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Monitoring Network Optimization for Flood Forecasting and Warning Purposes

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ABSTRACT: The hydrological-hydraulic risk mitigation as well as the flood forecasting and warning activity require the knowledge of the main hydrological quantities and, hence, cannot prescind from observations. The distributed or semi-distributed hydrological models need detailed measurements and the new technologies (radar, remote sensing), providing spatially distributed information, have to be validated through ground acquisition. Therefore, a reliable hydrometeorological network is fundamental for Civil Protection activities, particularly for flood-prone areas where significant flooding events occurred in the past. The aim of the paper is to identify reliable procedures for streamflow, rainfall and thermometric networks optimization considering as case study the hydrometeorological network operating in an inlet Italian region (8400 km^2). As regards the streamgauge network, different criteria were adopted. At first, the real-time monitoring of each tributary with an area greater than 100 km^2 was guaranteed. Then, further stage control locations were defined considering the historical flood damages and, finally, the monitoring of incoming floods and releases from artificial reservoirs was finalized. The raingauge network optimization was investigated considering the precipitation spatial variability for different temporal aggregation scales. Using monthly data, geostatistical techniques allowed to identify the areas where the precipitation field was poorly represented by the existing network which, hence, was densified and checked at the daily time scale. Finally, the thermometric network was analyzed through the Kriging approach with external drift for considering the variability with altitude and redundant stations were identified using a cross-correlation analysis at hourly time scale. The proposed procedures provided a suitable and modular proposal for monitoring network optimization.

INTRODUCTION

The problem of the hydrological-hydraulic risk mitigation in the flood-prone areas is more and more felt on the Italian territory, like elsewhere in the world. In this contest, the knowledge of the main hydrological quantities is fundamental and depends on accurate data acquisition. The development of more and more complex hydrological modeling (spatially distributed or semi-distributed) requires data with high spatio-temporal resolution (Grayson and Bloschl, 2001). Moreover, the new technologies (radar, remote sensing), able to provide spatially distributed information, need to be validate with ground observations. On these bases, a reliable hydrometeorological network is essential within a reliable flood forecasting and warning system methodology which should identify the flood-threats in a timely manner such requiring on-line information on the basin hydrometeorological conditions. In this contest, the real-time rainfall data can be used for direct flood-threat recognition based on fixed rainfall thresholds or can be employed as input data for rainfall-runoff modeling. Analogously, the water level data acquired through the telemetering stations allow the direct identification of threat conditions through the comparison with pre-fixed thresholds or can be employed as input data for flood wave propagation models which can be part of the forecast modeling system or can be the system itself. As regards the thermometric measurements, they are fundamental data when the snow melting process can affect significantly the flood wave formation and also for evapotranspiration assessment within a water balance modeling for soil moisture estimation.

On these bases, reliable procedures for hydrometeorological networks optimization have been investigated for addressing the adequacy of the network operating on the territory of the Umbria region (~8400 km^2), located in Central Italy, in terms of component of a flood forecasting system. Different criteria and approaches were employed to study the streamgauges, the raingauges and the thermometric networks. In particular, the problem of streamgauges location was mainly addressed through empirical considerations, while the raingauges network adequacy

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was deeply investigated by geostatistical techniques (Rodriguez-Iturbe and Mejia, 1974; Bacchi and Kottegoda, 1995). Finally, the analysis of the thermometric network was carried out through the Kriging with external drift approach (Hengl *et al.*, 2003) and through cross-correlation analysis.

GENERAL CRITERIA FOR MONITORING NETWORK OPTIMIZATION

The identification of a set of criteria for hydrometeorological network adequacy assessment as a component of a flood forecasting methodology is a difficult task. However, reference approaches for addressing the improvement of an existing monitoring network can be very useful, particularly during the set up phase of the system itself. Obviously, the criteria to be applied should depend on the network type but also on the climatic conditions and on the territory characteristics and vulnerability. In particular, considering the more recent contributions on the monitoring networks optimization for flood forecasting and warning applications and the most widespread analytical methodologies, a set of criteria can be found out, as shown in Figure 1. Specifically, the optimization procedure can be identified through three steps: knowledge, empirical rules and analytical rules.

Knowledge

The characteristics of the existing monitoring network along with the territory and climate properties have to be considered to address the optimization of the monitoring network. The knowledge of territory (orography, geomorphological properties, urban and rural areas location) is fundamental since, for instance, the local orography governs the spatial distribution of precipitation over complex terrain. Moreover, information on historical flooding events could be a basic tool to optimize stations location for flood mitigation purposes. The appropriate spatial distribution of the measurement stations should also consider the location of urban and industrial areas adjacent to rivers and floodplains where a continuous water level monitoring should be carried out. The climate characteristics knowledge can also be very useful since the precipitation type influences the spatial resolution of the raingauges network.

