A hydrometeorological approach for probabilistic flood forecast

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[1] We propose a new methodology for evaluating predictive cumulative distribution functions (CDF) of ground effects for flood forecasting in mountainous environments. The methodology is based on the proper nesting of models suitable for probabilistic meteorological forecast, downscaling of rainfall, and hydrological modeling in order to provide a probabilistic prediction of ground effects of heavy rainfall events. Different ways of nesting are defined as function of the ratio between three typical scales: scales at which rainfall processes are satisfactory represented by meteorological models, scales of the hydrological processes, and scales of the social response. Two different examples of the application of the methodology for different hydrological scales are presented. Predictive CDFs are evaluated, and the motivations that lead to a different paths for CDFs derivation are highlighted.

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1. Introduction

[2] As far as some environments are concerned, nonstructural policies for flooding defense have established themselves as an absolute necessity. For instance, in the case of the Mediterranean, the orography is particularly high near the coast. Many relevant settlements, throughout history, have been developing highly complex urban areas in the rare terminal planes [*Ferraris et al.*, 2002; *Siccardi*, 1996]. As a consequence, vulnerability reduction by restructuring the urban settlements is often impossible to be effectively applied for vulnerability reduction. Some classes of basins allow the use of traditional alert systems: rainfall observations and flood formation and propagation modeling are used to produce forecasts, which allow for the timely implementation of measures and procedures leading to human safety. In the case of other types of basins, either independent or nested within the above mentioned ones, the use of alarm systems, entirely based on measurements of both flow and rainfall rates, is, many times, limited by the very short times of the watershed response, which is often much shorter than the reaction times of a prepared population. Hydrometeorologists are then expected to predict with reliability and in a certain advance the future amounts of rainfall, so as to use them as forecasts for the modeling of river flows. An early alert, useful for the implementation of civil protection measures on a given territory, becomes, consequently, a real possibility.

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[3] For hydraulic infrastructures, it is, nowadays, a common professional approach to base their design on the evaluation of the return period, i.e., the inverse of the annual probability of the extreme event such infrastructures must curb. In the same manner for hydrometeorological alerts, decision support centers are expected to develop, on a shared basis, a procedure that refers to the exceedance probability estimates of dangerous effects. Such procedure is certainly more complex than the procedure used for infrastructures design [*Chow et al.*, 1988]. It must integrate, at the appropriate timescales and space scales, the uncertainty implied in the numerical weather forecasts, in their transformation into input for hydrological models and in the modeling of the catchment response.

[4] In the last few years there have been several attempts at the matching of meteorological models with hydrological models but they have sorted contrasting results [*Lin et al.*, 2002; *Bacchi et al.*, 2002]. Nowadays, however, scientists have reached, thanks to an increasing interest for the operational solutions originated from scientific issues, a good level of maturity and are fully aware that it is not possible to tackle such a problem in deterministic terms [*Krzysztofowicz*, 2001] (the scientific community has focused on such topics as demonstrated by the last EC call for indirect Research and Technologic Development programme (RTD) actions under the specific programme for research, technological development, and demonstration: Integrating and strengthening the European Research Area (*Official Journal of the European Union*, 2004/C 159/03, available at http://europa.eu.int/eur-lex/en/archive/2004/c_15920040616en.html)). Decision makers, final consignee of the forecasting procedure results, have realized the value of a forecast that includes the estimate of its uncertainty.

[5] This work intends to propose a new methodology for evaluating predictive cumulative distribution functions (pCDF) [*Krzysztofowicz*, 2001] of ground effects for flood forecasting in mountainous environments and encourage a discussion which might lead to a shared procedure. The ingredients of the methodology are probabilistic meteorological forecast, downscaling of rainfall and hydrological modeling. They have to be properly nested, taking into account the interactions between scales of the models and processes involved, in order to correctly evaluate pCDFs. Such chain must prove able to tackle and quantify the uncertainty associated to each individual ring of it and also the uncertainty associated to the matching of the models operating at extremely different time-space scales. It will also be shown how the uncertainty, originating from different scales, can influence not only the reliability of the result, but also the design of the forecasting chain.

[6] The methodology, analyzed in section 2, will be discussed using two examples describing different applications of the forecasting chain. Such examples use tools which are not the only ones available in the scientific world, but they identify a logical path which goes to make the background necessary to tackle the problem. Despite the present limits of such approach, many of which will be overcome by technological and scientific advancements, the use of a chain containing the described ingredients is often the only possible way to mitigate the impact of floods on environments similar to the Mediterranean one.

2. Forecasting System

2.1. Ensembles of Hydrometeorological Forecasts

2.1.1. Meteorological Ensembles

[7] Since 1992 the European Centre for Medium-Range Weather Forecasts (ECMWF) and the U.S. National Center for Environmental Prediction (NCEP) have been using the ensemble prediction system (EPS) as a main tool for the forecasting system. EPS has proved able to produce different future scenarios of numerical meteorological forecasts through the appropriate perturbations of the initial conditions of the global solving algorithm [*Buizza et al.*, 1999; *Toth et al.*, 2001]. At the ECMWF the perturbations of the initial conditions are based on the technique of singular vectors, organized so as to develop those ensembles presenting, at short-medium range, the maximum spread of results compared with a series of variables over an area of interest [*Buizza et al.*, 2003]. By applying such technique, the condition of a complete ensemble which does not include the representation of an extreme event in Europe, has occurred considerably less frequently than in the past when only a deterministic solution for future weather conditions was used.

