U.S.- Italy Research Workshop on the
Hydrometeorology, Impacts, and Management of Extreme Floods
Perugia (Italy), November 1995

HYDROMETEOROLOGICAL ASPECTS OF THE 1994 FLOODING IN THE UPPER PO RIVER BASIN: FREQUENCY CHARACTERISTICS AND REAL-TIME PREDICTABILITY

Armando Brath
Institute of Hydraulic Structures
University of Bologna
Viale Risorgimento,2 40136 Bologna, Italy

Abstract. The predictability of the flood event that occurred in the Piedmont region (Northern Italy) during November 1994 is investigated. Statistical analyses are performed on available observation of rainfall and streamflows in order to assess the return period of the flood event. The possibility of forecasting similar flood events is also investigated. At the present state of technology real-time flood forecasting is limited in the region, mainly due to the lack of reliable real-time forecasting of rainfall. The analyses of quantitative precipitation forecasts provided by some meteorological models seem to indicate the need for considerable improvements in the predictive ability of Limited Area Models (LAM) before they can be used as operational tools for real-time forecasting. However, quantitative rainfall forecasts obtained from the General Circulation Model of the European Center for Medium Range Weather Forecasting (ECMWF) are in good agreement with the observed precipitation fields. Because of the insufficient space-time resolution, these rainfall forecasts are at present not suitable for real-time flood forecasting systems in small basins. On the other hand, their use for flood warning in medium and large basins seems to offer interesting perspectives.

1. INTRODUCTION

In November 1994, an intense rainfall event occurred in northern Italy. Heavy precipitation occurred over a large region, including both Piedmont and Liguria, but its effects were catastrophic in the southern part of the Piedmont, particularly in the Tanaro River basin. Analysis of the synoptic charts shows that the rainfall event was due to favorable large and meso-scale meteorological conditions, which favored prolonged, intense precipitation (Buzzi et al., 1995).

In order to analyze the characteristics of the rainfall event, pluviometric data were collected from available sources for the entire Piedmont. Figures 1a), 1b), and 1c) show maps of the daily rainfall totals for November 4th, 5th, and 6th respectively. Figure 1d) shows a map of the total rainfall depth for the entire event. The rainfall event can be divided into three periods; during the first one (starting in the afternoon of November 4th), the most intense precipitation occurred in Liguria and in the southernmost part of the Piedmont (upper Tanaro River basin); in this last region, the rainfall intensity became very high in the night of November 4th. In the second period, which includes most of November 5th, heavy rainfall became more widespread, expanding into the remaining part of the region; daily rainfall totals exceeding 200 mm were revealed in the region. During the third period, the heaviest rainfall occurred in the pre-Alpine region, between the Pellice and Sesia rivers. This period is from the late afternoon of November 5th through the 6th, after which precipitation was still heavy in the southern Piedmont, but persisted in central and northern parts of the region at a reduced intensity, which nonetheless led to considerable accumulations.

2. ASSESSMENT OF THE FREQUENCY CHARACTERISTICS OF THE EVENT

In this section, statistical analyses are performed on the available data, in order to estimate the return period of the flood event. To this end, the analyses are mainly focused on the Tanaro River basin, where effects of the flood were the most severe. Peak discharge observations are analyzed first. However, this analysis-- the most natural choice in order to assess the frequency characteristics of a flood event—is inadequate for this case. The available discharge measurements are very sparse, and in some cases, not completely reliable, being greatly affected by major modifications to the river morphology and the extensive flooding that occurred in the upper parts of the river basin. Thus, the rest of the analysis is focused on statistical characterization of the point and areal average rainfall totals of the flood event.

2.1. ANALYSIS OF DISCHARGE DATA

As previously mentioned, the set of available discharge observations for the flood event of November 1994 is relatively poor. At present, only a small number of gauges is in operation in the region. Although a large number of the gauging stations have been operated in the past by the Italian agency devoted to the measurements and the collection of hydrologic data (S.I.M.N., acronymous of Servizio Idrografico e Mareografico Nazionale), only a few are still in operation. For various reasons (shortness of the available record, lack of a recent updating of the depth-discharge curve, etc.), hydrometric observations from other networks are not suitable for use in the present analysis. Some of the gaging stations were destroyed or seriously damaged during the event, especially in the Tanaro River, where the flood was of catastrophic proportions. The reliability of the peak discharge estimates based on hydrometric measurements can not be considered completely reliable for several reasons. One of the most important of these is that the measured hydrometric levels were in some cases strongly affected by flooding occurring upstream as previously mentioned. Thus, they should be lower than the natural ones, which were measured in absence of upstream flooding.

It follows that estimating the return period of the event based on statistical analysis of discharge observations is subject to several limitations in the case in question. Accordingly, in the following sections, statistical analyses of rainfall data are also performed, in order to more accurately represent the frequency characteristics of the examined flood. In the remaining part of the present section, the results of the statistical analysis of the available hydrometric data are presented.

The Gumbel distribution of the annual maximum discharges for the Tanaro River at Farigliano is shown in Fig. 2. From this distribution, the return period of the observed peak discharge (estimated at 2,000 m^3/s) is estimated to be 100 years. Similarly, a return period of about 200 years is estimated in Fig. 3 for the Tanaro River at Montecastello. Similar analyses were performed for other rivers in the region and the results are summarized in Table 1.

