REGIONAL FLOOD FREQUENCY ANALYSIS THROUGH A RAINFALL-RUNOFF MODEL: APPLICATION TO A COASTAL REGION IN NORTHERN ITALY

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Abstract

The paper presents the application of a new methodology for flood risk assessment at the regional level for Liguria, a thin area by the sea, characterized by a complex orography and subject to highly convective storms. The peak discharge for given return periods is derived from a statistical analysis of rainfall and discharge records and through a suitable rainfall-runoff model for the estimation of the index discharge at ungauged sites. From the discharge data analysis the dimensionless growth curve was derived. The rainfall data analysis allowed the regionalization of depth-duration curves from which synthetical precipitation events of given return periods could be derived.

It is shown that the results are consistent with historical records at the gauging stations and reproduce a set of properties of observed peak discharges, such as the area-discharge relationship. Moreover, the modeled derived characteristic response times match well those obtained from literature empirical laws. The methodology seems to represent a reliable tool for flood risk assessment at regional scale.

1 INTRODUCTION

Many methods are used to characterize spatially intense rainfall and peak discharges for given return periods.

Some are based on single site time series and identify cumulate frequency curves that are valid for the site itself. These kind of methods can be applied when the local time series are long enough to give reliable estimates for the design return periods. When the local time series are short a better estimate for high return periods can be obtained from a regional statistical analysis. Such methods identify statistical homogeneity among non-dimensional values derived from statistically independent local series and give a non-dimensional growth curve for each statistically homogeneous area. The parameter that makes data non-dimensional and vice-versa is called index value. A law relates local time series to the index value and gives the dimensional cumulate probability function for each site. The advantage of a regional approach is that being, the data base for the identification of the growth curve longer, the estimates for high return periods are more reliable.

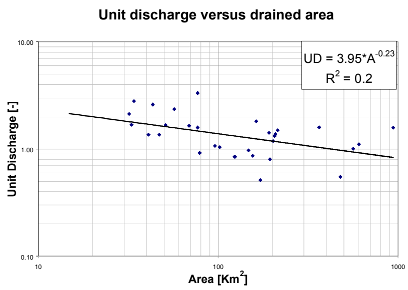

Figure 1.1: unit discharge versus drained area shows, on a log-log plot, a low correlation.

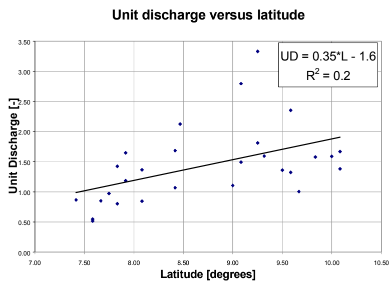

Figure 1.2: unit discharge versus longitude shows a low correlation.

Another great advantage of the regional technique is that if the index value depends only on the geographical position or morphological characteristics of the site, the local frequency curve can be obtain for any site within the region.

The regional analysis for rainfall values of sites within the Liguria Region has been carried out with success as reported by Boni [Boni et al., 1998]. The regional analysis of discharge data presents greater problems related to the difficulty encountered in relating the index discharge with geographical or morphological characteristics of the site. For example figure 1.1 and figure 1.2 show that the discharge for unit area for the gauged sites depends only weakly from drained area and geographical position.

Therefore, an approach to solve the problem of estimating index discharge for ungauged sites based on hydrological modeling has been attempted.

2 THE REGIONAL FREQUENCY ANALYSIS

A regional approach allows to use all data of an homogeneous region in the same statistical analysis. It is better than a single-site analysis because it avoids the problems related to non homogeneous duration of the time series, gives a lower uncertainty on the return period of rare events and allows to have estimates also for ungauged sites. The data used for the analysis are annual peak discharges derived from gauges of the Italian National Hydrographic and Sea-monitoring Service (SIMN). Data has been in part published on report number 17 of 1970 and in part was derived directly from level charts and published level-discharge curves.