[8] Each member of the forecasting ensemble forms a future numerical series of weather conditions, compatible with the set of the observed and assimilated initial conditions. It is still an open question whether the set of the members of the ensemble is to be considered a uniform sampling according to the probabilistic basis of events they represent. It may seem an irrelevant detail, but in sections 3 and 4 it will be shown how such detail is, in reality, of extreme importance for the development of an operational chain. As a theory allowing the evaluation of distribution of probability of the initial conditions is not available, meteorologists have, so far, accepted the fact that each member of a specific set may be considered equiprobable and, as reminded above, basing their evaluation on experience, they are led to think that such members considerably cover extreme possible events.

[9] Aware as we are of such limits, we have used [*Ferraris et al.*, 2002] the tool provided by limited area model (LAM) ensemble prediction system (LEPS) [*Molteni et al.*, 2001; *Marsigli et al.*, 2001, 2004], and we recommend its operational use (LEPS methodology is based on the reduction of the ensemble dimension; EPS members are grouped in clusters, and one representative member is chosen for each cluster; every representative member is used as initial and boundary conditions of a high-resolution LAM whose results generate LEPS). In fact, EPS techniques are the only way available today to describe in terms of probability the occurrence of an event of hydrological interest which originates from a specific member of the ensemble.

[10] Let us assume it is of interest, over a spatially determined time invariant area a_i, to know in terms of probability the volume of precipitation V_{ij} as forecast over an interval of time $t_j - \Delta t/2$, $t_j + \Delta t/2$. Let v^k be the consequent realization at the kth member of the set with probability p_k of occurrence: we accept that the random variable V_{ij} is, in terms of probability, distributed in such a way that $P[V_{ij} \le v^k] = \sum_{i=1}^{k} p_i$ where $k = 1, 2, \ldots n$; n number of members of the set; p_i the probability of occurrence of the ith member of the set; v^k the kth-ordered realization of the consequent n volumes of precipitation. If we accept the equiprobability of members, then $P[V_{ij} \le v^k] = k/n$.

[11] It is then possible to quantify what we named uncertainty of the scale external to hydrology [*Ferraris et al.*, 2002], indicated, in this work, as l_{met}: it can be defined as the lowest space-timescale over which $P\ [V_{ij} \le v^k]$ coincides with the real probability of exceeding the volume v^k. This is the same as saying that, if s identical worlds existed, with a very large s, as long as the random variable $\tilde{V}_{ij}$ were observed over the area a_i and in the interval $t_j - \Delta t/2$, $t_j + \Delta t/2$, it would be $\tilde{V}_{ij} \overset{d}{=} V_{ij}$, where $\overset{d}{=}$ stands for equality of the probability density functions (PDFs) of the two variables.

2.1.2. Getting Down to Hydrological Scales

[12] As the scale decreases, a second source of uncertainty emerges. It is due to the large difference between the solved meteorological scales and those of the hydrological models. Though solving algorithms of tridimensional atmospheric states can be used at a very fine scale, the boundary conditions are still dictated by the grid of global models. Being the knowledge of the atmosphere at the scale of LAMs scarce because of the limits of the observational network, the added information is provided by little more than random perturbations of the large-scale solution, perturbations substantially correlated with the orography, which is obviously described in more complete details [*Davies and Brown*, 2001].

[13] Whenever the external uncertainty is considered negligible, like some meteorologists still think, the rainfall intensities are usually not enough to create runoff due to slope saturation, within the time intervals flash floods take

to form. In order to produce precipitation fields consistent with hydrological scales, Hydrology must, then, disaggregate quantitative precipitation forecasts (QPF) in time and space. Such procedure must preserve the expected value and the statistic properties of the large-scale field. It must also introduce appropriate moments of the PDFs of the variable of interest at hydrological scales.

[14] A disaggregation model based on multifractal theory [*Deidda et al.*, 1999; *Deidda*, 2000] was developed and has been operative for some time. It is still used in this work. (The comparison, recently carried out by *Ferraris et al.* [2003] among different models of downscaling has not shown, though, the preponderance of a typology of model neither as capability of reproducing the statistic properties of precipitation nor in terms of efficiency and simplicity of calculation. The choice of the best model for the operational downscaling then falls back on the parameters and on their simplicity of evaluation in real time right from the forecast precipitation fields. A new model of disaggregation for the creation of precipitation fields at a small time-space scale, independent from the constrain of self-similarity and self-affinity [*Rebora et al.*, 2004] is now being made operative. In this work, however, all the examples are based on the procedure of multifractal disaggregation.) It basically consists of a probabilistic tool which gives the necessary piece of information about the uncertainty at the internal scale of hydrological processes.

[15] The disaggregation of precipitation fields in time and space needs the time variable to be consistent with space variables. In the multifractal disaggregation model an assumption of the scale behavior of the time process of precipitation is necessary, i.e. the process must be self-similar, or self-affine, at least over the range of scales of interest (the assumption of self-similarity corresponds to the extension to rainfall fields of the Taylor's hypothesis of frozen turbulence; such a hypothesis had already been put forward by *Zawadzki* [1973]). The time coordinate is rescaled as $\lambda\tau^{-1} \propto$ cost = U at every scale λ, where U is the velocity of advection of the dynamic field, as long as the process is accepted to be self-similar. Alternatively, every scale is rescaled with a velocity parameter $U_\lambda \propto \lambda^H$, where H is the scaling anisotropy exponent, which depends on the scale itself, as long as the process is accepted as self-affine [*Venugopal et al.*, 1999; *Deidda et al.*, 2004].