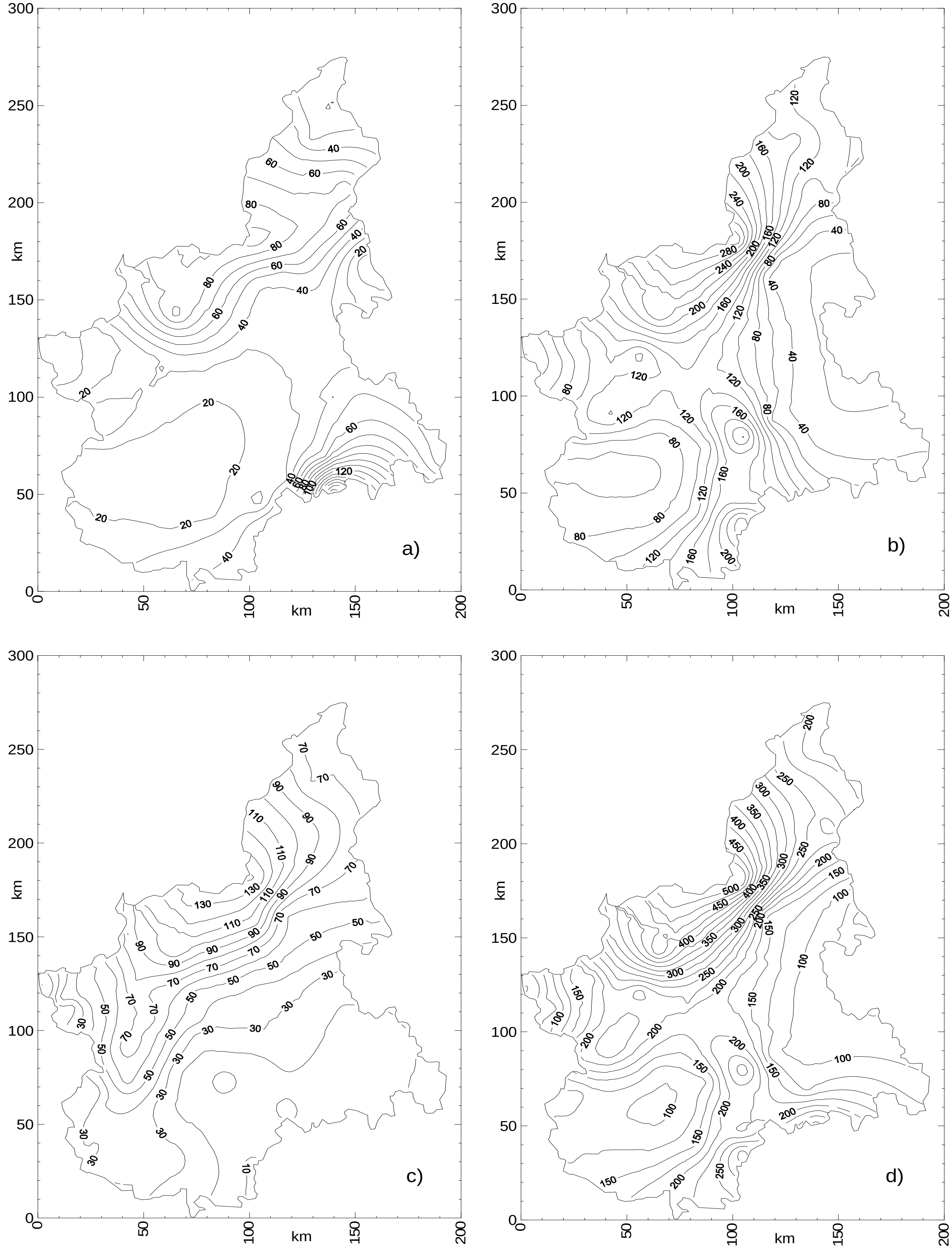

Figure 1 - Maps of daily rainfall depth (in mm) for (a) November 4, (b) November 5, (c) November 6, and (d) total rain depth.

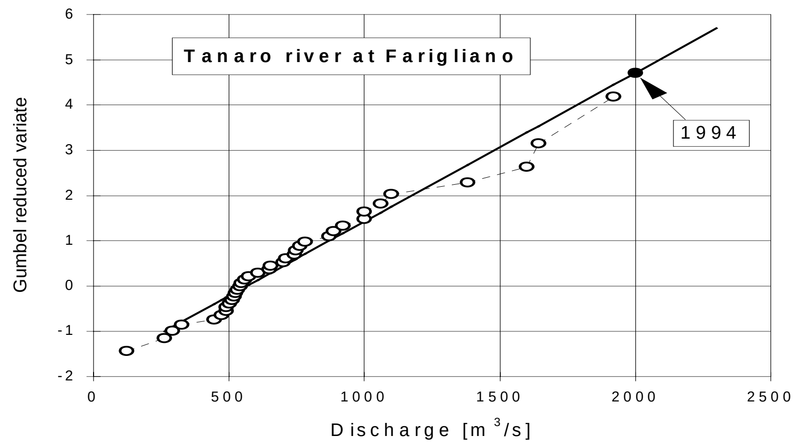

Figure 2 - Probability distribution of the annual peak discharges for the Tanaro River at Farigliano, compared with the observed peak discharge of the November 1994 flood event.

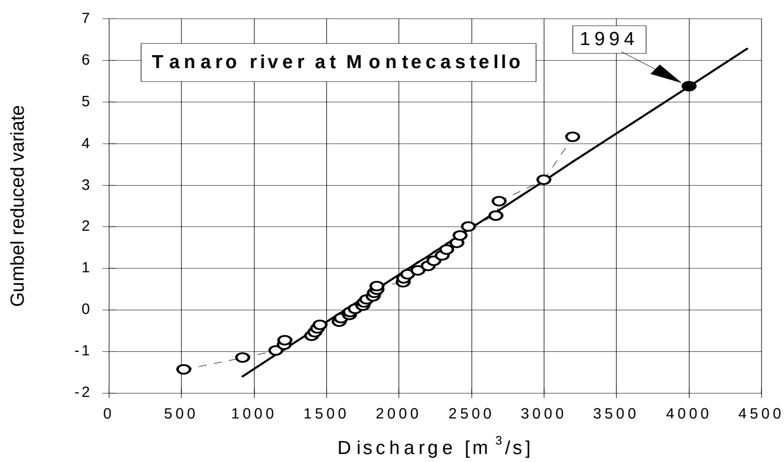

Figure 3 - Probability distribution of the annual peak discharges for the Tanaro River at Montecastello, compared with the observed peak discharge of the November 1994 flood event.

