FLOOD VOLUME ESTIMATION AND FLOOD MITIGATION: ADIGE RIVER BASIN

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Abstract: In the present work, we describe an extended flood risk analysis carried out in the Adige River basin in Italy. The methodologies adopted were used in a comparative approach that highlighted the limits and potentiality of some methods with respect to others. Principles presented may be considered of interest for general problems of flood risk management. The work carried out shows interesting results along with a broad number of specificities that may constitute a useful support for those who will apply hydrological analyses on large-size basins. The study basin covers a wide area of about 12,000 km^2. In such a case, a satisfactory analysis becomes complex because of the large number of phenomena involved in flood generation that need to be taken into account.

Keywords: flood risk, water management, flood volume estimation, Adige River

1. INTRODUCTION

Flood risk management is critical for territories that remain vulnerable despite the proliferation of advanced technologies. Population is exposed to higher risks as cities increase their boundaries, neglecting or sometime forgetting about natural river systems. Flood risk management represents a problem that is not easily addressed due to many political, social, and economic factors. In addition, prediction remains difficult because of the numerous mechanisms involved the generation of floods. Moreover, the use of relatively short gauging records, and the uncertainty in the flow rating curves, as well as the errors involved in the measurements of extreme events influence the reliability of flood prediction.

E. Wiegandt (ed.), Mountains: Sources of Water, Sources of Knowledge, 243–264.

Therefore, it is mandatory to base analyses on methodologies able to interpret hydrological dynamics, and that are sufficiently consolidated to be accepted and fully understood by politicians, who bear the response-bility for making decisions of high economic and social impact. Methodologies must be reliable and able to provide the most detailed information as is possible. Hydrological data should not be merely analyzed with statistical tools, but further investigation from annals, journals, and technical reports may provide a more comprehensive framework for hydrological studies.

The objective of the present work is to reduce the high level of uncertainty about the prediction of hydrological extremes by using multiple approaches to achieve a more reliable estimation of flood peaks and their corresponding flood volumes. The methodology uses both statistical models and rainfall-runoff simulations in order to quantify hydrological response. Elaborations based on systematic data are enriched by the use of historical research on the documented events.

Annual maxima series of rainfall and floods represent the most common database, containing information about the event time, which is useful to detect seasonal frequency of the events (see part 3). In some cases, local measurements are not sufficient to provide consistent frequency estimates. Regional models, based on the concept of spatial homogeneity of the populations of annual maxima, may improve statistical models' performance removing limitations due to short series, error in the measurements, etc. (see part 4).

Flood volume estimation is central to a quantitative study. In fact, this is the most important variable for the design of water works for flood mitigation. In the case of the Adige River, it was particularly complex to estimate because of the nonunique behavior of the basin. In this study we compared three different methodologies including a rainfall-runoff model with the specific task of estimating the flood volume (parts 5, 6, and 7). In the rainfall-runoff model, the hydrological processes are interpreted by using a conceptual model, which calculates the runoff and the subsurface runoff that contributes to the stream flow. The model, in combination with other methodologies, is applied to investigate the variation of the hydrograph at different return periods. The analyses allow a reliable prediction of flood risk in terms of flood peak and flood volume.

The comparison of different sub-catchments highlights substantial dissimilarity in their hydrological behavior. Such a condition becomes critical in the phase of defining possible solutions for flood mitigation. In this context, it is important to note that the main purpose of this research was to find ways to safeguard the city of Trento on the Adige River.

2. THE ADIGE BASIN AND THE VULNERABILITY OF THE CITY OF TRENTO

The Adige is one of the most important Italian rivers. Its basin has an area of 11,954 km^2 and the main river course is 409 km long. The river originates in the Province of Bolzano, crosses the Trentino Region, the city of Verona, and finally empties into the Adriatic Sea. The main tributaries stem from Alpine saddles and rims and are characterized by slight gradients. Secondary streams begin at higher altitudes and flow down into the recipient branches after a short stretch.

Because the focus of this chapter is to find ways to safeguard the city of Trento, characteristics of the whole river basin are relevant. At the station of Trento (in S. Lorenzo) the basin has an area of about 10,000 km^2 and, for the purpose of this study (see Figure 1), can be divided in 3 sub-catchments: Adige at "Bronzolo" (6,926 km^2), Noce (1,372 km^2) and Avisio at Lavis (934 km^2). The city of Trento is located, as shown in Figure 1, on the border of the main River and is close to the Avisio and Noce outlets. The city of Trento is thus in a highly vulnerable location given its downstream position along the main river.

Figure 1: Description of the Adige River Basin up to Trento and its Major Tributaries: Avisio, Noce, and Bronzolo's Watersheds. (Map Obtained Using a Digital Elevation Model of 240-M Resolution.)

2.1. A Brief Review of Past Extreme Events

Among the floods that occurred in the recent past, one major event (November 1966) deserves special attention as it affected vast areas and caused serious damage to the Provinces of Trento and Bolzano. The flood event of November 1966 was characterized by two antecedent phenomena: (1) the increase of temperature that caused snow melt above 2,500 m with the consequent increase of torrent level; (2) the contrast between two airflows, one warm coming from the south and one cold coming from the north, which joined to form a persistent cyclone zone in the north of the Alps, thereby provoking a severe storm over entire Northern Italy. Extreme floods were also recorded in the Arno River and the Brenta River, with the tide reaching its maximum levels in the lagoon of Venice.

Even if this event were considered the most intense flood event of the last two centuries for the Adige, its severity at Trento was moderated by two factors (see Table 1). The flood peak was reduced by the river bank breaches upstream from the city (according to Dorigo, 1967, breaches caused a reduction of the peak of about 144 m^3/s) and by the flood storage operated by the "S. Giustina" dam, which accumulated 12 mm^3 of water (Menna, in 1998, estimated that the reduction of the peak flow was of about 300 m^3/s).

Table 1: Hydrological Data Describing the Flood Event of November 1966.