The time series cover 42 sites and have length going from 3 to 60 years. For the regional analysis only those series with more than 9 years of data have been selected, for a total of 931 years.

The statistical model used for the analysis is the TCEV (Two Component Extreme Value) proposed by Rossi & Versace (1984). The model hypothesizes that the statistical population is made up of two components, ordinary and extraordinary, explained by two different kind of extreme meteorological conditions [Boni, 1999]. The parameters of the distribution can be derived for each single site or on regional basis.

2.1 The growth curve

The growth curve represents the probability distribution of the non-dimensional random variable. It describes the relationship among discharge values of different frequency. For the discharge data, as for rainfall data, the TCEV distribution was used. The parameters of the distribution have been calculated for the annual maximum discharges made non-dimensional with the average of each local data set. The estimate of the parameters was carried out following the hierarchical procedure proposed by Arnell and Gabriele (1991). The method allowed to find the two parameters Λ_*, θ_* of the first level of regionalization and the parameter Λ_1 of the second level of regionalization that define the cumulate frequency curve of the non-dimensional variable $x' = \frac{x}{\theta_1}$ given in equation 2.1; where the parameter θ_1 is the average of the series. The values of the parameters appear in table 2.1 and table 2.2.

$$F_{(X')}(x') = e^{-\Lambda_1 e^{-x'} - \Lambda_* \Lambda_1^{\left(\frac{1}{\theta_*}\right)} e^{-x'\theta_*}} \qquad (2.1)$$

The goodness of fit of the theoretical curve on the data has been carried out using different methods:

1. a sinthetic confidence interval at 90% quantile was obtained with ten thousand generations from the theoretical distribution; the procedure is necessary since the TCEV can't be inverted analytically;

2. the Pearson test has been performed for both hierarchical levels used to find the parameters.

The result of the first method appears in figure 2.1; it shows that the historical values fall within the confidence interval, i.e. the parameters found give rise to an acceptable theoretical distribution. The second check shows that it is acceptable to hypothesize that the Liguria region is an homogeneous region for the asymmetry and variation coefficients, shown in table 2.1 and table 2.2.

Λ_*	θ_*	Sample CS		Generated CS	
		Mean	Standard Deviation	Mean	Standard deviation
0.2687	3.9788	1.814	1.000	1.716	0.914
Levels of freedom		D	χ^2 90%	χ^2 95%	χ^2 99%
3		2.006	6.2	7.8	11.2

Table 2.1: parameters for the first level of regionalization; statistics of the asymmetry coefficient and results of the Pearson test.

Λ_1	Sample CV		Generated CV	
	Mean	Standard deviation	Mean	Standard deviation
8.2528	0.717	0.257	0.681	0.182
Levels of freedom	D	χ^2 90%	χ^2 95%	χ^2 99%
2	0.626	4.6	6.0	9.2

Table 2.2: parameters of the second level of regionalization, statistics of the variation coefficient and results of the Pearson test.

Therefore the analytic expression of the growth curve is:

$$F_{(x')}(x') = e^{-8.2528e^{-x'} - 1.2216e^{-x' 3.9788}} \quad (2.2)$$

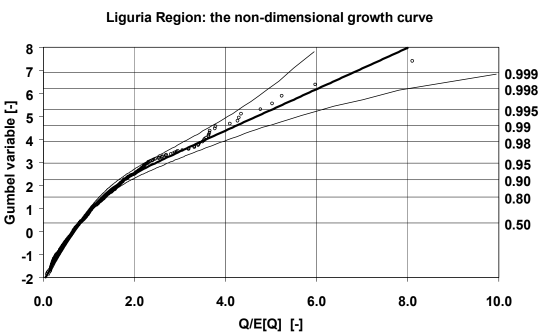

Figure 2.1: the regional growth curve: the non-dimensional data set (empty dots) is compared with the theoretical growth curve (continuos thick line). The 90% confidence interval (continuous thin line) show the good agreement of the model and measured data.