[16] What follows is a general description of the disaggregation process. As stated before, an area a_i (the l_{met} scale is just the diameter of the area a_i), for the members of a meteorological ensemble or for clusters of members with the same characteristics, must be singled out. This area a_i must be spatially determined and time-invariant. The volume of precipitation V_{ij}, on the area a_i, predicted in a $t_j - \Delta t/2$, $t_j + \Delta t/2$ time interval, must be known in terms of probability and considered reliable as $P\ [V_{ij} \leq v^k] = \sum_{h=1}^{k} p_h$, $k = 1, 2,\ldots n$ where n is once more the number of members or the number of clusters of the set. For each realization, the disaggregation, so as to reach the hydrological scale of interest, must be carried out, within time $\delta t = \Delta t\ \tau^{-1}$ and space δx, $\delta y = \Delta t\ U_\lambda \lambda^{-1}$, thus generating a considerable number, e.g., γ, of distinct series of Π_{mq}^k elementary volumes of future rainfall over the mth cell of the domain a_i, $m = 1, 2,\ldots\lambda^2$, for all the time scanning rate δt_q, $q = 1, 2,\ldots\tau$ filling the Δt interval (the hydrological scale l_{hydro} can be defined as the time-space scale below which the variability of the rainfall field is dumped by the process of integration due to morphological dispersion). Figure 1 shows an example of a disaggregated three-dimensional field.

[17] The probability distribution of the elementary volumes of precipitation over the mth cell of the domain a_i for all the time intervals δt_q is therefore conditioned by the occurrence of V_{ij}: $P\ [\Pi_{mq}^k \leq \pi^\theta | v^k] = \sum_{j=1}^{\theta} p_j$, where p_j is the conditioned probability of occurrence of the elementary volumes of precipitation π^θ, with $\theta = 1, 2,\ldots\tau$, as generated by the disaggregation process. Once the independence of the process of disaggregation from the meteorological event at large scale is accepted, the elementary volume of precipitation over an mth cell of the a_i domain, within the time scanning δt_q in the course of the jth time interval of the event, is, then, unconditionally probability distributed as follows:

$$P\left[\Pi_{mq} \leq \pi^\theta\right] = \sum_{i=1}^{k} \sum_{j=1}^{\theta} p_i p_j;\quad \theta = 1, 2, \ldots \tau;\ k = 1, 2, \ldots n \tag{1}$$

The ensemble of all the possible realizations of precipitation described in terms of probability at the spatial hydrological scale δx, $\delta y = \Delta t\ U_\lambda \lambda^{-1}$ and time hydrological scale $\delta t = \Delta t\ \tau^{-1}$ form an ensemble of hydrometeorological forecasts over the area a_i within the interval jth of meteorological forecast of amplitude Δt. The number of distinct pluviometric time series, variably correlated to one another, is obtained from the product of the number of n members that form a meteorological ensemble (nowadays n is of the order of 50–100 per day) multiplied by the γ number of distinct series of disaggregation (the authors' experience shows that $\gamma = 100$ has nearly always proved sufficient to sample in terms of probability the conditioned basis of events of the process of disaggregation), multiplied by the number λ^2 of the elementary spatial cells into which the area a_i, reliably covered by meteorological forecasts, has been discretized (a $\lambda = 100 \div 1000$ ratio is not uncommon). The examples described in paragraphs 3 and 4 show two significant results.

2.2. Basin Catchment Scales

[18] The application of the full hydrometeorological probabilistic chain is not needed everywhere on the concerned region. The scales of basin catchment, catchments which are objective of the ensemble of hydrometeorological forecasts, and, in particular, their ratios with meteorological and social scales, indicate the strategy to adopt in the forecasting process. Let us consider Figure 2. The abscissas show the ratio between the timescales of the response of catchment t_c and the timescale t_s of the social response of the flood risk prone areas near the outlet of the catchment. t_s is the order of magnitude of the time necessary to implement reliable safety measures (the timescale of the social response for the concerned area is reported in the civil protection plans and is of the order of 12 hours in most flood-prone urban areas. In some particular cases, for example, industrial installations, t_s can be much smaller). The ordinates show the ratio between the diameter l_{met} of