2.2. ANALYSIS OF POINT RAINFALL DATA

In order to estimate the return periods of point rainfall totals that accumulated during the event, DDF (Depth-Duration-Frequency) curves were generated for the several sites of the region where sufficient historical data on annual maxima of rainfall depths were available. According to the characteristics of the rainfall event and the available rainfall measurements, rainfall durations of 1, 2, 3, 4, and 5 days were considered. Therefore, observations of annual maxima of rainfall depths for durations of 1, 2, 3, 4 and 5 days were collected and the Gumbel distribution was found best to describe the frequency behavior of the observed data. The following formulation of the DDF curve has been adopted, as is usual in Italy:

$$h(d,T) = a(T)\, d^{n(T)} \qquad (1)$$

where *h(d,T)* represents rainfall depth at a point for duration *d* and return period *T*, and *a(T)* and *n(T)* are coefficients, which depend on the return period considered. DDF curves were compared with the maximum rainfall depths that occurred at corresponding sites over durations of 1, 2 and 3 days. The results show that the return period of the rainfall event was very high for several stations -- in many cases the estimates of T are greater than 100 years -- and clearly indicate the severity of the flood event.

Table 1. Peak discharge [m^3/s] and return period for some rivers of the Piedmont

River	Station	Area km^2	Qmax Nov.1994	T years
Dora Baltea	Tavagnasco	3313	2438	44
Orco	Pont Canavese	617	379	2
Stura di Lanzo	Lanzo	582	810	9
Bardonecchia	Beaulard	203	9	1
Dora Riparia	Ulzio	262	15	1
Dora Riparia	S.Antonino di Susa	1048	249	27
Chisone	S.Martino	581	410	7
Po	Meirano-Moncalieri	4885	1416	8
Po	S.Mauro Torinese	7408	2952	4
Tanaro	Farigliano	1522	~ 2000	~ 100
Tanaro	Montecastello	7985	~ 4000	~ 200

However, as expected, the estimates of the return period of the point rainfall observations were found to be highly variable, depending on the site considered. In some basins, which were subject to uniform spatial distribution of rainfall, these estimates show some regularities (e.g. the Tanaro basin). In other cases, where the spatial distribution of rainfall was highly variable, the estimates are strongly affected by the location of the point under examination. This behavior is characteristic of several basins located in the central part of Piedmont, where rainfall was very heavy in the downstream part of the valley but light in the mountainous part of the basin. Figure 4 is an example of a comparison between DDF curves and maximum observed rainfall for durations of 1, 2 and 3 days, for three sites in the Stura di Lanzo river basin: Ceres, Malciaussia, and Usseglio. As clearly demonstrated, for the first gauge (Ceres) the statistical analysis of point rainfall clearly indicates the catastrophic nature of the event; indeed, the estimates of return period are always greater than 500 years, regardless of the duration considered (1, 2, or 3 days). However, for the other two sites, the analysis indicates a rainfall event of ordinary nature: estimates of the return period are in the range of 10-30 years, depending on both the site and the duration (1, 2 or 3 days) considered.

In similar instances, the estimation of the return period of the event based on the analysis of the available point rainfall measurements could alone lead to poor results. Therefore, a statistical analysis has been performed to assess the frequency characteristics of the areal average rainfall for some basins of the region. This is described in the following section.

2.3. ANALYSIS OF AREAL RAINFALL

In order to analyze the frequency characteristics of the areal rainfall, DDF curves of areal average rainfall have been estimated for some catchments. The following basins have been considered: Tanaro River basin at Nucetto (A=375 km^2), Tanaro at Farigliano (A=1,522 km^2), Tanaro at Alessandria (A=5,258 km^2), Tanaro at Montecastello (A=7,985 km^2), Stura di