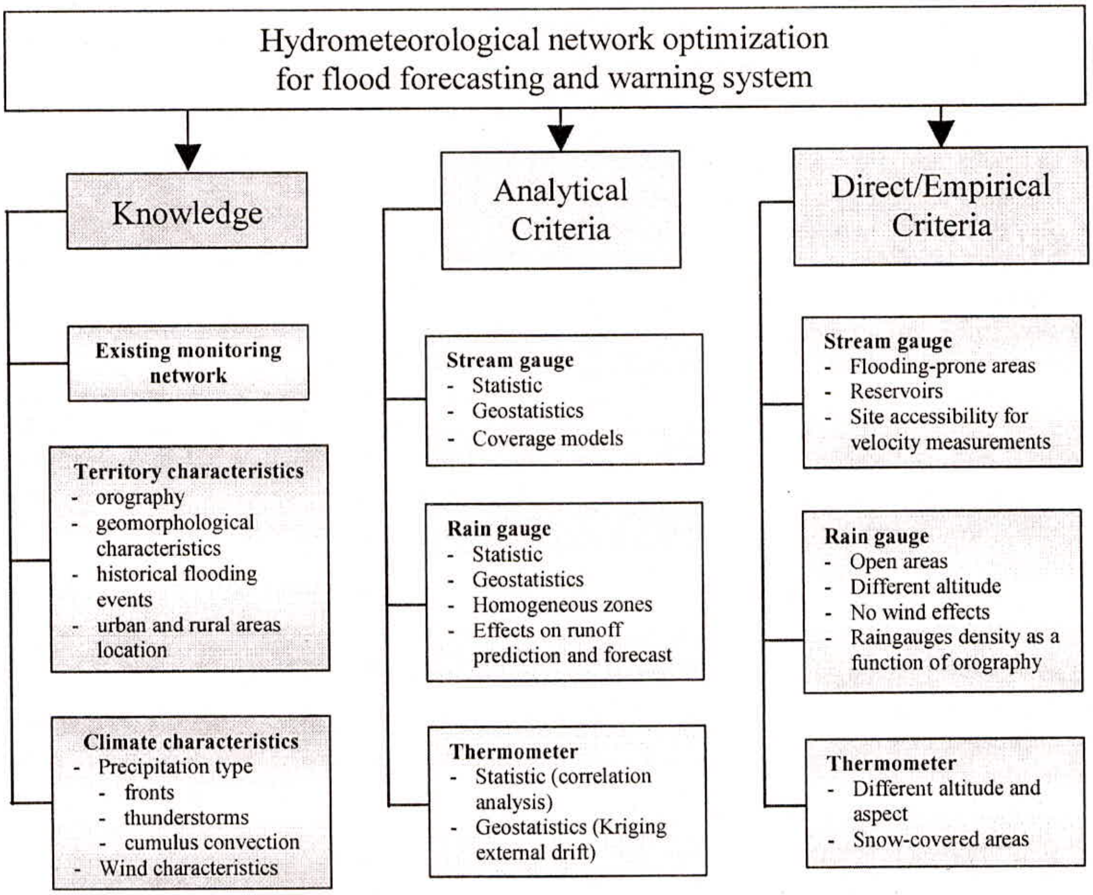

Fig. 1: Overview of the criteria for monitoring networks optimization

Clearly, optimization criteria based on the knowledge statement have to be integrated with a more deep analysis based on empirical approaches or more sophisticated statistics and/or geostatistical methodologies. The most widespread, summarized in Figure 1, have been selected from the scientific literature considering the different network types.

Empirical Rules

The problem of streamgauges location can be mainly addressed through empirical considerations. Obviously, a streamgauge has to be located at accessible sites and should monitor water level at appropriate sites upstream historical flooding prone regions, particularly when urbanized areas are involved, and upstream and downstream artificial reservoirs for incoming and released water volume monitoring.

As regards the raingauges network, the optimization criteria have to address the issue of accurate precipitation field assessment considering the orography and wind effects. At first, it should be verified if the number of raingauges and their spatial distribution are appropriate to provide reliable data for direct threat-recognition based on fixed rainfall thresholds and/or accurate inputs for discharge prediction through rainfall-runoff modeling. To this end, some empirical criteria can be adopted suggesting to locate the raingauges in open areas where the wind effect, typically causing underestimation of the rainfall rate, can be considered negligible. In complex topography areas, sensors at different altitudes should be installed for orographically induced rainfall effect monitoring. Obviously, the time step data acquisition (hourly, semi-hourly, etc.) should be consistent with the floods characteristics. As regards the spatial density, different authors have developed relationships for evaluating the number of sensors as function of basin area, topographical properties and climatic conditions. Specifically, the World Meteorological Organization (Linsley *et al.*, 1985) recommended a minimum spatial resolution of networks with general purposes depending on the topographical and climatic characteristics of the region (flat, temperate: ~30 km^2; mountain, temperate: ~13 km^2; mountain, convective: ~5 km^2; arid-polar: ~80 km^2).

When the snow melting influences significantly the flood formation process, the measure of snow water equivalent and air temperature becomes very important. Obviously, the estimate of surface runoff produced by snow melting can be part of a real-time control system since a sudden snow melting process can cause flooding making the temperature measurements fundamental in areas characterized by abundant snowfalls and very fast thermometric changes.

Of course, also the reliability of a thermometer network can be assessed through empirical criteria. In particular, the sensors should be located at different altitudes and also on the bases of the local topography, geomorphology, soil use, exposure to sunlight and presence of snow-covered areas.

Analytical Rules

The streamgauges network assessment and optimization can be based also on statistical approaches (Burn and Goulter, 1991), on clustering technique (Anderberg, 1973) used to identify groups of similar gauging stations, and on entropy-based methods (Bueso *et al.*, 1998; Lee, 1998; Mogheir and Singh, 2002) which allow to quantify the relative information content. Geostatistical methods (Moss, 1982; Tasker, 1986), most commonly based on the standard error in estimating regional discharge at ungauged sites (Villeneuve *et al.*, 1979), or coverage models (Drezner, 1995; Drezner and Hamacher, 2002), which deal with the network design as a facility location problem, can also be employed. Also for the raingauges network, the optimization can be based on statistical and/or geostatistical approaches. These latter (Rodriguez-Iturbe and Mejia, 1974; Bras and Rodriguez-Iturbe, 1976; Eagleson, 1967, Shih, 1982; Bacchi and Kottegoda, 1995) are mainly finalized to evaluate the spatial error distribution in estimating the precipitation field. Statistical methods compute the correlation coefficients by using the available data; otherwise, entropy analysis (Shannon and Weaver, 1949; Chapman, 1986; Al-Zahrani and Husain, 1998; Sarlak and Sorman, 2006) can be used at the purpose. An alternative approach, known as cluster analysis (Anderberg, 1973; Jolliffe, 1972), consists in identifying in the area of interest physiographical homogeneous zones and in locating in each of them at least one station. Finally, also the thermometric network optimization can be addressed through statistical approaches based on correlation analysis and geostatistics criteria as the Kriging approach with external drift (Bonaccorso *et al.*, 2002; Jedidi *et al.*, 1999).