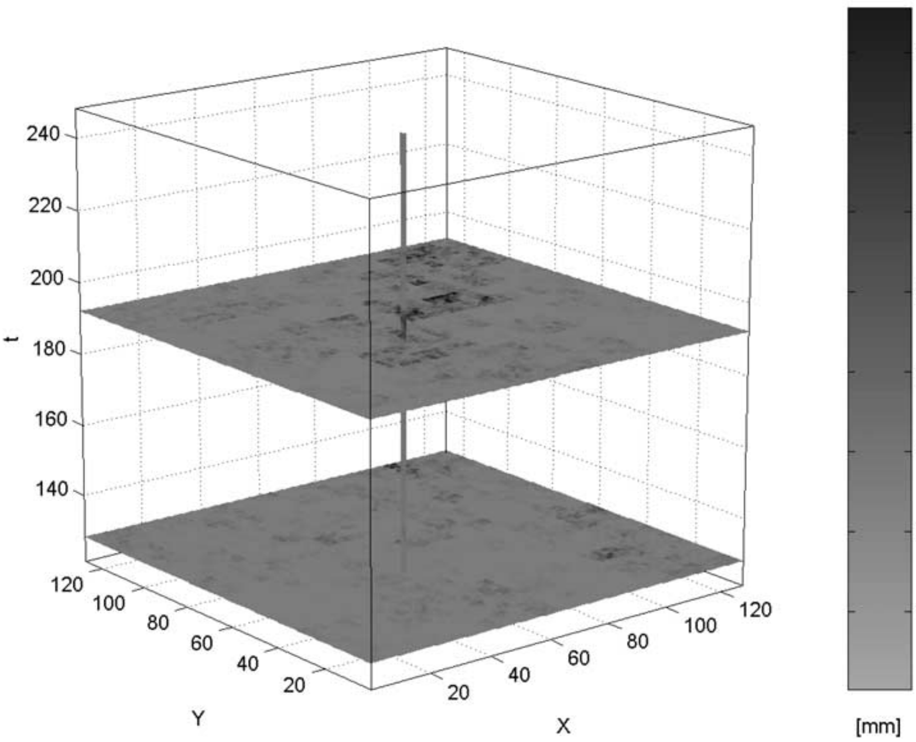

Figure 1. Output of a disaggregation in space (XY) and time (t). X and Y are expressed in grid coordinates and the grid spacing is 3 × 3 km; t is expressed in time steps of the model (each step is about 10 min). The different tones show cumulated precipitation in each individual time step (in mm).

the area a_i, for which the meteorological forecasts are considered reliable, and the spatial scale l_{hydro} of the catchment.

[19] For abscissa values of the order of $t_c/t_s = 2$ or larger, it is of no advantage to use weather forecasts: the hydrometric prevision can very well be based on the observation of the most appropriate precursors, say the observed precipitation on the catchment and, in some cases, the water levels observed in upstream sections, or both. In such a case the uncertainty associated to the forecast is only the hydrological one. Such an "internal" source of uncertainty, in most cases, it proves negligible in respect of the sources of uncertainty dealt with in paragraph 2.1.

[20] For the $t_c/t_s < 2$ the role of the ensemble of hydrometeorological forecasts becomes crucial. In fact, according to the value of the ratio $l_{\mathrm{met}}/l_{\mathrm{hydro}}$, the forecast may aim just at one outlet section only, as shown by point 3, or at a group of outlets, of adjacent or nested catchments, as shown by point 4. In any case, the flood peak at the section of interest is distributed in terms of probability: $P[Q > q_s] = 1 - F_Q(q_s)$, where $F_Q(q_s)$ is what we call "predictive CDF" [*Krzysztofowicz*, 2001] and q_s can assume the meaning of threshold flow rate on which a warning is conditioned. This is true whether it results from single hydrological models, when $t_c/t_s > 2$, or from hydrological ensembles, single-site or multicatchment, when $t_c/t_s < 2$. Whenever the exceedance of such value is feared, an alert must be immediately issued to the inhabitants at risk or to the infrastructure managers. The determination of the value of the exceedance probability of the threshold (procedure which assumes the role of operational rule for issuing alerts) is to be jointly addressed by the peripheral autonomous systems and by the central systems of civil protection.

[21] Figure 2 identifies also a region where it would be possible to feed hydrological models directly with the results of meteorological models, without the necessity of using stochastic procedures for rainfall downscaling. This is possible when the scale l_{met} is considerably smaller than l_{hydro}. In recent times many improvements have been done to lower the value of l_{met} but still limits are present, especially if operational use is considered. The dashed area limited by the hyperbole-like curve in Figure 2 identifies a domain that nowadays can be considered undefined, because of technical and scientific limitations in reliably forecasting precipitation on small scales in terms of both value and localization.

3. Example 1: Single-Site Forecast

[22] In the first example of probabilistic forecast, a basin (the Tanaro River at Montecastello) where the ratio t_c/t_s is less than 2 is considered. According to the conceptual scheme presented in Figure 2, it becomes necessary to turn to a set of hydrometeorological forecasts. The area of this basin (a = 8000 km^2) determines the size of the hydrological scale l_{hydro} which turns out to be a little less than 90 km. If the "external scale" is of the same size or just a bit larger (i.e. $l_{\mathrm{met}}^2/l_{\mathrm{hydro}}^2 < 10$), the single-site forecast becomes, then, possible. The prevision of extreme hydrological events must therefore be carried out starting with the probabilistic rainfall fields, forecast through a system of meteorological ensembles. In such a way, it becomes possible to associate