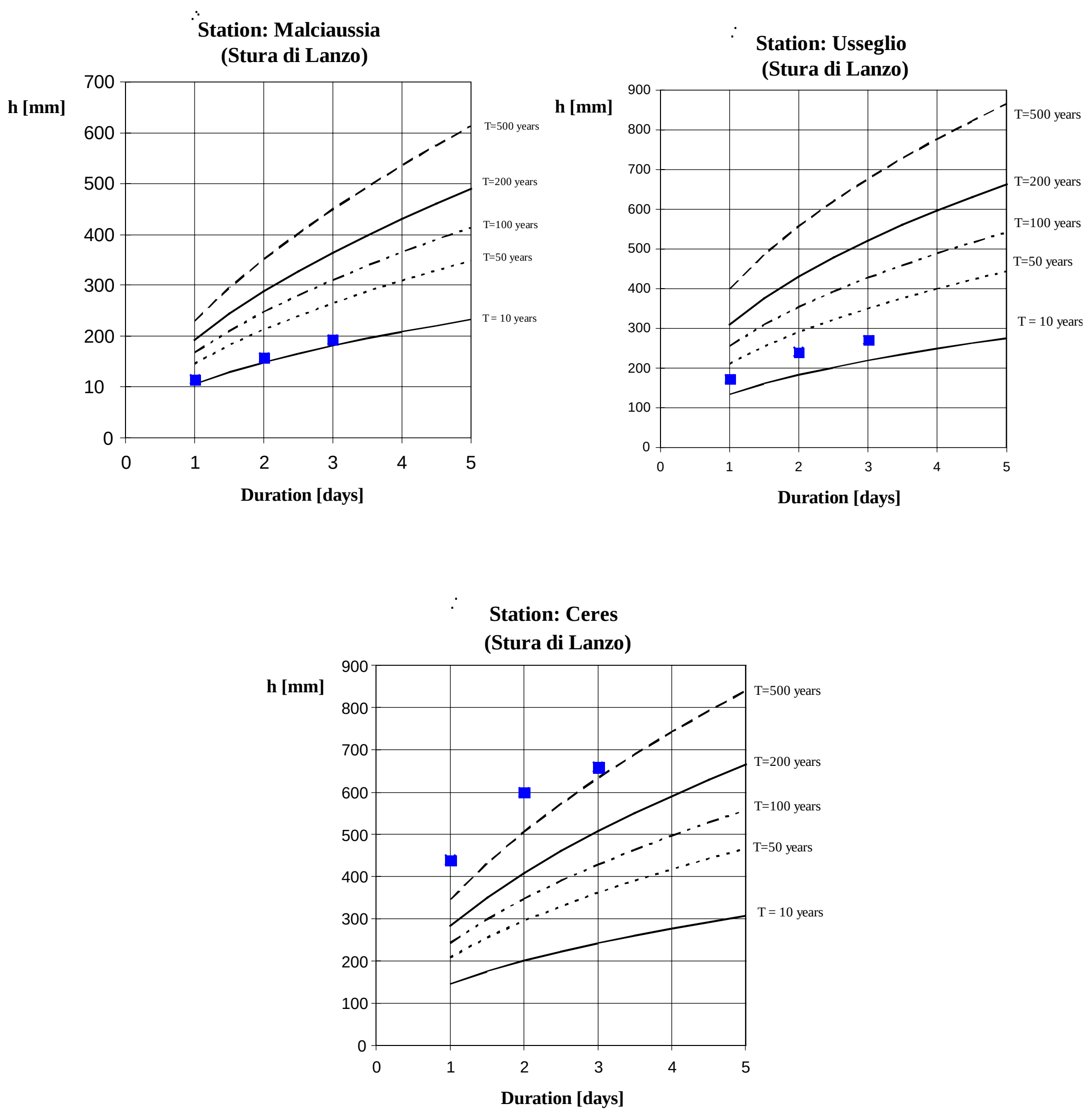

Figure 4 - Depth-Duration-Frequency curves of the point rainfall for three rain gauges in the Stura di Lanzo River basin, compared with the maximum rainfall depths observed during the November 1994 event.

Lanzo at Lanzo (A=582 km^2), Dora Riparia at S.Antonino di Susa (A=1,048 km^2), Orco at Ponte Canavese (A=617 km^2) and Chisone at S.Martino (A=581 km^2). Historical observations of daily rainfall depths measured at all of the rain gauges located within each catchment we collected. Areal averages of daily rainfall depths were estimated by weighting these observations according to the Thiessen method, and the series of the annual maxima of the areal average rainfall depth for durations of 1, 2, 3, 4 and 5 days were extracted. A statistical analysis of these series was performed to estimate areal DDF curves:

$$h_A(d,T) = a(T)\, d^{n(T)} \qquad (2)$$

where $h_A(d,T)$ denotes the areal average rainfall depth for area *A* in duration *d* with return period *T*, and *a(T)* and *n(T)* are coefficients of the DDF curve. By weighting the daily point rainfall observations available from the flood of November 1994, the values of areal average of daily rainfall over the catchments were estimated. From these latter values, the maxima of the areal average rainfall for durations of 1, 2 and 3 days during the flood of 1994 were obtained. In Fig. 5, the DDF curves are compared with the maximum areal rainfalls that occurred during the event of November 1994. As expected, the results indicate that those catchments located in the Tanaro River basin are characterized by the highest values of return periods for the maximum daily areal rainfall occurrences during the November 1994 event. The greatest return period, estimated at approximately 300 years, occurred in the Tanaro River basin upstream of Nucetto. Elsewhere in this basin, return periods of 200, 100, and 200 years were computed for the catchments upstream of Farigliano, Alessandria, and Montecastello, respectively. The maximum rainfall amounts recorded for durations of 2 and 3 consecutive days were generally characterized by lower values of the return period (70-100 years for durations of 2 days, 40-50 years for durations of 3 days). However, for the basin upstream of Montecastello, the return periods for durations of 2 and 3 days are also high (T=200 years and T=80 years, respectively). Nonetheless, as the time of concentration of all of the examined basins is less than one day, the estimates of 1 day rainfall durations can be considered to offer the most relevant information in this case.

For the other basins, the estimates of the return periods of the areal rainfall observed during the flood of November 1994 are much lower than those obtained for the Tanaro River basin. For the Stura di Lanzo River basin, upstream of Lanzo, the return period is estimated at about 20 years for the maximum daily rainfall. For the Orco River basin at Pont Canavese, the estimates of the return period are close to 50 years regardless of the duration of rainfall (i.e., durations of 1, 2 or 3 days). For the Dora Riparia basin at S.Antonino di Susa, T is about 20 years for both durations of 1 day and 3 days, and it is about 40 years for durations of 2 days. Finally, for the Chisone basin at S.Martino, the return period of maximum daily rainfall is estimated at about 20 years, whereas T ranges between 20 and 50 years for both durations of 2 and 3 days. As previously mentioned, given that the times of concentration for all of the examined basins are significantly less than 24 hours, the most significant estimate of the return period appears to be for the 1 day rainfall.