ANALYTICAL CRITERIA

For sake of completeness, the basic theoretical background of the analytical methodologies employed for the analysis is following reported.

Geostatistical Approach

The mathematical basis is briefly described remembering that more details can be found in Journel and

Huijbregts (1978), Issaks and Srivastava (1989) and Goovaerts (1998). The geostatistical method assimilates the physical space-time variation of a hydrometeorological variable to a stochastic process. Each measurement $z(\underline{x})$ is thus interpreted as a particular realization of a random variable denoted $Z(\underline{x})$, where $\underline{x} = (x, y)$ identifies the spatial coordinates. The application of the Kriging technique allows to estimate the unknown value of the hydrological quantity, $z^*(\underline{x}_0)$, at the unsampled location $\underline{x}_0 = (x_0, y_0)$ starting from the knowledge of N neighbouring and contemporary observations $z(\underline{x}_i)$. The estimator $z^*(\underline{x}_0)$ is defined as a linear combination of the observed values (Goovaerts, 1998),

$$z^*(\underline{x}_0) - m^*(\underline{x}_0) = \sum_{i=1}^{N} \lambda_i \left[z(\underline{x}_i) - m^*(\underline{x}_i) \right] \quad \ldots (1)$$

where λ_i are the weight assigned to $z(\underline{x}_i)$ and $m^*(\underline{x}_i)$ is the mean of the variable $Z(\underline{x}_i)$. λ_i values are assessed requiring the estimator $z^*(\underline{x}_0)$ to be unbiased and optimal,

$$E\left[Z^*(\underline{x}_0) - Z(\underline{x}_0) \right] = 0 \quad \ldots (2)$$

$$Var\left[Z^*(\underline{x}_0) - Z(\underline{x}_0) \right] = \text{minimum} \quad \ldots (3)$$

Depending on the selected temporal scale, it is possible to surmise more or less restrictive stationary hypotheses for the stochastic process. In general, with larger time scales (i.e., annual scale) the second order stationary hypothesis as well as the isotropy, described by Delhomme (1978), is applied. However, in several applications a monthly or daily temporal aggregation has to be considered for which a less restrictive hypothesis is adopted consisting in the stationary of the first and second order moments for the increments of $Z(\underline{x})$ (Journel and Huijbregts, 1978; Isaaks and Srivastava, 1989), that is,

$$E\left[Z(\underline{x} + h) - Z(\underline{x}) \right] = 0 \quad \ldots (4)$$

$$Var\left[Z(\underline{x} + h) - Z(\underline{x}) \right] = 2\gamma(h) \quad \ldots (5)$$

where $\gamma(h)$ is the semivariogram function describing the spatial structure of the hydrological quantity and calibrated on the available experimental observations. This function is the central concept for geostatistical approach and can be estimated as,

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[z(\underline{x}_i) - z(\underline{x}_i + h) \right]^2 \quad \ldots (6)$$

with $N(h)$ the number of pairs of data points separated by a distance h. Since only the increments are supposed to be stationary, the semivariogram can increase indefinitely with increasing distances or it can stabilize around a limiting value, called the sill, equal to the variance of the data. The distance at which the sill is reached is called the range representing the extent of the zone of influence of an experimental point; at distances beyond the range, correlation between points are nil. The correlation length, directly linked to the range, is a measure of the spatial continuity of the variable. Finally, the nugget effect represents the semivariogram discontinuity at the origin due to micro-climate effects and to measurement errors, too. The empirical semivariogram is computed from the experimental data and then it has to be interpolated considering the most common theoretical functions. Then, the weights λ_i can be computed in different way depending on the statistical characteristics of the mean of the random variable. If the mean can be considered stationary in space, the model is called "*simple Kriging*" and equation (1) becomes,

$$z^*(\underline{x}_0) - m = \sum_{i=1}^{N} \lambda_i \left[z(\underline{x}_i) - m \right] \quad \ldots (7)$$

In this case, the weights, are assessed as the solution of the system,

$$\begin{cases} \sum_{i=1}^{N} \lambda_i \gamma(h_{ij}) + \mu = \gamma(h_{j0}) & \text{with } j = 1, \ldots, N \\ \sum_{i=1}^{N} \lambda_i = 1 \end{cases} \quad \ldots (8)$$

where μ is a Lagrange multiplier, h_{ij} is the distance between $\underline{x}_i$ and $\underline{x}_j$, h_{j0} is the distance between $\underline{x}_0$ and $\underline{x}_j$. When the mean of the variable cannot be assumed constant, the method is the "*simple Kriging with varying mean*" or the "*Kriging with an external trend*".

Cross-Correlation Analysis

Cross-correlation analysis is very useful for data at half-hourly time scale allowing to verify the redundant stations and is based on root mean square error, ε, and correlation coefficient estimation, ρ, defined as,

$$\varepsilon = \left\{ \frac{1}{N} \sum_{i=1}^{N} \left[T_i(\underline{x}_1) - T_i(\underline{x}_2) \right]^2 \right\}^{1/2} \quad \ldots (9)$$

$$\rho(\underline{x}_1, \underline{x}_2) = \frac{Cov(\underline{x}_1, \underline{x}_2)}{Var(\underline{x}_1) Var(\underline{x}_2)} \quad \ldots (10)$$

where $T(\underline{x}_k)$ is the observed values and N is the number of observations, while $Cov(\underline{x}_1,\underline{x}_2)$ is the covariance function and $Var(\underline{x}_k)$ is the variance function.