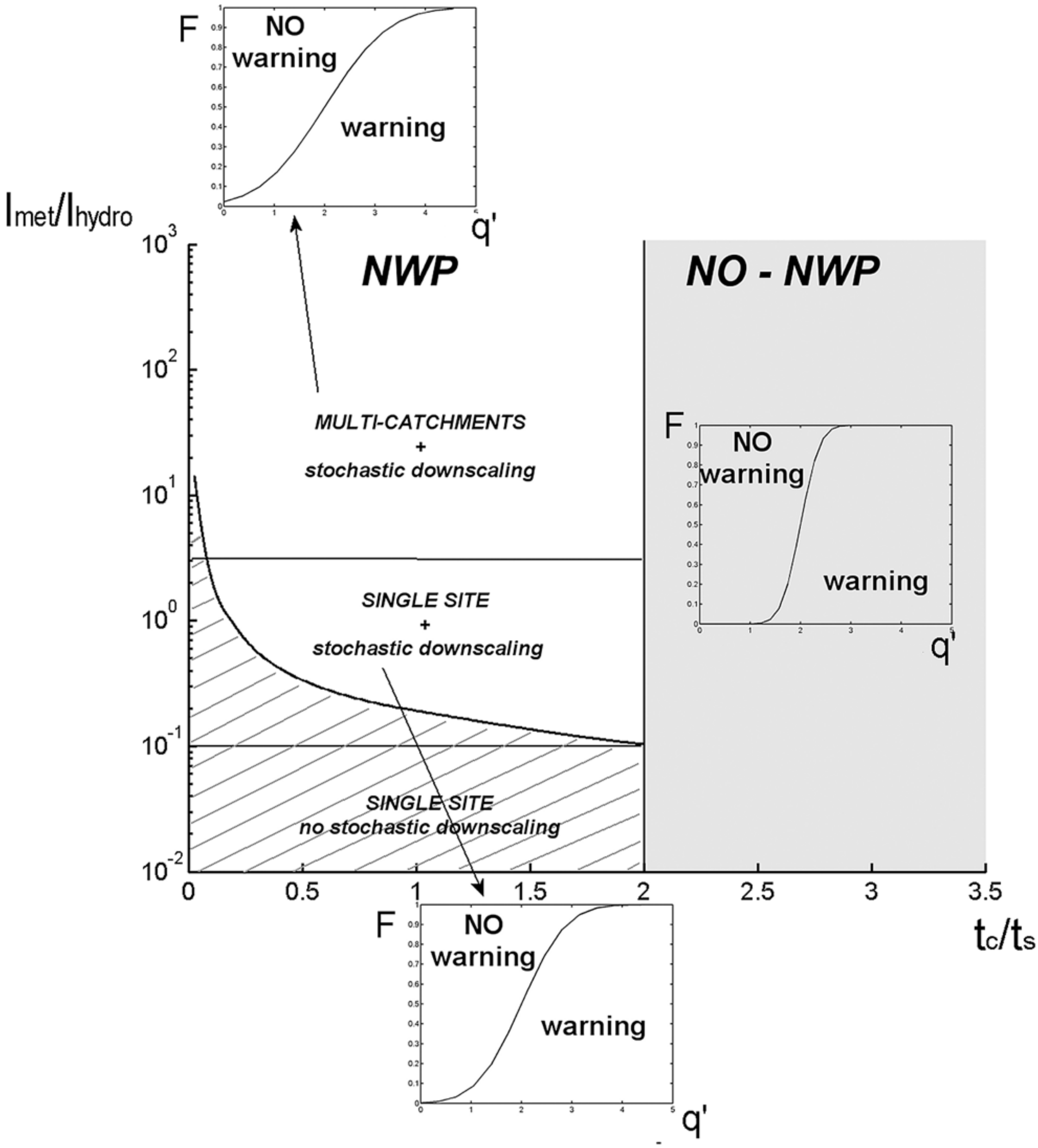

Figure 2. Different methodological approaches to use when producing hydrometeorological ensembles useful for civil protection procedures of alert at the varying of the scales of the processes involved. The variable t_s is the timescale of the social response of a population informed of a possible oncoming flood, t_c is the timescale of response of the analyzed basin, l_{met} is the space scale at which rainfall processes are satisfactorily represented by meteorological models, and l_{hydro} is the space scale that describes the analyzed hydrological basins. NWP, numerical weather prediction.

to each individual forecast a degree of likelihood to use as estimator of the probability of occurrence or of the degree of the uncertainty of the "external scale". The evaluation of the ground level effects is obtained by disaggregating each field of forecast rainfall into a consistent number of equiprobable scenarios at the small-scale δx, $\delta y = \Delta t\, U_\lambda \lambda^{-1} \ll l_{\mathrm{hydro}}$ and using each one of them as input for a rainfall-runoff model. Such procedure allows the evaluation of probability of exceedance of the peak flow. What follows shows the result of the application of this procedure at a single site, through a simulation, described in detail by [*Ferraris et al.*, 2002] in their study of the flood that took