The analysis preformed clearly shows the extraordinary nature of the flood event in the Tanaro River basin (T=100-200 years); for the remaining basins, the rainfall event, although not exceptional, can be considered quite intense ($T \cong 50$ years for the Orco basin at Pont Canaves and $T \cong 20$ years for the Stura di Lanzo basin at Lanzo, the Dora Riparia basin at S.Antonino di Susa, and the Chisone basin at S.Martino).

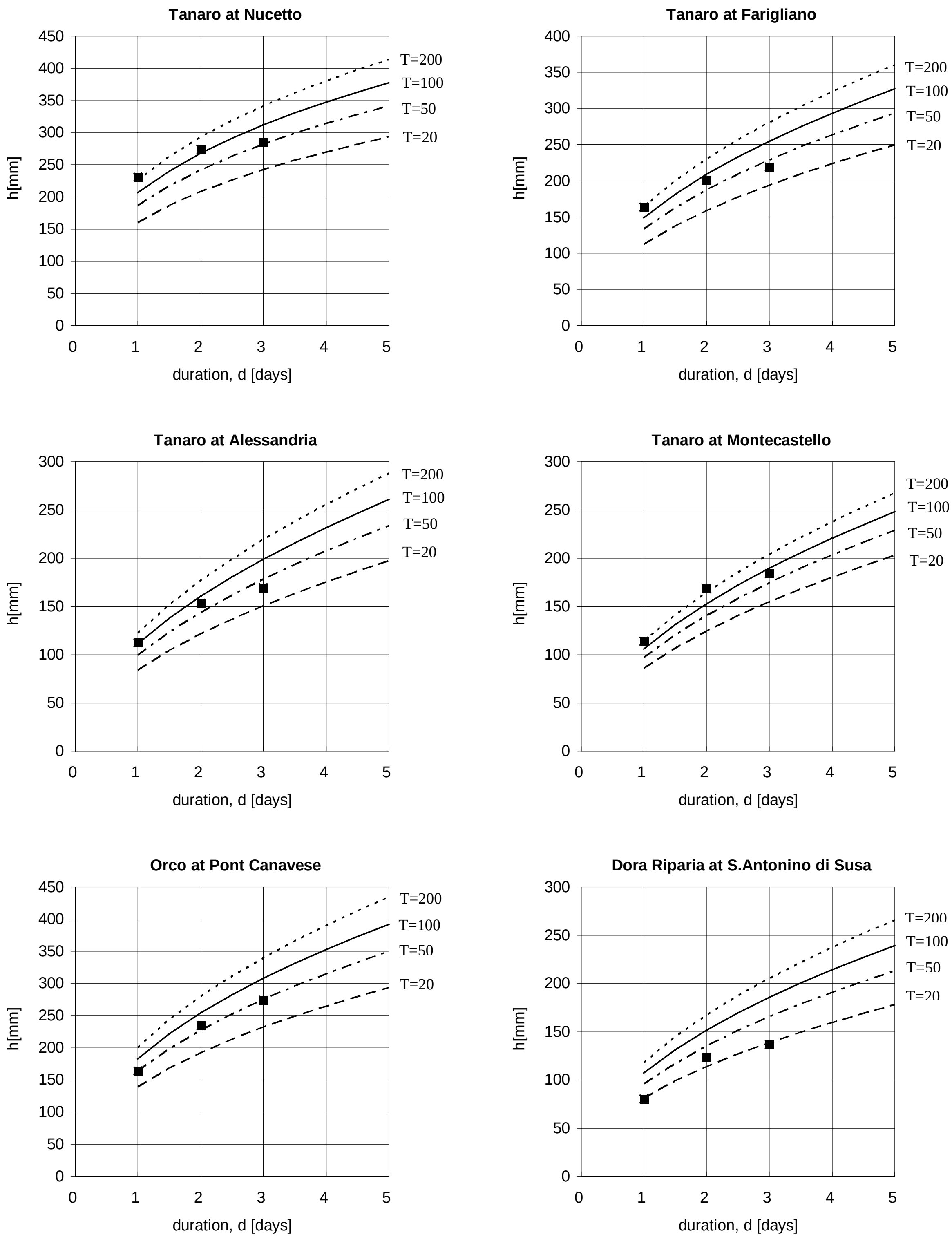

Figure 5 - Depth-Duration-Frequency curves of the areal average rainfall for four basins, compared with the maxima of the areal average rainfall observed during the November 1994 event for durations of 1, 2, and 3 days.

3. REAL-TIME PREDICTABILITY OF THE FLOOD EVENT

In this section, the possibility of real-time forecasting the flood event of November 1994 is investigated. Several studies have been devoted to assessing the benefits of a flood-warning system (U.S. Army Corp of Engineers, 1985). However, this is a very difficult task, given that these benefits depend to a great degree on the particular characteristics of the area subject to flood hazard. For instance, the extension of the flooded area, the number of inhabitants, the density of population, and the topography all play an important role in determining the effectiveness of a flood-warning system. Moreover, the effectiveness of a flood-warning is highly dependent on how the community perceives the warning message, believes it, understands the risk, and on several other factors which affect the public response to flood- warning (Mileti, 1993).