CASE STUDY

The criteria shown in Figure 1 were considered to assess the adequacy and to identify the optimization actions for the real-time hydrometeorological network operating in the Umbria territory (8400 km^2), located in Central Italy and characterized by a complex orography with elevation ranging from 200 to 800 m a.s.l. (see Figure 2). The existing real-time network belonging to the Umbria Region (UR) has been operating from several years through radio bridges. Moreover, a local recording meteorological network of the Italian National Research Council (CNR-IRPI) has been operating since 1987 in a portion of the territory. Other hydrometeorological data with lower temporal resolution are also available as from 1929, when the Hydrographic and Mareographic National Service (SIMN) started its activity in study area.

RESULTS

Results of the hydrometeorological network optimization were listed subdivided for network type: streamflow, rainfall and thermometric network.

Streamflow Network: Analysis and Optimization

The streamflow network of the Umbria Region, mainly addressed to flood forecasting and warning purposes, is made up of 59 real-time stations and 5 local-recording stations. Figure 2(a) shows the location of the streamgauges, well distributed along the main rivers. The network adequacy was assessed through different criteria. First of all, each main tributary of the Tiber River with a drainage area greater than 100 km^2 has been checked in terms of monitoring and the redundancy of data acquisition and gauging stations was verified. Then, considering the historical flood information the flooding-prone areas to be monitored were selected and, finally, the monitoring of inflows and outflows at the main artificial reservoirs was ensured considering their significant role within a real-time flood warning system (Guo *et al.*, 2004; Kundzewicz and Xia, 2004). On the whole, the

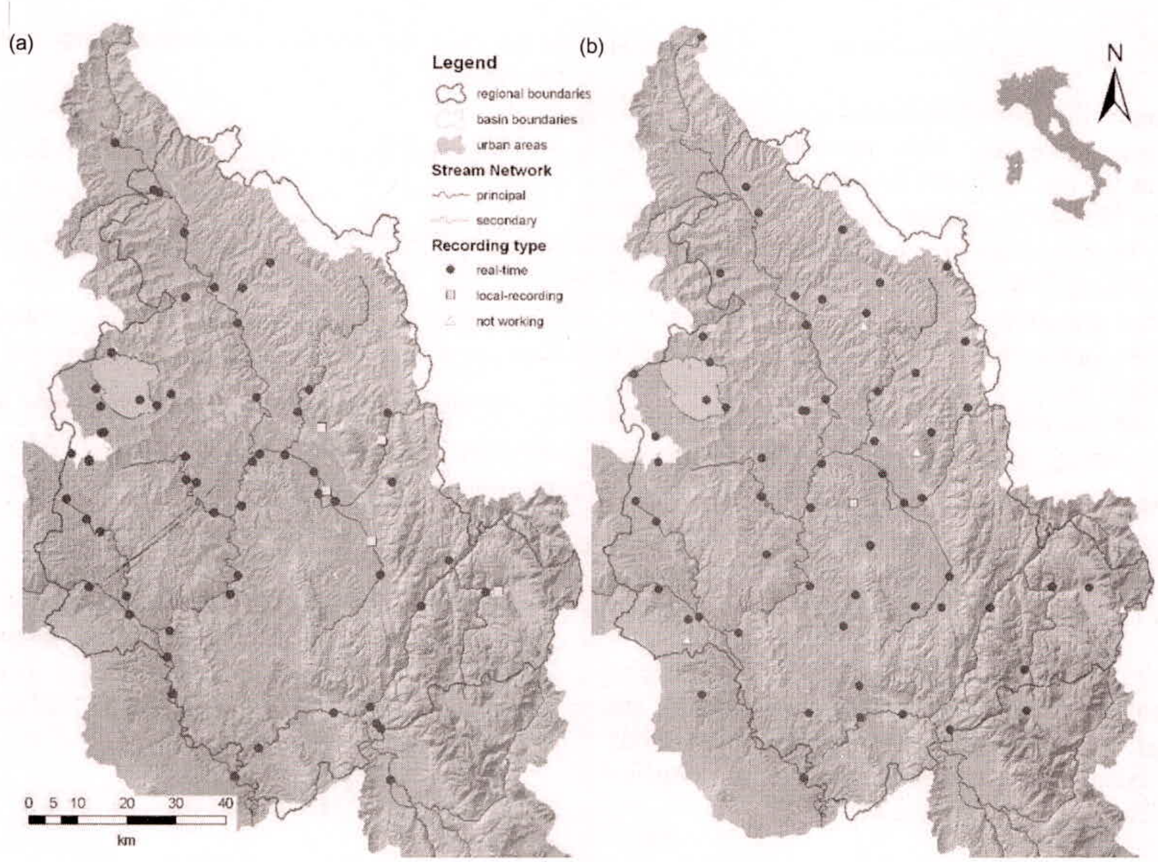

Fig. 2: Tiber River basin and Umbria region territory: morphology and (a) streamflow network, (b) raingauge network

streamflow network was found appropriate for flood prevention and warning purposes, except for the areas crossed by a tributary, the Marroggia river, where flash-flood events are typically caused by intense and short duration rainfall events.

Based on the previous analysis, the optimization of the hydrometric network requires some actions with different priority level: addition of 13 new gauges and removal of 2 useless stations, conversion of 2 gauges from real-time to local recording and control of 7 existing measurement sites. The optimized stream-gauges network will consist of 75 stations.