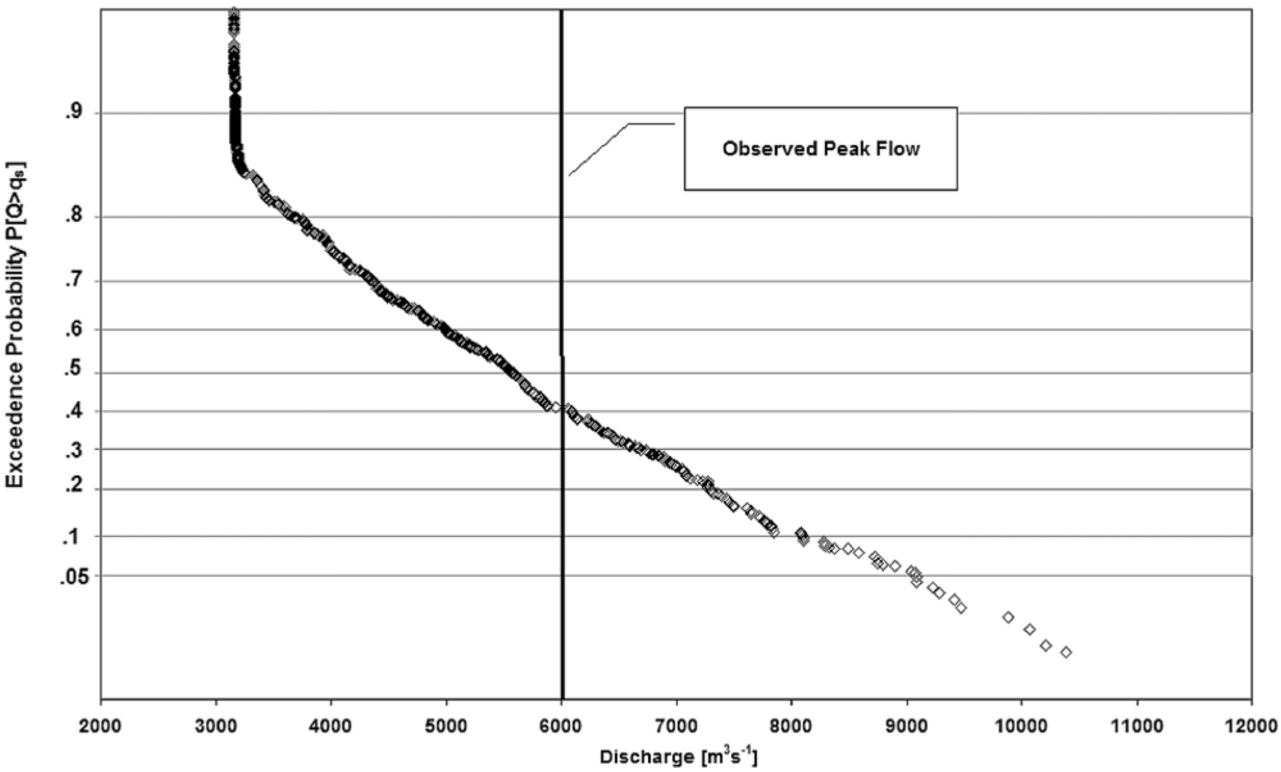

Figure 3. Function $1 - F_Q(q)$ estimated on the basis of the hydrometeorological ensemble, on probabilistic Gumbel chart.

place in the northwest of Italy between 4 and 6 November 1994. Five clusters of EPS members were obtained through the meteorological modellistic tool LEPS of the hydrometeorological service of the Emilia-Romagna region [*Marsigli et al.*, 2001]. The model of disaggregation used was the above mentioned multifractal one. The used external scale l_{met} was of the order of 300 km. The predicted velocity of advection of the rainfall field was of 12 m/s. The interval of time Δt was, then, equal to 24 hours. The elementary volumes of rainfall, obtained through disaggregation reached a scale $\delta x \delta y = \Delta t\ U_\lambda \lambda^{-1}$ of the order of 3 km with $\lambda = 100$. The hydrometeorological ensemble was formed by 500 hydrograms which resulted from the $\gamma = 100$ series of disaggregation of each one of the $n = 5$ meteorological clusters. Every flood hydrogram was obtained, with identical hydrological conditions, through the hydrological rainfall-runoff model DriFt [*Giannoni et al.*, 2000, 2003]. The predictive probability of exceedance of a generic threshold value q_s is equal to

$$1 - F_Q(q_s) = P[Q > q_s] = 1 - \frac{1}{\gamma} \sum_{k=1}^{5} \mu_k p_k \qquad (2)$$

with μ_k number of flood hydrograms whose peak flows did not exceed the threshold q_s for the kth cluster and p_k probability of occurrence of such cluster. Figure 3 shows the function $1 - F_Q(q_s)$ on the probabilistic Gumbel chart. The mark on the axis of the abscissas shows the peak flow estimated during the flood event. It is interesting to note that with $q_s \cong 4000$ m^3/s, which is an acceptable full-bank flow rate, the decision maker would have estimated, 24 hours before the event, a value of the probability of exceeding q_s of about 70%, and would have issued a warning.

4. Example 2: Multicatchment Forecast

[23] If the order of magnitude $O(l^2_{met}/l^2_{hydro}) > 10$ (superior mark on the axis of the ordinates in Figure 2) the single-site approach described in the previous paragraph must be changed.

[24] Like in the single-site procedure, the description of the rainfall process must be carried out through the disaggregation from the scale l_{met} to the scale δx, $\delta y = \Delta t\ U_\lambda \lambda^{-1}$.

[25] According to expression (1), the probability $P[\Pi_{mq} \leq \pi^\theta]$ is independent from the space-time position in the interval ($\Delta t\ U$, Δt) - position determined by the indices m and q. Therefore, by extracting in such time-space region from the rainfall fields, generated from v^k, two subsets, determined in unintersected subregions a_1 and a_2, for such subsets it is valid:

$$P^{a_1}\left[\Pi^k_{mq} \leq \pi^\theta\right] = P^{a_2}\left[\Pi^k_{mq} \leq \pi^\theta\right] \qquad (3)$$