November 1966	Basin area (km^2)	Peak discharge (m^3/s)	Virtual discharge considering river banks break and S. Giustina storage (m^3/s)	Antecedent rainfall during the previous 32 days (mm)	Total rainfall (mm)
Noce Rupe	1,372	575		146.3	168.8
Avisio at Lavis	934	1,048		166.0	184.4
Adige at Bronzolo	6,926	1,380			
Adige at Trento	9,763	2,321	2,321+ 444 ≅ 2,765		

The stream flow hydrograph may better describe the dynamic of the flood event from a hydrological perspective (see Figure 2). It is observed that the stream flow of the Noce at S. Giustina is the outflow of a dam, thereby minimizing the flood peak discharge. In fact, it increases slowly compared to other hydrographs and does not have the typical recession curve of natural systems. On the other hand, the hydrograph of the Avisio River highlights a short lag time and high peak flow. This condition is directly reflected by the hydrograph recorded at Trento. It may be considered the main factor responsible for the fast increase of the recorded flow at Trento. Comparing the peak discharges of each subbasin with their relative size, one may observe that the peak discharge of the Avisio was almost 50 percent of the peak recorded at Trento. This amount is surprisingly high if compared with the relative surface of the subbasin that is only 10 percent of the total basin (see Table 1).

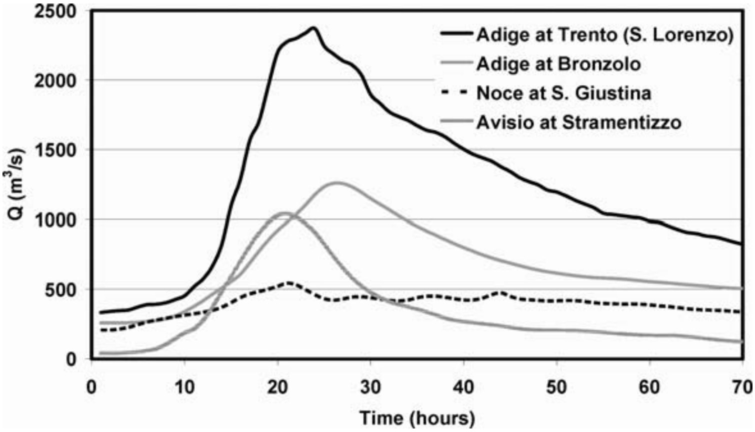

Figure 2: Historical Hydrograph Recorded, during the Flood Event of November 1966, at the Water Level Gauges of Trento, Bronzolo, S. Giustina, and Stramentizzo.

More recently, minor flood events occurred in the Adige River basin. These did not affect the city of Trento, but the risk was significantly high. At these occasions, large areas situated immediately upstream to Trento, were surrounded by water, producing an involuntary flood mitigation with respect to the major city. This behavior is recurrent and somehow affects the shape of the Cumulated Distribution Function (CDF) of floods in some stations of the Adige River upstream to Trento (see part 5).

3. RAINFALL DYNAMICS AND SEASONALITY EFFECTS

Rainfall is a fundamental starting point for flood studies. It has been analyzed in two ways: in terms of its frequency of extremes and in terms seasonality effects on precipitation. In particular, the spatial distribution was investigated with the aim of verifying if it displays any anomaly that may justify the high values of stream flow recorded on the Avisio sub-basin.

Rainfall spatial distributions may be extremely heterogeneous, constituting a critical point in the flood risk assessment. In this particular case, the mean rainfall maxima have been analyzed across the basin at durations of one, two, and three days (see Figure 3). The spatial distribution appears fairly homogeneous around values 40–80 mm for durations of one day. With increases in duration, differences becomes higher, showing that higher depth occur in the central part of the basin. Moreover, the Avisio subbasin (outlined) does not differ significantly from the remaining part of the basin, implying that the rainfall distribution is not responsible for the peculiar flood response of the subbasin. Analogous analyses were carried out on the shape parameters of the rainfall maxima distribution obtaining similar results, not reported here for reasons of space.

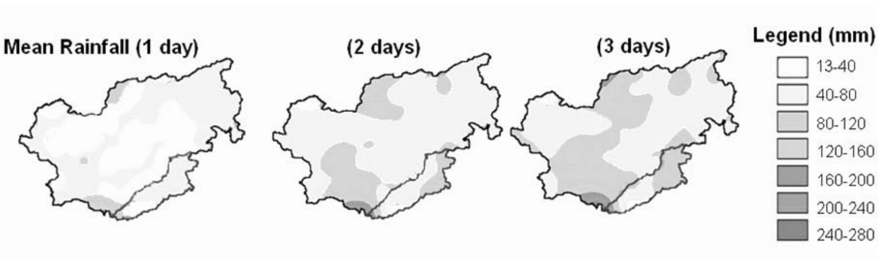

Figure 3: Maps of the Mean Values of the Rainfall Maxima Over Durations of 1, 2, and 3 Days. (Maps Obtained Using the Technique of Kriging with Exponential Semivariogram Based on Rain Gauges Data.)

Furthermore, we analyzed two different samples of rainfall: the first with ordinary and the second with extraordinary data. In Figure 4a and Figure 4b, we describe the frequencies of rainfall maxima at different durations ranked by season: autumn, winter, spring, and summer. The first graph considers a dataset with all the rainfall annual maxima, while the second contains only the annual maxima over a threshold equal to 1.5 times the mean of the ordinary component.

The analyses produced interesting results: (1) the annual maxima of short duration (1–3 h) occur essentially during summer periods (50–70 percent of the events), with both the complete record and the extraordinary maxima having the same behavior; (2) The annual maxima for greater duration (12–24 h) occur in 50 percent of the cases in the autumn, with peaks of 65 percent for the extraordinary component; (3) the duration of 6 h represents an intermediate duration between the two regimes. In general, it was found that short duration rainfall is more relevant during summer, while the longer durations are more relevant in the autumn. The rainfall annual maxima have a strong seasonal influence that becomes more and more significant with the increase of the event severity (threshold).