Raingauge Network: Analysis and Optimization

The existing raingauge network consists of 60 real-time stations and 2 local-recording gauges (see Figure 2b), operating since 1988, with a mean density of 1 station per 140 km^2. As well known, the uncertainties in precipitation information affects significantly flood simulation and prediction results making the selection of a reliable network a fundamental issue within a real-time flood forecasting and warning system. In particular, the spatio-temporal variability of rainfall field was investigated for various temporal aggregation scales keeping in mind that for flood forecasting and control purposes the daily and sub-daily temporal scale is essential, particularly when short hydrological response times are of concern. The analysis was addressed to verify the existing network reliability in representing the rainfall field through the geostatistical approach and considering also the historical raingauges operating since 1929.

The study considered, at first, the monthly time scale because of the more easily identifiable correlation structure and the higher number of available data. The geostatistical methodology allowed to determine the standard error estimation of the rainfall field, indicated henceforth as 'estimation error', expressed as the root square of the Kriging variance and linked to the network density and its distribution on the territory. In particular, for the present study the simple Kriging was adopted. The obtained results were verified at the daily time scale for a limited area of the region (Chiascio river basin) where the dense raingauge network belonging to CNR-IRPI is located.

The availability of a dense rainfall network with a high time resolution allowed an accurate geostatistical analysis through three main steps. During the first step, the mean of the monthly precipitation recorded in November for the period 1989–2001 was considered. The rainfall field obtained through the Existing Network (EN) of the UR was compared with that derived from the Historical Network (HN), consisting of the raingauges belonging to UR, CNR-IRPI and SIMN with a density of 1 raingauge every 70 km^2 (see Figure 2(b)). In this way, it was possible to compute the "real" error for the existing configuration and, to identify the stations to be added through a threshold error. The comparison was based on the prediction error computed as $\varepsilon_p = |p_{EN} - p_{HN}|/p_{HN}$ where p_{EN} and p_{HN} is the rainfall estimated at the same location with the existing and historical network, respectively. Figure 3a shows the spatial distribution of ε_p for the EN. Assuming a threshold of 10%, the historical stations to be added to the EN network were selected through an iterative procedure. The optimized network so identified, shown in Figure 3b, needs the addition of 23 stations.

The second step concerned the areas where rainfall information is not available. Specifically, the classical Kriging procedure was adopted to compute the map of estimation error of the design network derived in the first step. The Kriging approach was applied considering 3 different semivariograms for 3 identified "homogeneous" regions (mountain, hilly and plain) shown in Figure 4(a). The statistic analysis showed that the mountain areas have the highest rainfall mean value along with the highest variability. The computed semivariograms, shown in Figure 4(b), pointed out the different behaviour of the 3 regions and, in particular, the lowest variability for the plain and the highest for the mountain. The ungauged areas were selected and the addition of other 13 stations was designed taking account of the network purpose and in order to reduce the estimation error. Figure 5 shows the comparison between the estimation error map for the design network of the first step (5(a)) and for the optimized network identified in the second step (5(b)).

The last step was aimed to verify the design network at the daily time scale for the area of the Chiascio basin characterized by more detailed pluviometric observations (1 raingauge every 33 km^2) and a complex topography. The comparison between the rainfall field obtained from the historical stations (56 raingauges) and the existing network (29 raingauges) was performed considering 4 events with a significant total precipitation. Results obtained in terms of error spatial distribution were similar to the monthly time scale case, highlighting a systematic error in two areas where 2 further gauges was designed. Finally, the restoration of 2 historical stations was decided as well as the addition of 2 stations for reservoirs monitoring.

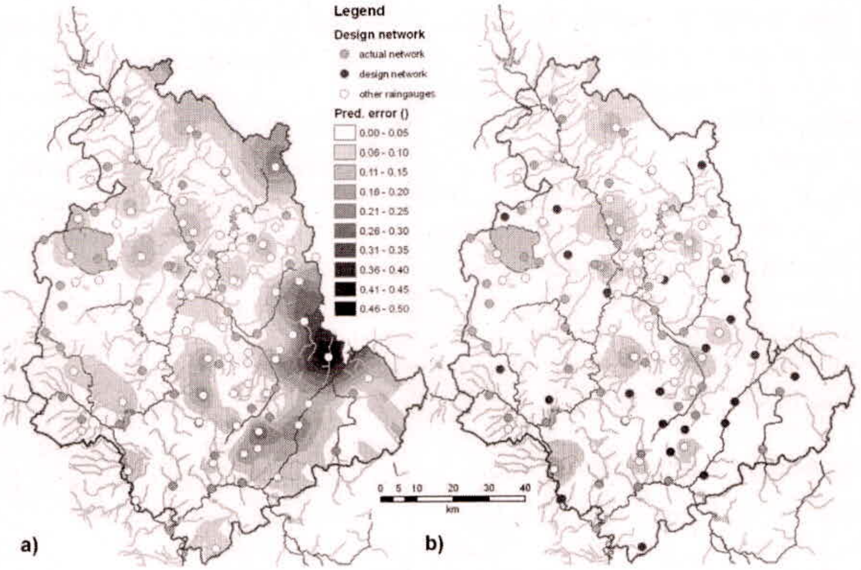

Fig. 3: Prediction error map for rainfall field obtained through the: (a) existing, and (b) first step design network. The benchmark rainfall field was obtained with the historical network

