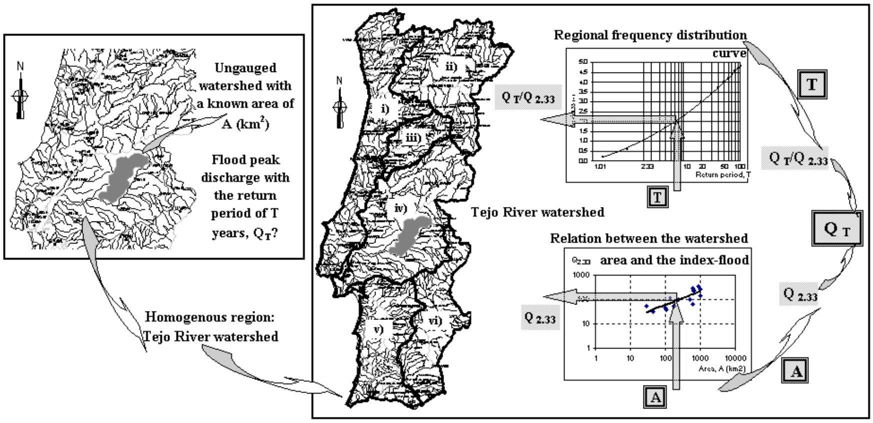


Figure 9: Index-flood method. Evaluation of flood quantiles based on the values of the watershed area and the return period. Schematic steps.

## References

[1] Dalrymple, T., *Flood Frequency Analysis*. U.S. Geological Survey Water Supply Paper 1543-A., Reston, Va, 1960.

[2] Dias, A. T., Caudais instantâneos máximos anuais em Portugal Continental. Proposta de regionalização. Master Thesis, IST, Lisbon, 2003.

[3] Dias, A. T. & Portela, M. M., "Caudais instantâneos máximos anuais em Portugal Continental. Proposta de regionalização", *6º Simpósio de Hidráulica e Recursos Hídricos dos Países de Língua Oficial Portuguesa (6º SILUSBA)*, Vol. 2, pp. 327-344, Cabo Verde, 2003.

[4] Powel, R. W., A *Simple Method of Estimating Flood Frequencies*. Civil Eng., 13 (2), pp. 105-106, 1943.

[5] Rao, A. R. & Hamed, K. H., *Flood Frequency Analysis*. CRC Press LLC, N.W. Corporate Blvd., Boca Raton, Florida, U.S.A, 2000.

[6] WMO, World Meteorological Organization, *Guide to hydrological practices. Data acquisition and processing, analysis, forecasting and other applications*, WMO-Nº. 168, 5th Edition, 1994.
[7] Yevjevich, V., Stochastic Processes in Hydrology. Water Resour. Publ., Fort Collins, Co., 1972.