2.2 The index discharge value for gauged sites

The index discharge is the parameter that corresponds to the third level of regionalization (parameter θ_1) and allows to have dimensional cumulate frequency curves. In the present work as index value for the peak annual discharge the average of each local series was used. For example, in figure 2.2 is shown the cumulate frequency curve of annual peak discharges on probabilistic paper for the station of Pogli d'Ortovero on the Arroscia river. The figure shows the comparison of the theoretical growth curve with the local time series. The indicative estimate of the peak discharge uncertainty increases with discharge since stage-discharge curves are calibrated only on low flows. In the case of Pogli all observations fall into the 95% Kolmogorov interval.

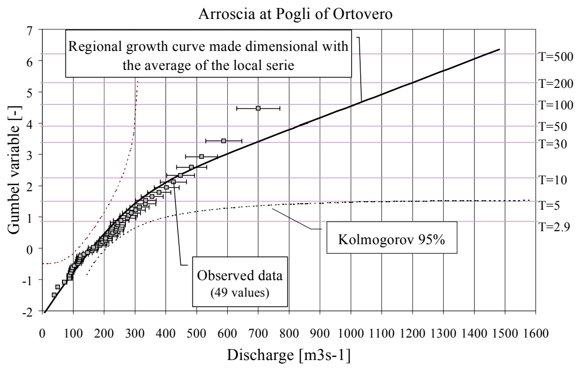

Figure 2.2: the cumulate frequency curve of annual discharge maxima for the gauging station on the Arroscia river at Pogli d'Ortovero.

For each gauged site it is therefore possible to have the cumulate distribution of annual peak discharges. Of the 33 stations used for the analysis all passed the Kolmogorov test at the third level of regionalization. For ungauges sites it is necessary to find a law that relates morphological characteristics to the index value.

2.3 The index discharge value for ungaged sites

The analysis of the unit discharge, rate among discharge and drained area, showed that there is a low correlation among this parameter and the main geo-morphological characteristics of the area: as shown in figure 1.1 and figure 2.1 for drained area and longitude. This is probably due to the non-linear behavior of the discharge generating processes that give rise to the necessity to find a method to keep into account both spatial and temporal variability and the simultaneous effect of different morphological characteristics.

Therefore, a model based approach is thought to be a better way to estimate index discharge. The model used for the prevent work is based on a rainfall runoff model named DRiFt that was developed by Giannoni et al (1998). The rainfall runoff model uses a geomorphologic unit hydrograph approach for flood routing and a SCS CN approach for infiltration.

3 THE HYDROLOGICAL INDEX DISCHARGE

The use of a rainfall runoff modeling approach allows to take into account the spatial variability of soil and morphological characteristics. These and the rainfall dependence on longitude are prone to explain better than simple empirical laws the relationship between index discharge and morphological and geographical characteristics. Therefore, the approach is suitable for the estimation of index discharge of ungaged sites.

The original drainage network data is derived from a DEM at 225 by 225 m. The DRiFt model uses a morphologic filter to distinguish among hill slope and channel and identifies a drainage network that interprets better the hydrological behavior of natural basins. Moreover the model is robust and of simple implementation [Giannoni et al., this volume].

The rainfall runoff model can take into account spatial variability of both rainfall and soil characteristics. The main contributions of a regional scale analysis for the identification of average annual discharge maxima is related to the identification of the CN parameter from land use maps and the construction of a critical rainfall event. The following paragraphs regard this two themes.

3.1 The critical event

The meteorological events that generate high discharges in the Liguria Region have a characteristic duration ranging from 8 to 34 hours as shown by Deidda (1999), with an average of about 12 hours [Boni et al., 1997]. Due to this characteristic of the typical storms over the area, the total duration of critical events was chosen to be 12 hours.