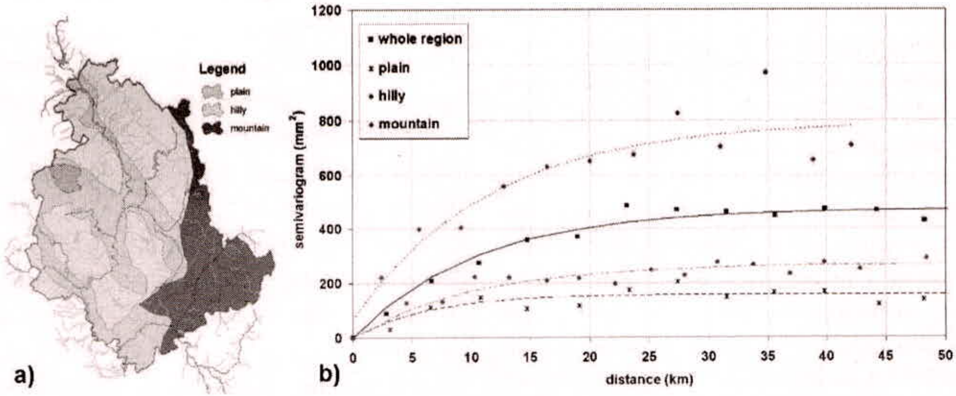

Fig. 4: (a) "homogeneous" areas in the Umbria Region; (b) theoretical (lines) and empirical (points) semivariograms for monthly rainfall

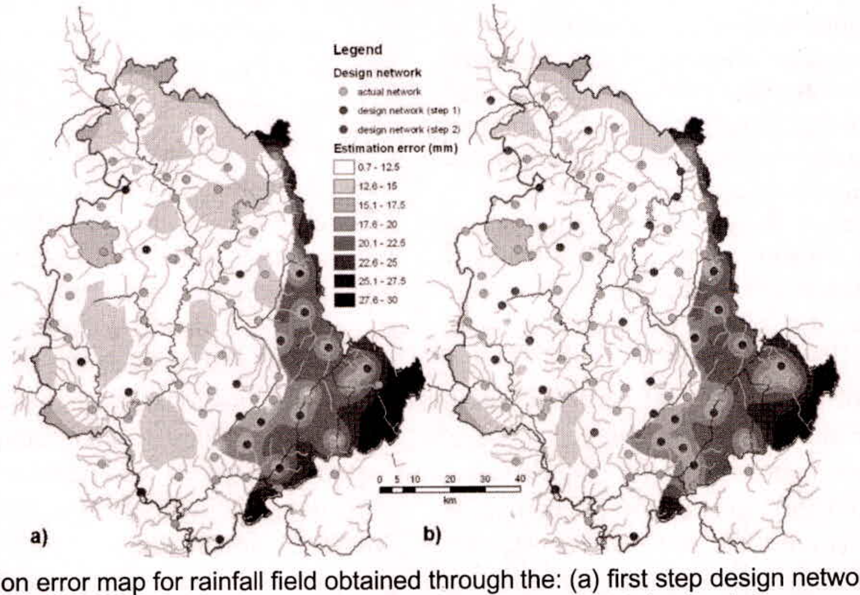

Fig. 5: Estimation error map for rainfall field obtained through the: (a) first step design network (optimization on historical network), and (b) second step design networks (optimization for ungauged areas)

On the basis of the previous analysis, the optimized network was defined and shown in Figure 6(a). As it can be see, most actions are located in the eastern mountain area of the region. In particular, the design raingauges in the Upper Chiascio area (red set) will be very useful for flood forecasting and for monitoring the subtended basin of the Casanuova dam. Moreover, the raingauges located in the Marroggia floodplain (blue set) will be important both for the prone-area monitoring and for the imminent weather radar installation which requires a detailed ground rainfall information for calibration. Finally, the raingauges located along the Nera river (green set) will be useful for flood protection purposes.

Thermometric Network: Analysis and Optimization

The temperature measurement within a flood forecasting and warning system is important for snow melting and evapotranspiration estimate. The UR thermometric network is made up of 52 real-time stations and 1 local-recording station operating since 1988. The mean density of the network, not uniformly distributed, is 1 station every 160 km^2.The optimization analysis was carried out considering the capability of the existing network to describe the temperature field through a geostatistical analysis, a cross-correlation analysis and considering the historical data. The spatio-temporal variability of temperature field was investigated for various temporal aggregation scales. Specifically, the analysis was at first carried out considering the monthly and daily time scale using geostatistical approaches and, then, at the sub-daily time scale through a cross-correlation analysis. For modeling the soil-vegetation-atmosphere dynamics the last two temporal resolutions are required. As the temperature is linked to the altitude, their relationship was investigated through a linear regression considering the mean monthly temperature values for the period 1998–2001. As expected, a strong data fitting to the orography trend was found. As thermometric sensors are mainly located at low and middle altitudes, it can be inferred that the existing network is not suitable for snow melting estimate since in the region snow cover can be found typically above 1000 m a.s.l.

The Kriging approach with external drift (Hengl *et al.*, 2003) was adopted in order to avoid the trend linked to the strong correlation between temperature and altitude (Bonaccorso and Cancelliere, 2002). The map of estimation error was computed for the period of August since the maximum variability was observed during this month (Figure 7(a)). Moreover, the analysis at the daily time scale was carried out for August 21^{st}, 1998, which was the day with the highest variance (see Figure 7(b)). The monthly and daily error maps show a similar error pattern and allowed to identify the new monitoring locations on the basis of a fixed threshold error. In particular, 10 new sensors has to be added in the areas where new raingauges were also designed.