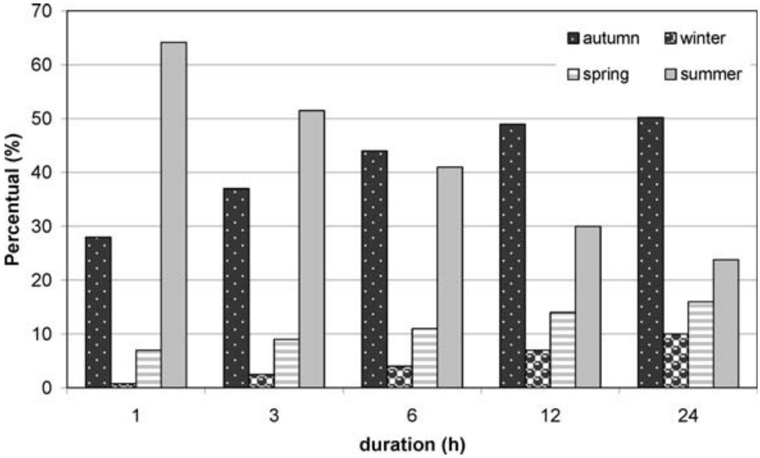

Figure 4a: Distribution of the Annual Maxima of Rainfall for the Duration from 1 to 24 H—Ordinary.

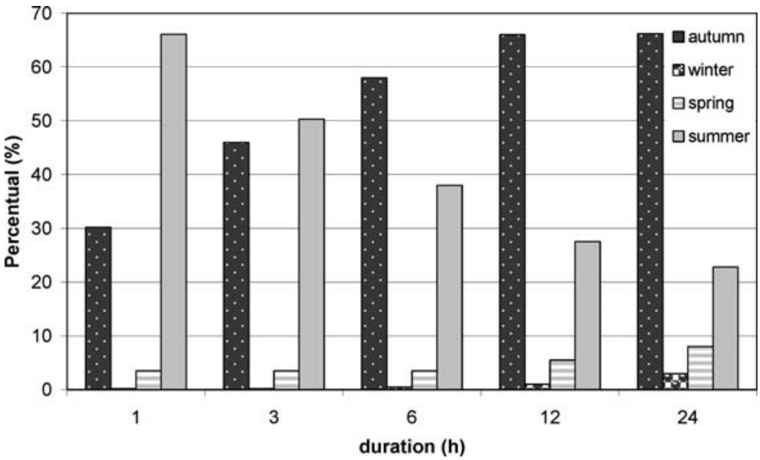

Figure 4b: Distribution of the Annual Maxima of Rainfall for the Duration from 1 to 24 h—Extraordinary Precipitation. (Obtained Introducing a Threshold on the Rainfall Data Equal to 1.5 Times the Mean Value of Rainfall Depth of the Ordinary Component.) Each Symbol Distinguishes the Percentage of Events Occurred in the Different Season for a Given Duration.

In principle, the catchments produce the maximum peak discharge under a constant rainfall intensity of durations equal or greater than the catchment lag time (τ). The parameter τ depends on many factors including the basin area. In the specific case of the Adige at Trento, τ assumes a value of about 20 h. In light of the basin characteristics and of the above results, one may observe that the most dangerous period is autumn, which is when there are higher probabilities for extreme rainfall events of duration comparable with the lag-time of the basin in this period.

During the autumn, two simultaneous movements produce precipitating cells: (1) the flux from the South interacting with the terrain relief and producing typically orographic precipitation; (2) the movement of the weather system to the East and deviating the direction to Northeast. This last condition is more critical for the eastern side of the Adige. In Figure 5, the dominant direction of the Mediterranean storms during autumn is oriented from the South to the Northeast, while the atmospheric movement is directed from West to East. This analysis may provide significant information in the phase of planning a flood forecast system.

Figure 5: The Dominant Direction of the Mediterranean Storms during Autumn (in Transparent the Atmospheric Flux and in Black the Movement Direction).

4. FLOOD FREQUENCY ANALYSIS

The primary objective of frequency analysis is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions (Chow et al. 1988). Data observed over an extended period of time in a river system is analyzed assuming that the flood peaks are independent and identically distributed. Furthermore, it is assumed that the floods have not been affected by natural or man-made changes in the hydrological regime in the system. This last assumption is not always realistic, especially for the most severe events that may produce flooding and that also reduce the peak flow downstream to the flooded area. For this reason we recommend a careful review of historical information regarding the recorded floods using contemporary scientific, academic, and engineering publications along with technical reports and any other available sources.

An efficient approach for the estimation of the flood peak and/or of the peak volumes associated with different probability levels or return periods derives from regional analysis. This approach reduces estimate uncertainties and overcomes the lack of hydrological data (Cunnane 1989). In Italy, such an approach is adopted by the VAPI procedure (Evaluation of Floods in Italy), which refers to a probabilistic model, known as two component extreme values or TCEV (Rossi et al. 1984). The expression of the probability distribution is the following:

$$F_X(x) = P[X \le x] = exp(-\Lambda_1\, exp(-x/\theta_1) - \Lambda_2\, exp(-x/\theta_2)) \qquad (1)$$

where Λ_1, Λ_2, θ_1, and θ_2 are parameters with the same meaning of the Gumbel distribution parameters. The TCEV introduces the distinction between an ordinary component (1) and an extraordinary component (2).

Using the VAPI procedure, it was possible to characterize the flood probability distribution at each sub-catchment of the study area. For this, we used the records of about 13 stream gauges, thus obtaining probability distributions that fit the distribution of the recorded extreme floods well, especially in the case of small and midsized subbasins (two examples are given below). The entire basin area was considered homogeneous. The regionalization model was useful to predict the basin response at the higher return period and to interpret some incoherent aspects of the recorded data. In particular, the probability distributions obtained with the regionalization approach are able to interpret nonlinearities in flood peak distributions, including for cases where the data do not reveal such non linearities.