Within the critical meteorological events high intensity spells of shorter duration can give rise to peak discharges for the small basins drained at the measuring sections. Small drained area is typical of the Liguria Region and therefore it is important to identify the critical event duration for each basin. This depends mainly on drained area and basin morphology and can be identified by the rainfall runoff model and a height-duration frequency curve.

From the regionalization of precipitation annual maxima for the duration of 1,3,6,12 and 24 hours carried out by Boni [Boni et al., 1997]it is possible to choose height-duration frequency curves for each longitude within the region.

The spatial distribution of rainfall is less important due to the small areas drained by the typical Liguria basins (from 15 to 600 Km^2) and therefore rainfall intensity was kept constant in space over each basin.

The temporal distribution of rainfall could not be determined a priori from the available information and therefore a synthetic hyetograph was constructed using a simplified Chicago procedure. The hyetograph is, as shown in figure 3.1, made up of two steps with a peak at the end. The peak duration is derived from a search of the maximum response obtained with the rainfall runoff model while moving along the height-duration frequency curve and is called “critical duration”. The height of the peak is the corresponding height on the height-duration frequency curve. The duration and height of the first step are the complements to h_c and Θ_c.

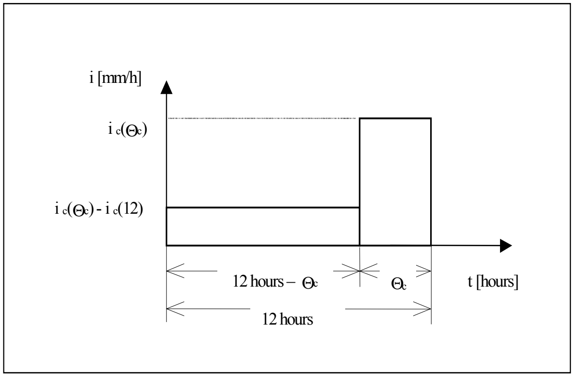

Figure 3.1: shape of the rainfall event: Θ_c is the "critical duration"; $i_c(\Theta_c)$ is the rainfall intensity obtained from h_c.

3.2 The infiltration method

The infiltration is calculated using the SCS CN method [McCuen, 1982]. This method is suitable for distributed conceptual modeling and does not require much information regarding soil and land use. The CN parameter can be identified starting from land use and litology maps available for the region in digital form with a resolution of 100m by 100 m.

During the last 20 years the Liguria Region has been producing digital thematic maps. The most important map on which the CN parameter is based is the Land Use map. There are two land use maps available at present for all the study area. The first, that will be referred as regional map was derived in the seventies from the digitalization of some thematic maps at the 1:15000 scale and air borne photographic images. The second is the land use map produced within the framework of the European project COR.IN.E..

The calibration of the CN parameter is targeted to the evaluation of annual maxima and therefore was calibrated to give a good agreement among measured and modeled index discharge for a set of twenty gauging stations over the entire region.

The calibration procedure is made up of five steps:

1. an a priori criteria to associate CN to land use classes was established on the basis of the SCS indications for a medium permeability soil;
2. for each Litological class a criteria to modify the CN value according to the different land use classes was assumed;
3. change of resolution and coordinate system to make the CN map coherent with the DEM;
4. run the model for a set of gauged sites to find index discharge, and iteration of the procedure acting only on the most frequent land use classes, to get a good agreement among simulated and measured values;
5. verification on the two hundred year return period simulated and statistically derived discharges for gauged sites.