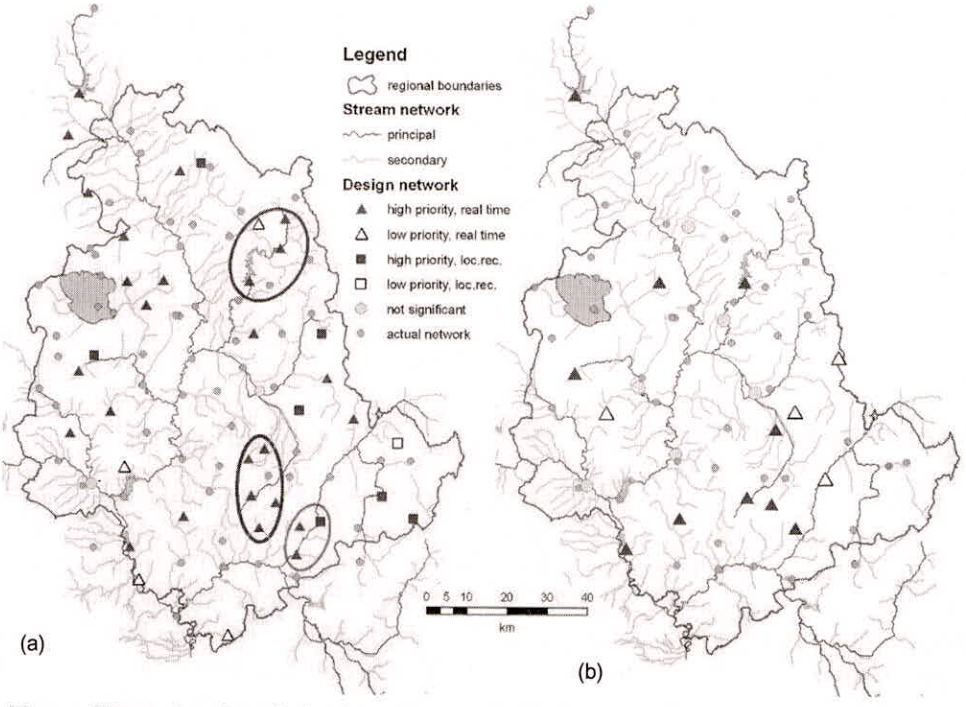

Fig. 6: Maps of the network optimization actions for the: (a) raingauge, and (b) thermometric ensors

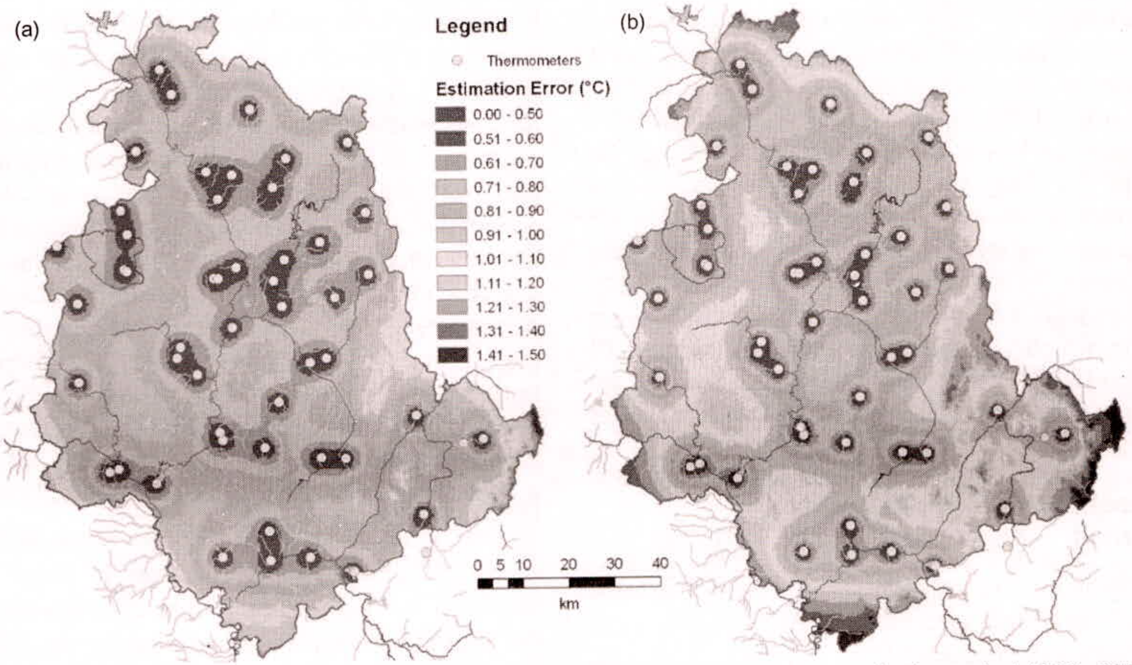

Fig. 7: Estimation error map for: (a) the mean monthly temperature of August in the period 1998–2001, and (b) the mean daily temperature of August 21st, 1998

The analysis was deepened considering both the mean, maximum, minimum daily temperature and the instantaneous (recorded every 30 minutes) values. In particular, for all these data the mutual correlation coefficient between all the thermometric stations for the 1998–2001 time series was computed. The correlation analysis allowed to group the station with high mutual correlation. For each group an investigation at the half-hourly temporal scale was carried out identifying 5 redundant stations to be removed. Finally, 4 stations for the reservoir monitoring were added whereas the historical information updating was guaranteed by the existing network. Moreover, it was verified that all historical stations operating in the region since 1951 were on-line working. The designed thermometric network is shown in Figure 6b consisting of 60 thermometers with a density of 1 station every 140 km^2.

CONCLUSIONS

The analysis of the Umbria Region hydrometeorological network was carried out with the main purpose to assess its adequacy as a component of a flood forecasting and warning system operating in real-time. In particular, the hydrological quantities (water level, temperature, rainfall rate) acquired through the monitoring network can be used for direct threat-recognition or, particularly for watersheds with short hydrological response time, can be employed as input for flood forecasting models. It was highlighted that rationalization and optimization actions are necessary in order to improve the network usefulness for different application fields. The approaches used for monitoring network analysis are based both on statistical and geostatistical approach (analytical criteria) and on practical criteria. The applied procedure allowed to identify the new required measurement sites and the redundant stations for the streamflow, rainfall and thermometric network. In particular, the combination of the analytical and practical approaches can be considered a robust procedure for evaluating the networks optimization within a reliable flood forecasting methodology which has to provide accurate and timely flood-threat recognition and warning dissemination. Moreover, as concerns the selected study area it has to be underlined that the suggested optimization actions can be very important to address the monitoring in the context of the activities of the Civil Protection Centre, operative in the region.