The case of the Avisio at Lavis is remarkable as it demonstrates the reliability of the regionalization model in hydrological analyses of extremes (Figure 6). In this case, the probability distribution of the recent records are less skewed with respect to the predicted CDF (continuous line) but, considering the recent data along with the historical data of the last two centuries, it is clear that the TCEV interprets the real basin behavior, even at the higher return period. This is even more remarkable if one realizes that the historical data were not used for the calibration of the model parameters. The analysis of flood distribution was based on systematic records obtained from the hydrological annals. Some additional information collected from old journals and other documents was also available about the most severe events that occurred in the last two centuries, between the years 1868–2000 (see triangle in Figure 6). Those are reported in the graph using the plotting position of Hazen (n−0.5)/N, where n is calculated considering these 5 events as the highest (with rank position ranging from 128 to 132) during the time period from 1868 to 2000 and N is the total number of events that is equal to the number of years (N=132).

On the other hand, the flood CDF refers to the stations upstream to Trento. Specifically Bronzolo and "Adige at Ponte Adige" show different behavior at the higher return periods. In those cases, the problem is not the limited extent of the records, but something else, as one can clearly see Figure 7. The probability distribution overestimates the peak flows for the higher return periods with respect to the plotting position of the recorded data. This discrepancy could be explained by looking at documentation on recorded flood events (see, e.g., Reichenbach et al. 1998; AVI project). In fact, as we expected, the marked peaks were associated with overspill and flooded area upstream to the stations due to the limited hydraulic capacity of the river cross section.

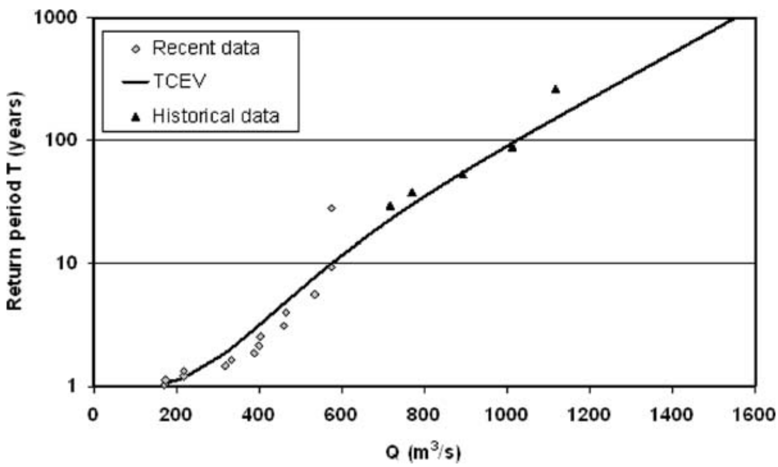

Figure 6: Probability Distribution of Floods for the Avisio at Lavis. The Continuous Line Represents the TCEV Distribution Estimated with Regionalization Model, Diamonds the Systematic Data, and the Triangles are the Historical Floods.

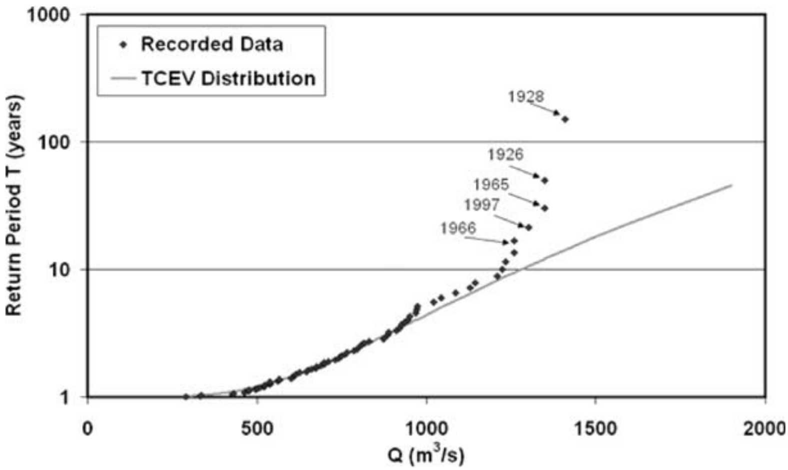

Figure 7: Comparison between the TCEV Distributions Estimated with Regionalization Model and Recorded Annual Maxima at Bronzolo.

Following the described approach, we estimated the flood peaks for all the small and midsized basins. Choosing a return period for the flood protection equal to 500 years, it followed that the peak flow of the Noce River is $Q_{T=500}$=600 m^3/s, while for the Avisio River $Q_{T=500}$=1,234 m^3/s. For the water level gauges of Bronzolo and Trento, we preferred the at-site model because it is able to account for the superimposition effects of different sub-catchment contributions (Adige at Bronzolo $Q_{T=500}$=2,000 m^3/s, and Adige at Trento $Q_{T=500}$=3,150 m^3/s).

5. THE HYDROGRAPHS OF THE ADIGE AT TRENTO

In flood management problems, the definition of hydrological risk includes several aspects. It refers not only to the peak discharges, but also to the flood volume and the shape of the flood hydrographs. The estimation of this latter variable is possible through the formulation of a synthetic hydrograph of a given return period obtained by statistically analyzing the flood volumes of recorded events. This is a frequently used technical practice.

If a long series of recorded hydrographs is available for a river section, the analysis of the flood volumes can be performed following different procedures. We decided to compare results of synthetic hydrographs, a hydrological model and statistical analyses to define the basin response at the higher return periods in terms of flood volumes.

The method adopted is based on the analysis of maximum average discharges of given duration and leads to the construction of the Flow Duration Frequency Reduction curve (FDF) that furnishes the maximum average discharge $Q_D(T)$ in each duration D for a given value of return period T (NERC, 1975). The return period is dependent on the probability distribution of flood peaks.