However, it is well known that these benefits are greatly dependent on the lead-time of the forecasting procedure, becoming higher with increasing lead-time: in fact, the longer the time interval between the issuance of forecasts and the onset of flooding, the more effective the civil protection actions can be undertaken. The dependence of these benefits on the available lead-time has not yet been assessed in a definitive manner, and probably could not be assessed in a general manner, because of the above mentioned reasons. Generally speaking, a lead time of 3-6 hours is normally assumed to be the minimum necessary to allow any mitigation of flood hazards (Nemec, 1987). In Italy, with the exception of the Po, Tevere, Arno and a few others, the majority of river basins have a flash-flood nature, with response times in the order of a few hours. Therefore, the extension of the lead-time for flood forecasting is rather limited and often so short as to allow for effective civil protection action. For these basins, it is advisable to extend the forecasting lead-time by using quantitative precipitation forecasting (QPF). The effectiveness of QPF for extending the lead-time of flood forecasting has been widely proven (Brath et al., 1988). Various techniques for QPF are available, based on either deterministic or stochastic approaches. At the present state of technology, however, these techniques are generally affected by a high level of uncertainty.

A first approach to QPF is based on the use of stochastic models of temporal rainfall. To this end, the application of ARMA models has been proposed (Brath et al., 1988; Burlando et al., 1993), although these models were found to be able to produce reliable forecasts only for lead-times of 1-2 hours. Therefore, only limited advantages can be realized by the use of these models for a real-time flood forecasting system. Similar conclusions can be drawn for the use of radar imagery for QPF (Obled, 1988; Schultz, 1993; Ranzi & Bacchi, 1994).

The most appealing perspective for QPF is offered by the use of meteorological models, which in recent years have attained a reasonable precision. One of the world’s most advanced models is the General Circulation Model (GCM) operating by the European Center for Medium range Weather Forecasting (ECMWF) in Reading, United Kingdom (see ECMWF, 1995), which provides rainfall forecasts up to 5 days in advance. A major limitation of GCM’s is related to their limited spatial resolution, which allows only a very rough representation of topography. However, the spatial resolution of ECMWF model has recently been enhanced; since 1991, the model has operated on a horizontal grid-step of about 50 km. This spatial resolution is still not adequate for use in Italy, where a satisfactory representation of such important mountain barriers as the Alps and Apennines predicates a much smaller grid-step (Paccagnella et al., 1992). For this reason, meteorological models operating on smaller areas (LAM, Limited Area Models), but with a finer resolution, have been developed. In Italy, one of the most advanced models for operational precipitation forecasting is that operated in Bologna by the Meteorological Service of

Emilia-Romagna Region (LAMBO model), which has a grid-step of about 18 km (Paccagnella et al., 1994). In this paper, the rainfall forecasts provided by both ECMWF and LAMBO models for the flood event of November 1994 have been considered. Further analysis of the rainfall forecasts provided by other LAM's for the same flood event are in progress. Due to data availability limitations, only daily rainfall predictions have been considered.

In Fig. 6, a map of the spatial distribution of the rainfall of November 5th in the Piedmont region, derived by kriging techniques from the available point rainfall observations, is compared with rainfall forecasts from the examined LAM. The forecasts, issued at 0.00 of 4 and 5 November, correspond to lead-times of 24 hours and 48 hours, respectively. The figure demonstrates that the predictive ability of the model is not satisfactory in this case. With regard to the forecasts issued at 0.00 of November 4th, it is observed that the model does not predict the occurrence of heavy rainfall of November 5th. The forecasts issued at 0.00 of 5 November show some improvements; in this case, heavy rainfall in the northern part of the region is predicted, although rainfall intensities are considerably underestimated. However, the model does not predict the occurrence of the phenomenon in the southern part of the region, which corresponds to the Tanaro river basin. Similar results were obtained for the precipitation forecasts from the LAM for both Novmeber 4th and 6th.

In conclusion, the performance of the LAM is unsatisfactory in the case examined; preliminary results of the on-going analysis of the rainfall forecasts provided by some other LAM's for the same flood event support this conclusion. This analysis indicates that considerable improvements must be made to LAM's before they can be considered operational tools for real-time rainfall predictions.

With regard to the GCM operated by ECMWF; one can observe that the quantitative precipitation forecasts are not presently suitable for use in quantitative flood forecasting systems for medium or small size basins, because of its insufficient spatial resolution. However, its use in the assessment of early warning of flood hazards for medium-large regions bears examination. To this end, a comparison follows of the values of rainfall forecasts provided by the ECMWF model with those of the areal average of the rainfall depths observed during the 1994 flood event. The cell of the computational grid of the model nearest to the Tanaro River basin has been considered. The rainfall values predicted by the model for this grid-point have been compared with the areal average rainfall computed for a 50 km x 50 km area, centered over the same point. Areal rainfall has been estimated by averaging the point rainfall measured at the gauging stations located inside the square using the Thiessen technique. Rainfall forecasts issued by the ECMWF model at 12 GMT on both 2 and 3 November have been examined. According to data availability, the following forecasts of cumulated rainfall have been examined: from +12 hours (+12 hours denotes 12 hours after the time at which the forecasts are issued) to + 36 hours, from +36 hours to +60 hours, from +60 to +84 hours.

In Fig. 7, the rainfall forecasts issued at 12 GMT, November 2nd, are compared with the estimates of the areal average rainfall occurred during the following days; Figure 8 is relative to the forecasts issued on November 3rd. Figures 7 and 8 demonstrate the satisfactory agreement between observed and forecast areal rainfall. The results indicate that the rainfall forecasts provided by the ECMWF's GCM could be used as a powerful flood-hazard forecasting tool for the Tanaro River basin. Accordingly, although the rainfall forecasts provided by this GCM are currently unsuitable for use in quantitative real-time flood forecasting systems, due to their insufficient spatial resolution, their use in the assessment of early warnings of flood hazard for medium to large offers interesting perspectives.