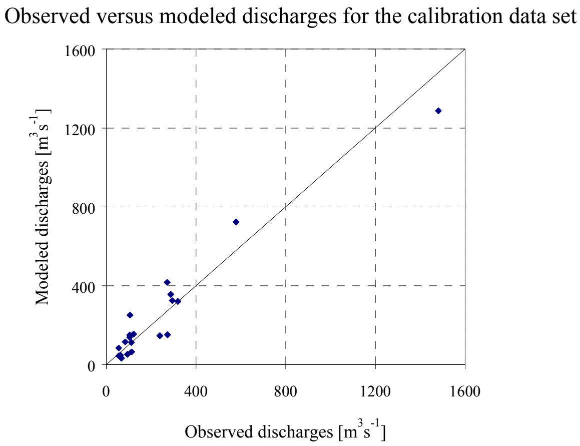

Figure 3.2: observed versus modeled average annual maximum discharges for the calibration set.

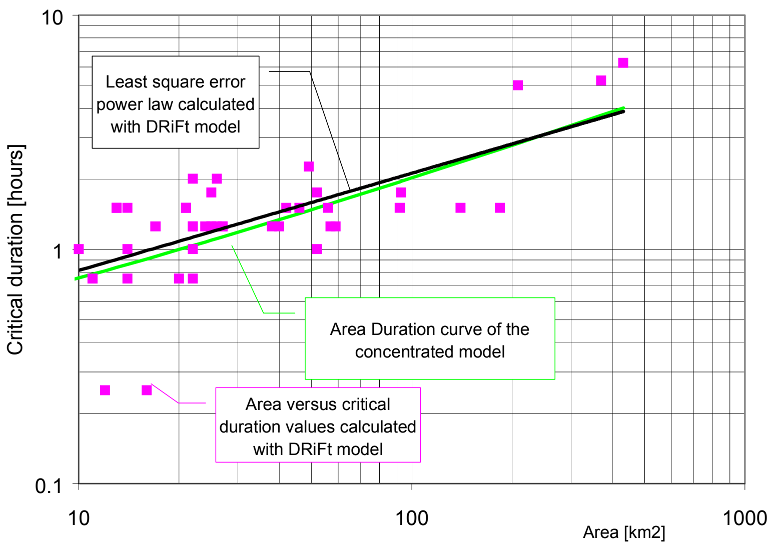

Figure 3.3: the least square power law fit from the Drift modeled data agrees with the empirical law used for the Liguria Region

The procedure was repeated for both available land use maps: the comparison didn't show relevant differences among the results obtained from the two. In figure 3.2 is shown the result of the calibration procedure for the regional map of the CN.

4 RESULTS AND CONCLUSIONS

Several results have been analyzed to see if the regionalization procedure produced gave acceptable results and to pinpoint the strong capacity of the model to picture correctly the physical processes involved in extreme flood generation. The main results are shown in figure 3.3, 4.1 and 4.2.

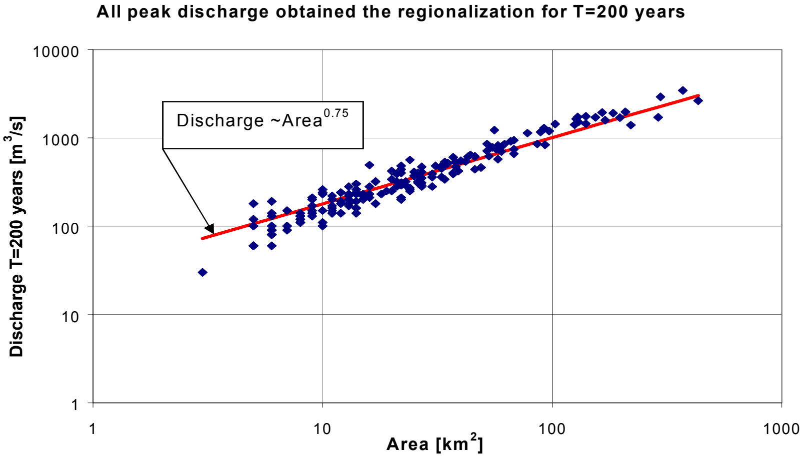

Figure 4.1: the regional peak discharge for a return period of 200 years versus the drained area shows a scaling law similar to the empirical area-discharge relationships.