The construction of synthetic hydrographs for the Adige at Trento is carried out by using 11 recorded events. Analyses of the records (surprisingly) reveal two systematically different responses that fall into two distinct categories. The first has a mean increase in discharge of 60 $m^3/s/h$ (Figure 8a), and the second a faster increase of the discharge of about 240 $m^3/s/h$ (Figure 8b). This behavior is unexpected and may produce significant errors in the flood risk evaluation if not accounted for. We will address this problem in detail later, but now we proceed assuming both the hydrographs equally possible at any return period. As we will see later, this is a wrong assumption.

The synthetic hydrograph can be constructed, under the simplifying assumption of symmetry respect to the time of the peak, according to the expression proposed by Fiorentino (1985):

$$q(t) = Q_T e^{-\frac{2|t|}{k}} \text{ for } t \in [-\infty, +\infty] \tag{2}$$

where Q_T $[L^3/T]$ is the peak flow referred to the return period, t [T] is the time, k [T] is a shape parameter of the hydrograph. Assuming the hydrograph collapsed in the positive t axis, it follows that the previous formula can be rewritten for computational purposes as:

$$q(t) = Q_T e^{-\frac{t}{k}} \text{ for } t \in [0, +\infty] \tag{3}$$

Equation 3 is particularly useful to derive an analytical function of the flood volumes over a given threshold q_o (Fiorentino & Margiotta 1998):

$$V_{q_0} = Q_T \int_0^{t_0} e^{-\frac{t}{k}} dt - q_0 t_0 = kQ_T\left(1 - e^{-t_0/k}\right) - q_0 t_0 \tag{4}$$

where $t_0 = -k \ln(q_0 / Q_T)$ is the time duration in which the discharge $q(t)$ reaches the value q_o.

In the case study, the shape parameter k at Trento may assume two different values: the first refers to the slow events (k_{slow}=92 h) and the second to fast events (k_{fast}=41 h). Using equation 4, it is possible to evaluate flood volume corresponding to a given threshold and for a return period of 500 years. The threshold q_o represents the hydraulic capacity of the cross section of the river that, in our case, is equal to 2,200 m^3/s. The flood volume, obtained following this procedure, ranges from 53.1 to 23.7 mm^3 moving from a slow event to a fast one.

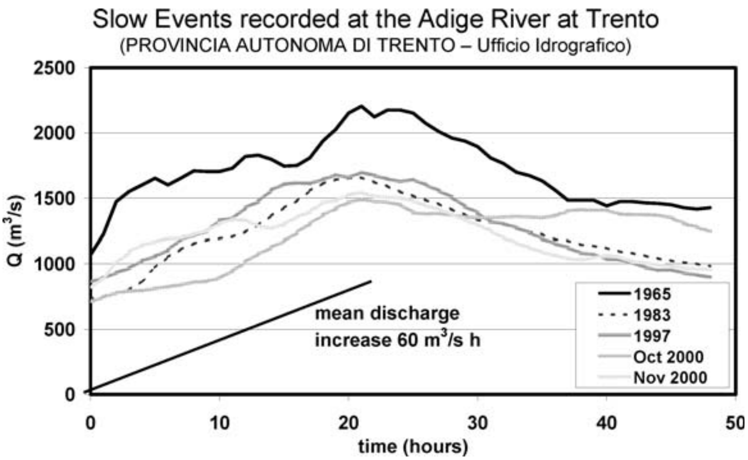

Figure 8a: Slow Events Recorded at the Water Level Gauge of Trento.

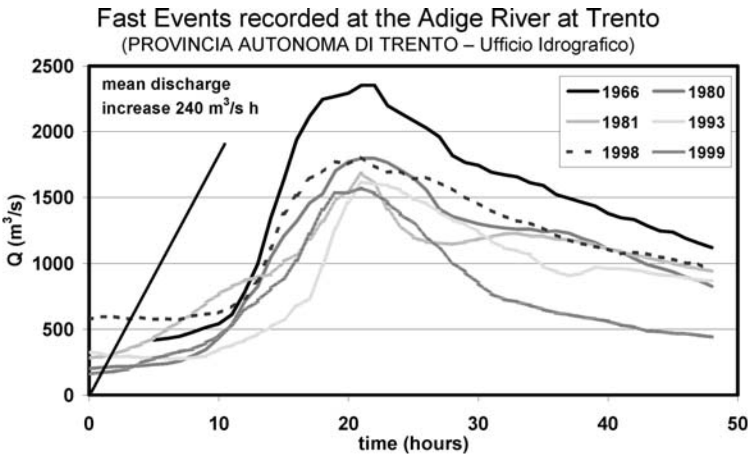

Figure 8b: Fast Events Recorded at the Water Level Gauge of Trento.

This method provides two significantly different results according to the two event dynamics. Neglecting the presence of two event typologies would lead to a value of the flood volume of about 35 mm^3. This value, as we will clarify later, still overestimates the flood volume of the basin at T=500 years. These uncertainties led to deeper analyses undertaken by using hydrological modeling.

6. HYDROLOGICAL SIMULATION AT EVENT SCALE

The simulation approach reduces uncertainty in flood volume estimation. To carry out our simulation, we use an event scale model that is able to reproduce the flood peak response of the basin. The hydrological elements relevant for a drainage basin, at this scale, are: (1) the precipitation input, which is the main cause of runoff; (2) superficial infiltration into the soil, which may store a significant amount of the precipitation; (3) direct overland flows, where discharging along successive streams can rapidly swell the flows of the main stream; (4) subsurface flow, which is runoff for shallow subsurface flow that contributes to the stream flow with a certain delay with respect to the superficial runoff; and (5) deep infiltration into groundwater, which represents only a loss term at event scale.

In the hydrological modeling, the soil state significantly influences the basin behavior (Manfreda et al. 2005) and it is therefore necessary to take into account its variability. To this end, Manabe (1969) suggested that the land surface water balance can be simulated by using a simple model of effective soil storage. In this case, runoff is generated for storage excess. Farmer et al. (2003) defined bucket models of appropriate complexity mainly oriented to ungauged basin prediction. In this case, we defined a bucket scheme to simulate the soil water storage state during extreme events.