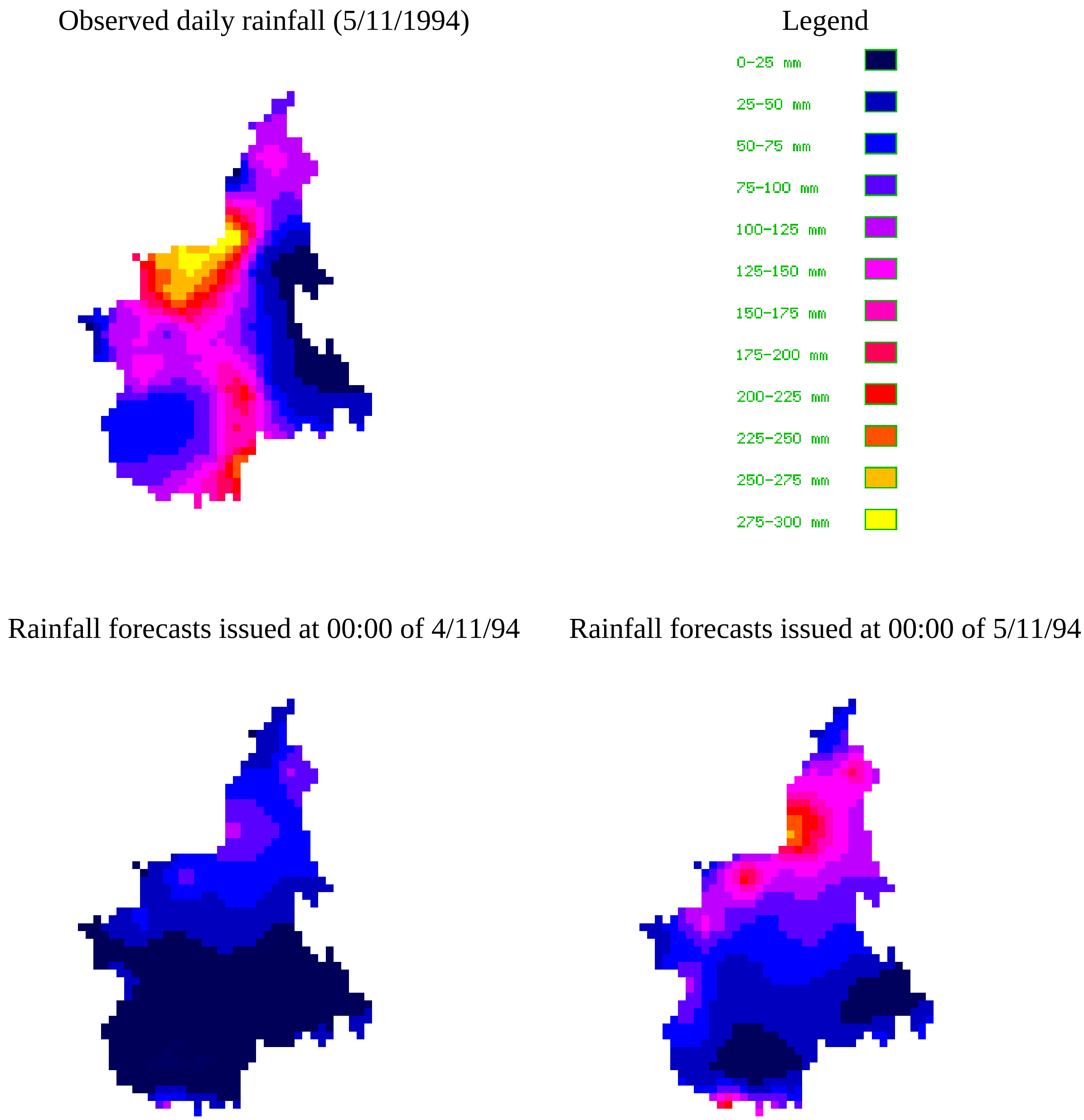

Figure 6 - Comparison between observed daily precipitation and rainfall forecasts provided by the Limited Area Model in the Piedmont region.

Due to the limited availability of data, and the small number of models examined, further analyses are needed before definitive conclusions can be drawn about the use of QPF provided by both GCM's and LAM's for real-time flood forecasting. The results described in this paper indicate that the predictive abilities of LAM's must be significantly enhanced before they can be used as operational tools for real-time rainfall predictions. However, the possibility of using rainfall forecasts provided by the GCM in the early assessment of flood warning hazards in medium to large regions is worthy of further exploration, and these results encourage research efforts in this direction.