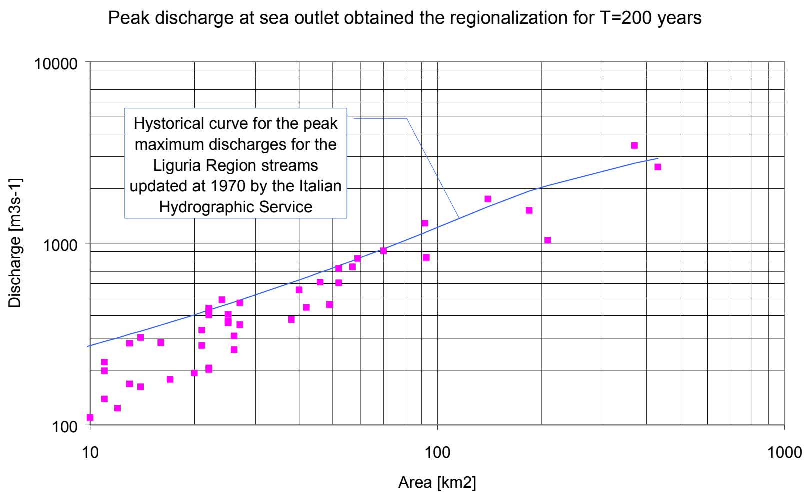

Figure 4.2: the regional method peak discharges for a return period of 200 years compared with the observed peak maximum discharge curve derived during about 100 years.

Figure 4.1 shows that the modeled area discharge relationship follows the empirical scaling law that is reported in literature. Figure 3.3 shows that the method used to derive the critical duration allows for natural dispersion although follows quite closely the commonly used relationships for the small basins of the Liguria region. Moreover as expected the 200 year return period convolution curve fits well the curve of maximum ever registered discharges (figure 4.2).

The verification of the entire procedure; comprehensive of rainfall-runoff model, rainfall synthetic event and calibration of the infiltration parameter CN was tested over the entire range of return periods with reference to a set of 48 river sections. The test is considered to be positive if the values fall within the 95% confidence interval. The test is positive for 13 basins over 48 and therefore it does not confirms that the procedure used is acceptable. Results are shown in Figure 4.3. The reason for such a bad agreement among the modeled data and the theoretical growth curve could be explained by the fact that the time series are so short that it is necessary to take away the exceptional data for the statistical analysis. Future work will investigate the effect of outlayers on the growth curve.

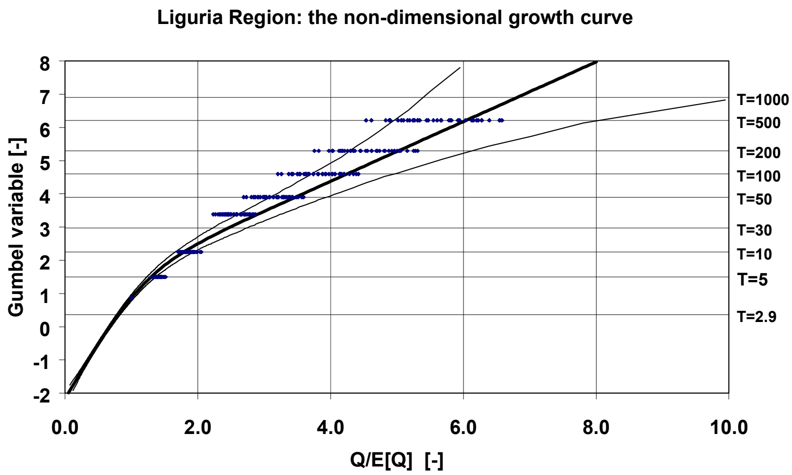

Figure 4.3: The verification of the regionalization procedure at the 48 river section for return periods of 500, 200, 100, 50, 30 10, 5 and 2.9 years.

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