The runoff is modeled according to De Smedt et al. (2000):

$$R_t = \begin{cases} C \dfrac{S_t}{S_{\max}} P_t & S_t < S_{\max} \\ P_t & S_t \geq S_{\max} \end{cases} \tag{5}$$

where R_t [L] is the amount of surface runoff, P_t [L] the precipitation, S_t [L] the total water content of the bucket at time t, S_{max} [L] the maximum water storage capacity of the bucket, and C [–] the runoff coefficient. Equation 5 states that the runoff is proportional to the soil water content until the cell reaches the saturation state. After that point there is no more infiltration into the soil and all the precipitation becomes runoff.

The soil moisture storage is the quantity of water held, at any time, in the active soil layer. It varies in time depending on rainfall, interflow, and groundwater recharge, according to the following water balance equation:

$$S_{t+\Delta t} = S_t + I_t - R_{out,t} - L_t \tag{6}$$

where: $S_{t+\Delta t}$ [L] is the total water content of the bucket at time t+Δt, I_t ($I_t = P_t - R_t$) [L] the infiltration amount during the time-step Δt, $R_{out,t}$ [L] the subsurface outflow in Δt, and L_t [L] the leakage in Δt.

The model accounts for the subsurface production assuming that the subsurface flow constitutes a fraction of the water exceeding a given threshold. The subsurface outflow is evaluated by the following equation:

$$R_{out,\ t} = max\{0, c(S_t - S_c)\} \tag{7}$$

where S_c [L] is the threshold water content for subsurface flow production, and c [1/T] is the subsurface coefficient. The groundwater recharge is evaluated according to (Eagleson 1978):

$$L_t = k_s \left(\frac{S_t}{S_{max}} \right)^{\beta} \Delta t \tag{8}$$

where: L_t [L] is the groundwater recharge in Δt, k_s is a parameter that interprets the permeability at saturation [L/T], β is a dimensionless exponent. Hydrological losses such as vegetation interception and evapotranspiration are neglected, because they are less relevant at the event scale.

The discharge is computed by using a linear relationship to the total generated runoff, and by considering a constant delay time to reach the basin outlet (Figure 9). Therefore, the discharge at the outlet is evaluated as the sum of the following components:

$$Q(t) = Q_s + Q_{sub} + Q_b = \alpha_s W_s + \alpha_{sub} W_{sub} + Q_b \tag{9}$$

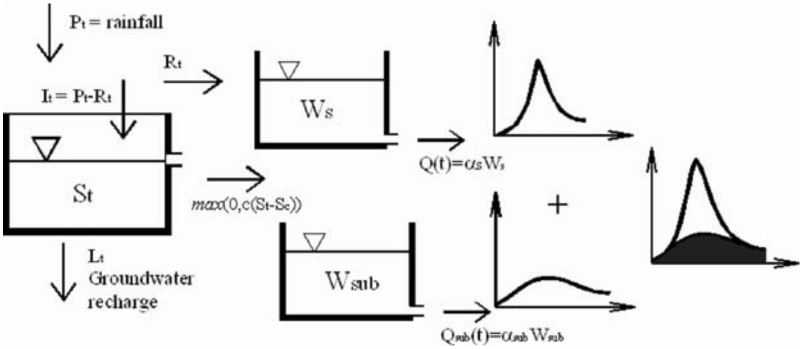

Figure 9: Lumped Model Scheme Used to Interpret the Catchment Response.

where: Q_s [L^3/T] is the discharge due to the superficial runoff; Q_{sub} [L^3/T] is the subsuperficial; Q_b [L^3/T] is base flow contribution, which is assumed constant; W_s [L^3] is control volume of the generated runoff; W_{sub} [L^3] is control volume of the generated subsurface runoff; α_s [T] is runoff recession constant; and α_{sub} [T] is the subsurface runoff recession constant.

Model capabilities are evaluated on the base efficiency and error functions such as: Efficiency (*EFF*), Absolute Average Error (*AAE*), and Root Mean Square Error (*RMSE*). For brevity we report only the expression of the efficiency:

$$EFF = \frac{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q_o}\right)^2 - \sum_{i=1}^{n}\left(Q_{oi} - Q_{ci}\right)^2}{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q_o}\right)^2} \tag{10}$$

where: Q_{oi} is the *i*th ordinate of the observed discharge, Q_{ci} is the *i*th ordinate of the simulated discharge, $\overline{Q_o}$ is the mean value of the observed discharge, *n* is the number of registrations.

The stream flow was interpreted as the sum of contributions coming from two sub-catchments: the Avisio and the remaining part of the Adige. Each of them was interpreted using the described bucket-scheme. In this way, we could also define the contribution of the Avisio sub-catchment to the peak flow of the Adige at Trento.

The model presented here has a simple structure, but at the same time it provides good results as confirmed by the event simulation reported in Figure 10. In this graph, we plot the recorded and simulated hydrographs of the Adige at Trento and Avisio at Lavis. The simulation provides efficiency higher than 90 percent. The model has been tested on four other rainfall-runoff events, and in all the cases the simulations provided are satisfactory. The model parameters are given in Table 2.

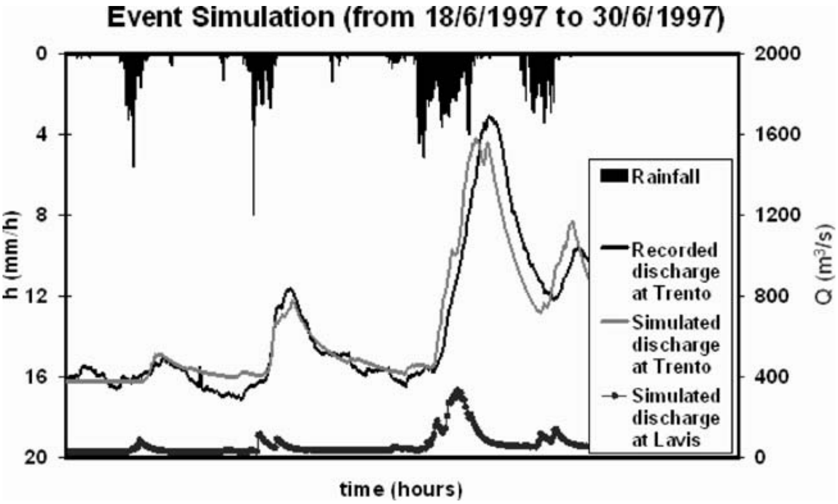

Figure 10: Model Simulation of a Recent Event that Occurred in June 1997 (EFF = 92.4%, RMSE = 109.9 m^3/s).