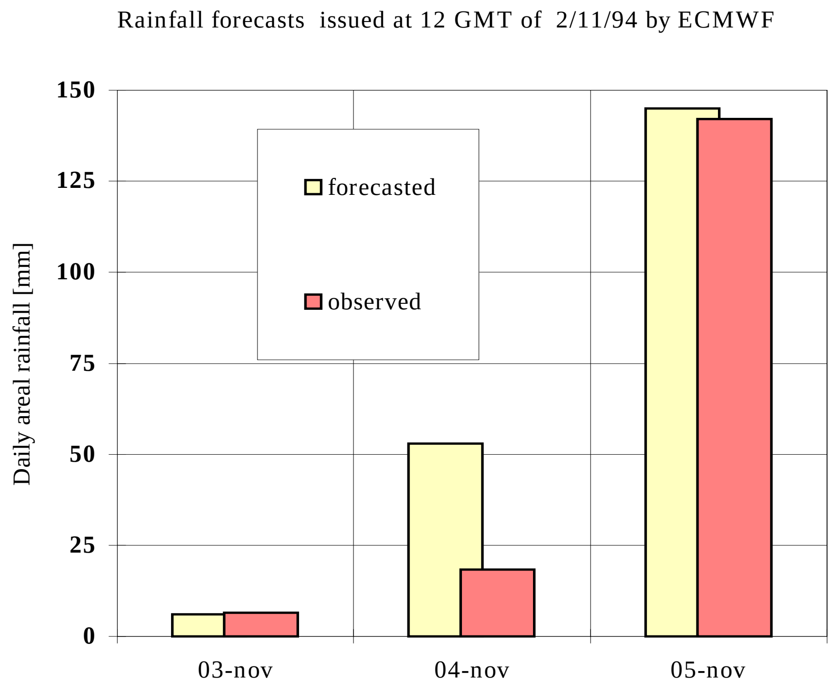

Figure 7 - Comparison between forecasts of areal average rainfall issued by the ECMWF GCM and observations, for a 50 km x 50 km square centered on the Tanaro River basin.

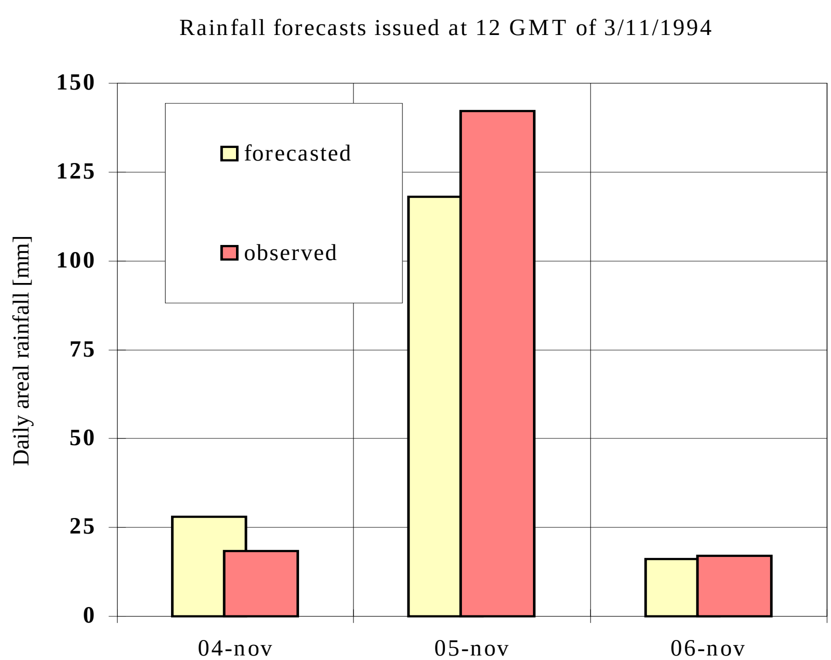

Figure 8 - Comparison between forecasts of areal average rainfall issued by the ECMWF GCM and observations, for a 50 km x 50 km square centered on the Tanaro River basin.

4. REFERENCES

Brath, A., P. Burlando and R. Rosso, (1988). Sensitivity analysis of real-time flood forecasting to on-line rainfall predictions, in Siccardi, F Bras R.L. (eds) *Selected Papers from Workshop on Natural Disasters in European-Mediterranean Countries*, pp.469-488, CNR-GNDCI, Perugia.

Burlando, P., R. Rosso, L.Cadavid and J.D. Salas, (1993). Forecasting of short-term rainfall using ARMA models, *J. Hydrology*, 144, 193-211.

Buzzi, A., N.Tartaglione, C. Cacciamani, T.Paccagnella and P.Patruno, (1995). Preliminary meteorological analysis of the Piedmont flood of November 1994, *Mesoscale Alpine Programme Newsletter*.

European Center for Medium-range Weather Forecasts, (1995). *The description of the ECMWF/WCRP level III-A global atmospheric data archive*, Reading, UK.

Mileti, D.S. (1993). Public response to flood warnings, in G.Rossi, N. Harmancioglu, V.Yevjevich, (eds.) *Coping with floods*, Proceedings of the NATO A.S.I. Seminar, Kluwer.

Nemec, J. (1987). *Hydrological forecasting*, D.Reidel Pub. Co., Dordrecht.

Obled, C. (1988). Rainfall studies and flash flood problems in the French Mediterranean region: Recent achievements and current problems, in Siccardi, F Bras R.L. (eds) *Selected Papers from Workshop on Natural Disasters in European-Mediterranean Countries*, pp.375-394, CNR-GNDCI, Perugia.

Paccagnella, T., S. Tibaldi, R. Buizza and S. Scoccianti (1992). High resolution numerical modelling of convective precipitation over Northern Italy, *Meteorol. Atmos.Phys.*, 50, 143-163.

Paccagnella, T., P. Patruno and C. Cacciamani (1994). Operational quantitative precipitation forecasting at the regional meteorological service of Emilia-Romagna region. The flood event occurred in Piedmont on November 1994, *Proc. Atmospheric physics and dynamics in the analysis and prognosis of precipitation fields,* Rome, 15-18 November.

Ranzi, R. and B. Bacchi (1994). Analysis and forecasting of rainfall fields observed using radar, in Rosso, R. et al. (eds) *Advances in distributed hydrology,* Water Resources Publications, Highlands Ranch, Colorado.

Schultz, G.A. (1993). Remote sensing for forecasting and control of floods, in G.Rossi, N. Harmancioglu, V.Yevjevich (eds.) *Coping with floods*, Proceedings of the NATO A.S.I. Seminar, Kluwer.

U.S. Army Corp of Engineers (1985). Assessment of the economic benefits from flood damage mitigation by relocation and evacuation, Institute of Water Resources, IWR Report 85-R-1.