A possible difference between the distribution of flood peak forecast for two basins, identical in terms of hydrological response b_1 and b_2 of l_{hydro} scale and belonging to the subareas a_1 and a_2, after the single-site forecasting procedure, must therefore be ascribed entirely to the variability of samples. Such variability is generated by the nonperfect description of all possible rainfall fields presenting one, and only one, total volume v^k at the scale l_{met}, which can be ascribed to the limited number of realizations. Therefore $Q_1 \overset{d}{=} Q_2$ holds, where Q_1 e Q_2 are forecast flood peaks for basins b_1 and b_2, respectively. The latter equation is equivalent to the definition of homogeneous region used in the procedures of analysis of frequency of the hydrological variables with a regional approach [*Boni et al.*, 2000]. Similarly, differences of the response, differences due to morphological peculiarities of hydrographic catchments of the l_{hydro} class, can be eliminated by following an approach similar to the approach used in the analysis of the regional frequency. By introducing the parameter "flood index," m_q [see, e.g., *Gabriele and Arnell*, 1991] derived from earlier statistic studies of peak flows, the following is valid:

$$P\left[\frac{Q_i}{m_q^i} > q_s'\right] = P\left[\frac{Q_j}{m_q^j} > q_s'\right] = 1 - F_{Q'}\left(q_s'\right) \tag{4}$$

where q', Q' are the growth factor of the peak flow, expressed in units of flood index; m_q^i, m_q^j are the flood index of two generic catchments b_i, b_j, i, $j \in [1, \nu]$, ν is the numerosity of catchments of class l_{hydro} and q'_s is a generic nondimensional threshold value expressed again in terms of units of flood index. Similarly to the single-site approach, $1 - F_{Q'}(q_s')$ can be experimentally evaluated using the hydrometeorological ensemble for the region analyzed. In this case it is formed by 500ν hydrograms (if $\gamma = 100$ and $n = 5$, see previous paragraph). The predictive probability of exceedance of q_s' is, in this case, equal to

$$1 - F_{Q'}\left(q_s'\right) = 1 - \frac{1}{\gamma\ \nu}\sum_{j=1}^{\nu}\sum_{k=1}^{5}\mu_{jk}p_k \tag{5}$$

with μ_{jk} number of flood hydrograms whose peak flows did not exceed the threshold q'_s for the jth basin and for the kth cluster.

[26] However, the question the decision maker asks the forecasting expert, is not about the estimation of the pCDF $F_{Q'}(q_s')$, but it is about the probability, as far as regional catchment basins are concerned, of exceeding at least once the quantile q_s' generating remarkable ground effects. In fact the forecasting procedure does not allow to discriminate one spatial localization from another. Civil protection procedures must be activated in time as to implement the necessary measures of prevention for areas, where people either live or work, near the outlet section of catchments of class l_{hydro} within their area of competence. The probability $P_{Q'}(q_s')$ that, in at least one of the latter the peak flow with a growth factor q_s' is exceeded, in the case of statistical independence of the series of the peak flow, is given by

$$P_{Q'}\left(q_s'\right) = 1 - F_{Q'}\left(q_s'\right)^{\nu} \tag{6}$$

It cannot be true in this case, as basins that are adjacent and belong to the same class may have, as far as the same forecast is concerned, series of strongly correlated peak flows. In such case, the function $P_{Q'}(q_s')$ must be built experimentally with the series of maximum peak flows forecast for all catchment basins of class l_{hydro} in the area of scale l_{met}. Such series must, also, be made nondimensional with the flood index m_q^i, $i \in [1, \nu]$. The value expressed by equation (6) thus represents only the highest limit of function $P_{Q'}(q_s')$.

[27] Figure 4 shows the result of such method applied at the Liguria region for the class of watersheds with $l_{\text{hydro}} \cong$ 10 km during the November 1994 extreme event [*Boni et al.*, 1996]. The hydrometeorological ensemble was built similarly to the example of paragraph 3. In this case, $l_{\text{met}} =$ 300 km and, as said before, $l_{\text{hydro}} = 10$ km. Also here the elementary rainfall volumes obtained from the disaggregation reach a scale δx, $\delta y = \Delta t\ U_\lambda \lambda^{-1}$ of the order of 3 km, with $\lambda = 100$. The hypothesis for the application of the method of multicatchment forecast, as shown in Figure 2, is verified. The flood indexes were obtained through the hydrological rainfall-runoff model cited in the previous paragraph [*Giannoni et al.*, 2000, 2003].

[28] From the analysis of Figure 4 it is made evident how large in the difference originated from the wrong application of a single site procedure in a region where a large number of catchments belong to classes with $(l_{\text{met}}/l_{\text{hydro}})^2 > 10$. The lower curve (curve 1) denotes the probability of exceeding the quantile with growth factor $q_s' = q_s/m_q$, i.e., the threshold $q_s = q_s' m_q$ at the outlet section of a specified basin catchment of the region, belonging to the l_{hydro} class. The upper curve, curve 2, denotes the probability of exceeding the quantile with growth factor $q_s' = q_s^i/m_q^i$, $i \in [1, \nu]$, i.e., the threshold $q_s^i = q_s' m_q^i$ at the outlet section of at least one generic ith basin catchment of the scale l_{hydro} filling the region, under the wrong assumption that they behave independently from each other. The curve 3, in between, is calculated experimentally, with regard to the special event that has being studied and of the given class of catchments: in this case curve 1 underestimated the probability of getting at least one inundation event by 5 and curve 2 overestimated it by nearly 2, in the range $q_s' \leq 1.8$. This result is not typical only of the analyzed case. It represents a general result, as it can be shown through comparing equation (4) with equation (6). The difference between the probabilities is too high to be neglected, and so it requires to implement the correct multicatchment procedure when safety of human lives or properties are at stake.