Table 2: Parameters of the Bucket Model.

	Adige	**Avisio**
C (−)	0.45	1.00
S_c (mm)	85	23
S_{max} (mm)	101	100
c (h^{-1})	0.05	0.011
Ks (mm/h)	22	48
β (−)	5.36	4.84
α_s (h^{-1})	0.041	0.16
α_{sub} (h^{-1})	0.025	0.025
Q_b (m^3/s)	420	0

After a complete analysis of calibration and validation, the bucket model was used to estimate the contribution of the Avisio sub-catchment to the peak flow at Trento and to verify the form variation of the hydrograph for a given return period. In particular, using rectangular rainfall pulses as input of the hydrological model, we could evaluate the basin and subbasin responses caused by rainfall of different durations. Rainfall depth of specified return period is evaluated by using the intensity duration–frequency relationship (IDF), estimated at basin scale.

In Figure 11a, we report the shape variation of the hydrographs at Trento, obtained using rectangular pulses with different durations and for a return period T=500 years. In light of the obtained results we could deduce that the two different hydrograph shapes, described in the previous paragraph, are mainly related to different characteristics of storms: the fast events are due to high intensity and short duration rainfall, while the slow event emerges from an event of longer duration. The distinction is not simply due to the rainfall dynamic, but also to the contribution of the Avisio River that becomes dominant in case of high intensity rainfall contributing to the peak flow in a high perceptual. In fact, the Avisio River basin may contribute up to 45 percent for high intensity and short duration rainfall (Figure 11b).

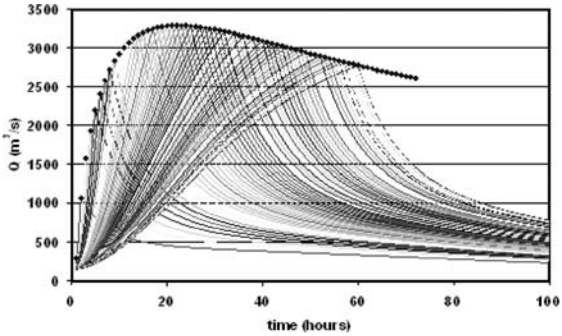

Figure 11a: Variation of the Hydrographs and Peak Flow Obtained by the Bucket Model Using Rectangular Pulses of Precipitation of Different Duration for a Specified Return Period (T=500).

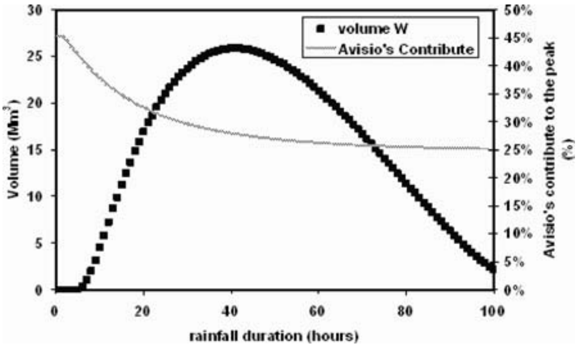

Figure 11b: Variation of the Volume Over the Threshold 2,200 m^3/s for a Precipitation of a Specified Return Period at Different Duration and Avisio's Contribution to the Adige's Peak at Trento.

The increase of rainfall duration causes an increase of the peak flow. After a certain value of rainfall duration (D = 20h) the peak starts to decrease with respect to its maximum value of 3,150 m^3/s. The maximum volume over the threshold of 2,200 m^3/s for each hydrograph is about 26 mm^3 (see Figure 11b). This value does not agree with either of the previous results, implying that the more dangerous event is something in between the fast and the slow event. At the same time, the results clearly indicate that only fast events may reach the peak flow of 3,150 m^3/s while slow events with the same probability have a lower value of the peak flow. Such a condition evidences that the estimation of the flood volume with synthetic hydrograph corresponding to a slow event is incorrect and represents a gross overestimation.

7. A STATISTICAL APPROACH FOR FLOOD VOLUMES ESTIMATION

The presence of different estimates of the flood volume may be incorporated by introducing a third model in order to facilitate a comparative analysis with different procedures. In this view, we pursued a direct estimate of the flood volume over a given threshold. This method is the only one, which provides a direct estimation of the flood volume.

Defining the stochastic variable W:

$$W = \int_0^t \left(q(t) - q_0\right)dt \tag{11}$$

where W [L^3] is the flood volume over the threshold q_0 [L^3/T], $q(t)$ [L^3/T] is the discharge during the time t. The variable can be estimated from the recorded hydrographs of the flood events. For every threshold we define flood volumes series of data from recorded events. For this purpose, it is necessary to consider a threshold sufficiently high to take into account only the runoff production but at the same time not a very high threshold, which could make the series too short. In our case, we fix such a threshold limit equal to 1,500 m^3/s, obtaining the series reported in Figure 12. The cumulative distribution function (CDF) used is the Power Extreme Value (e.g., Villani 1993):

$$F(X) = exp\left(-\Lambda\, exp\left(-\frac{X^{\gamma}}{\beta}\right)\right) \tag{12}$$

where γ is the shape parameter, $\beta = E[X^{\gamma}]$ is the position parameter, and Λ = expected number of flood events exceeding the threshold q_0/year.

Parameters γ and β are estimated through maximum likelihood fitting and are assumed independent from the threshold value. The parameter β was also verified for other threshold values higher than 1,500 m^3/s. The estimated values of the parameter at the station of Trento were $\gamma = 0.66$ e $\beta = 3.59$ Mmc$^{0.66}$.