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REFERENCES

Al-Zahrani, M. and Husain, T. (1998). "An algorithm for designing a precipitation network in the south-western region of Arabia." *Journal of Hydrology* (205), pp. 205–206.

Anderberg, M.R. (1973). *Cluster analysis for applications.* Academic Press, New York, pp. 131–155.

Bacchi, B. and Kottegoda, N.T. (1995). Identification and calibration of spatial correlation patterns of rainfall. *Journal of Hydrology,* Vol. 165, 311–348.

Bonaccorso, B., Cancelliere, A. and Rossi, G. (2002). "Definizione delle reti di misura delle precipitazioni e delle temperature con l'impiego di tecniche geostatistiche." *28° Convegno di Idraulica e Costruzioni Idrauliche, Potenza 16–19 settembre 2002.* 465–476, (in italian).

Bras, R.L. and Rodriguez-Iturbe, I. (1976). "Network design for the estimation of areal mean rainfall events." *Water Resources Research* (12 [6]), pp. 1185–1195.

Bueso, M.C., Angulo, J.M. and Alonso, F.J. (1998). "A state-space model approach to optimum spatial sampling design based on entropy." *Environmental and Ecological Statistics* (5 [1]), pp. 29–44.

Burn, D.H. and Goulter, I.C. (1991). "An approach to the rationalization of streamflow data collection networks." *Journal of Hydrology* (122), pp. 71–91.

Chapman, T.C. (1986). "Entropy as a measure of hydrologic data uncertainty and model performance." *Journal of Hydrology,* (85), pp. 111–126.

Delhomme, J.P. (1978). "Kriging in the hydrosciences." *Advances in water resources* (1[5]), pp. 251–266.

Drezner, Z. (1995). "Facility location." *Springer Verlag,* Berlin.

Drezner, Z. and Hamacher, H.W. (2002). "Facility location: theory ad algorithms." *Springer Verlag,* Berlin, pp. 547.

Eagleson, P.S. (1967). "Optimal density of rainfall networks." *Water Resources Research* (3 [4]), pp. 1021–1034.

Goovaerts, P. (1998). "Using elevation to aid the geostatistical mapping of rainfall erosivity." *Catena,* Vol. 34, 227–242.

Grayson, R. and Bloschl, G. (2001). "Spatial modelling of catchment dynamics." In: *Spatial patterns in catchment hydrology.* Grayson, Bloschl, ed., 51–81.

Guo, S., Honggang, Z., Hua, C., Dingzhi, P., Pan, L. and Bo, P. (2004). "A reservoir flood forecasting and control system for China." *Hydrological Science Journal,* Vol. 49(6), 959–972.

Hengl, T., Geuvelink, G.B.M. and Stein, A. (2003). "Comparison of Kriging with external drift and regression-Kriging." *Technical note, ITC.*

Isaaks, E.H. and Srivastava, R.M. (1989). *An introduction to applied geostatistics.* Oxford University Press. New York. pp. 561.

Jedidi, K., Bargaoui, Z., Bàrdossy, A. and Benzarti, Z. (1999). "Optimization of rainfall network." *Proceedings of the 2nd Inter-Regional Conference on Environment-Water,* September 1–3, Lausanne (Switzerland).

Jolliffe, I.T. (1972). "Discarding variables in a principal component analysis, I: Artificial data." *Applied Statistic,* (21), pp. 160–173.

Journel, A.G., Huijbregts, C.J. (1978). *Mining geostatistics.* Academic Press. London. p. 600.

Kundzewicz, Z.W. and Xia, J. (2004). "Towards an improved flood preparedness system in China." *Hydrological Science Journal,* Vol. 49(6), 941–944.

Lee, J. (1998). "Constrained maximum-entropy sampling." *Operations Research* (46 [5]), pp. 655–664.

Linsley R.K.Jr., Kohler M.A. And Paulhus J.L.H. (1985). *Hydrology for Engineers. McGraw Hill,* London.

Mogheir, Y. and Singh, V.P. (2002). "Application of information theory to groundwater quality monitoring networks." *Water Resources Management* (16), pp. 37–49.

Moss, M.E. (1982). "Concepts and techniques in hydrological network design." *Operational Hydrology Report (19), World Meteorological organization report (580).* Geneva, Switzerland.

Rodriguez-Iturbe, I. and Mejia, J. (1974). "The design of rainfall networks in time and space." *Water Resources Research,* Vol. 10(4), pp. 713–728.

Sarlak, E. and Sorman, A.U. (2006). "Evaluation and selection of streamflow network stations using entropy methods." *Turkish Journal of Engineering & Environmental Sciences* (30), pp. 91–100.

Shannon, C.E. and Weaver, W. (1949). *Mathematical theory of communication.* University of Illinois press, IL.

Shih, S.F. (1982). "Rainfall variation analysis and optimization of gauging systems." *Water Resources Research* (18 [4]), pp. 1269–1277.

Tasker, G.D. (1986). "Generating efficient gaging plans for regional information." *In integrated Design of Hydrological Networks, Proceedings of the Budapest Symposium,* IAHS Publication (158), pp. 269–281.

Villeneuve, J.P., Morin, G., Bobee, B., Leblanc, D. and Delhomme, J.P. (1979). "Kriging in the design of streamflow sampling networks." *Water Resources Research* (15 [6]), pp. 1833–1840.