5. Conclusions

[29] In this work an attempt is made to systematize a new methodology for the evaluation of predictive cumulative distribution functions (pCDF) of ground effects for flood forecasting in mountainous environments. The use of the approach here described is often the only possible way for the mitigation of flood impacts in all the environments, such as the Mediterranean Europe, where the scales of response of basins correspond to, or are inferior to, the times of the social response necessary for the implementation of measures of prevention.

[30] In such cases an alert system will have to operate by procedures based on estimates in terms of probability of exceedance of given thresholds. The forecast should be based on proper hydrometeorological ensembles. How to build up ensembles and how to implement a procedure is shown with reference to two examples describing recent extreme events in northern Italy. The first example deals with the case in which the ratio between the space scale l_{met}, at which rainfall processes are reliably predicted by the

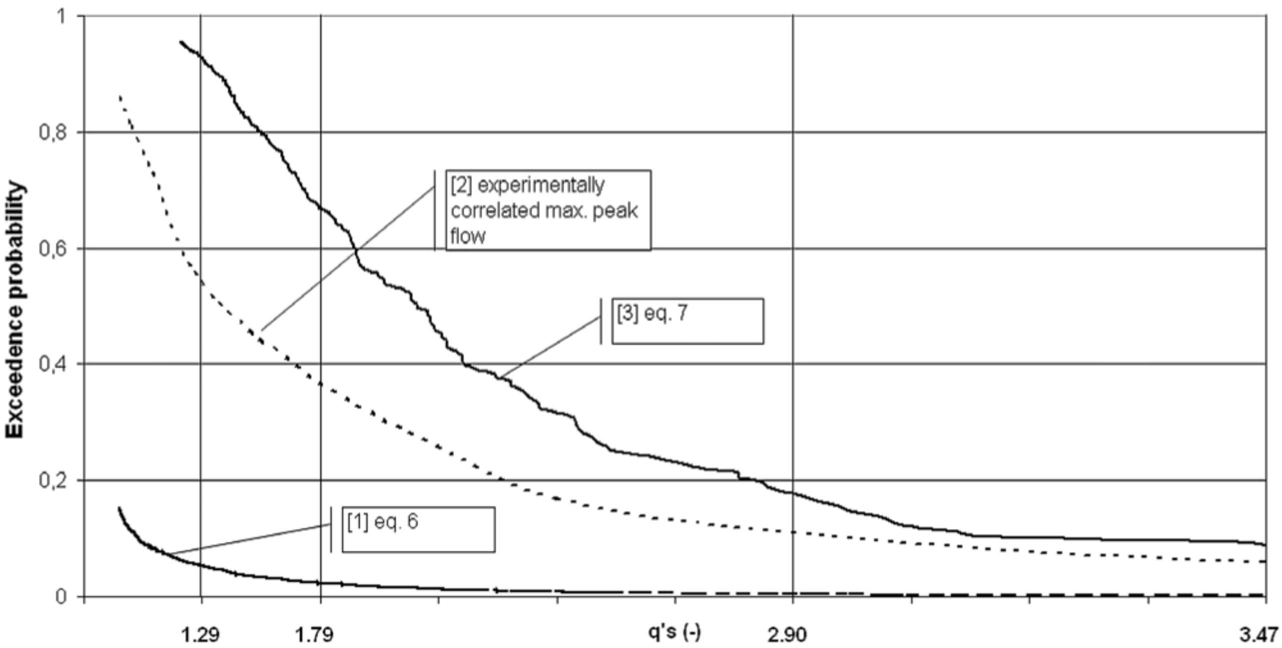

Figure 4. Exceedance probability of the quantile of maximum peak flows with a growth factor equal to q'_s. Curve 1 shows the probability of exceedance for a selected outlet section of a catchment belonging to class l_{hydro}. Curve 3 shows the probability of exceeding the quantile in at least one of the basins of that class, in case of a series of uncorrelated forecast maximum peak flows. Curve 2 is, though, similar to curve 3 for experimentally correlated maximum peak flows.

meteorological ensembles, and the space scale l_{hydro} of the basin are $(l_{\text{met}}/l_{\text{hydro}})^2 < 10$: we named it single-site procedure because it produces the exceedance probability of the peak flow in a given outlet section of the river under examination. The second example describes the case where $(l_{\text{met}}/l_{\text{hydro}})^2 > 10$: we named it multicatchment procedure because it produces the predictive exceedance probability distribution of the peak flow in at least one of the outlet sections of the catchment of size l_{hydro} in a given target region.

[31] The definition of the threshold q_s^i for the ith basin is matter of hydrological and river training experience and for this reason does not represent a critical issue in this context.

[32] The real critical issue is to establish the threshold exceedance probability upon which the issuing of a warning is conditioned: a low probability threshold would lead to a high number of false alarms, which have social and economical costs; a high probability threshold would lead to a high number unannounced events having impacts on the population and the infrastructures. Such crucial point is strictly connected with two basic concerns. The first concern regards the meteorological segment which models the processes: the open question in this case is the proper identification of the reliable meteorological space scale l_{met} from which forecasts may be disaggregated to the hydrological scale. The second concern is how to access, in real time, to a proper set of meteorological ensembles and to correctly transfer their individual probability of occurrence to the hydrologically relevant phenomena predicted at the scale l_{met}.

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