Using these hypotheses it is possible to extrapolate the probability distribution of the flood volumes over different thresholds. The threshold has a physical meaning—it represents the limited hydraulic capacity of the river cross sections—and the volume over the threshold represents the over spill of water.

The mean number of events is the number of times in which the threshold is exceeded, which means:

$$\Lambda = 1/T(q_0) \tag{13}$$

where $T(q_0)$ is the return period of the discharge q_0 deduced by the CDF of the maximum annual peak flow of the considered station (Trento).

This method allowed the estimation of flood volumes using a pure statistical approach based only on the recorded data, using both the peak flow series and the recorded hydrographs. In Figure 12, the probability distribution of the flood volumes for different thresholds is drawn. As is

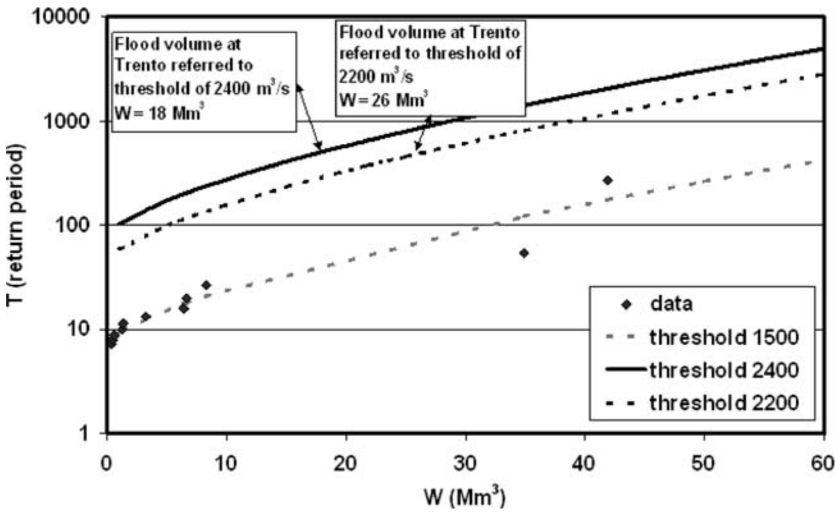

Figure 12: Probability Distribution of Flood Volumes over Different Thresholds for the Adige at Trento.

clear from the graph the estimated volume (with T = 500 years) over the threshold 2,200 m^3/s is 26 mm^3. This result is coherent with the one obtained from the previous analyses and corroborate each other.

8. FLOOD MANAGEMENT STRATEGIES: GUIDELINES

Flood risk mitigation is based on real time actions such as flood warning, flood forecasting, flood reservoir management, emergency planning, and long term actions such as land planning and zoning, structural protection measures, and property insurance. Risk management may be subdivided into three levels of actions: operations, planning, and design. The last two may be considered dynamic processes that account for variations in “sensitivity” toward risk through time (Plate 2002). Risk education is also a valuable way to evaluate differences between expert knowledge and people’s behavior (e.g., during crises and when assessing the needs for land planning). The overall objective of flood mitigation management is to integrate all the methodologies in order to reduce potential losses.

The flood risk, over the study area, can be managed by using an integrated system, which consists of a combination of a forecasting system and structures for flood mitigation. The protection actions can be further subdivided into three: (1) Setup of a flood forecasting system that permits the prediction of flood risk and the evaluation of the progress of floods, thereby enabling the responsible authorities and involved populations to take personal, material, and organizational decisions to reduce the detrimental consequences of the imminent flood. These decisions may range from routine responses (e.g., change of dam operation instructions) to preventive instructions to emergency measures (e.g., announcing a generalized alert). (2) Nonstructural action that may reduce the risk of ordinary events by increasing, for instance, the actual capacity of the river system. (3) Structural actions that can be necessary during extraordinary events to control flood peaks by storing floodwater. The flood control works should be arranged, when possible, considering water storage capacity of existing structures or realizing new structures if necessary.

9. CONCLUSIONS AND FINAL REMARKS

The Adige represents a stimulating case study that raises interesting questions and highlights numerous particular cases. In our opinion, the description of the outcomes of this work may be extremely useful for hydrologists facing similar problems. For the sake of brevity, we presented only the most significant results, which does not reduce the relevance of the present work.

The study introduces innovative strategies for flood volume estimates and underlines possible strategies for flood management. The methodologies presented here can be usefully applied to general problems of flood risk mitigation, in which the flood volume estimation is crucial. The work allows the reduction of uncertainties by using multiple analyses that highlight the limitations of procedures based on the use of synthetic hydrographs. The hydrological simulation and direct statistical approach provide a more accurate estimate of the basin response at the higher return periods. Particularly interesting is the coherence of the results obtained following the last two procedures described below.

In the first procedure, flood peaks data were studied using a regionalization model along with the TCEV model. The regionalization approach was particularly successful in small and medium size subbasins. Furthermore, the use of historical documents was found to be extremely useful in the analysis of model results and in the understanding of real behavior of the basin. Rainfall maxima were found to be fairly homogeneously distributed over the basin despite the remarkably different subbasins hydrological responses. This implied that the main differences in the peak flow distribution were related to the presence of less permeable soils in the Avisio basin rather than differences in the rainfall. Furthermore, ranking rainfall maxima according to seasons allowed the detection of the autumn season being the period with higher probability of events which are potentially dangerous for the area.

In the second procedure, the hydrological response of the basin was subdivided into two classes of events according to rainfall characteristics. Temporal dynamics of rainfall dictated the distinction between fast and slow events; but also the contribution of the Avisio subbasin was detected as responsible for the production of the so-called fast events.

While studying hydrologic risk, one may face a broad number of uncertainty factors. Rigorous analyses, if not physically based, may lead to unreliable results. For this reason, hydrologists must approach the problem with a critical sense in order to obviate rough errors without which overestimation or, even worse, underestimations of the flood events is possible.