FLOODMED
Monitoring, forecasting and best practices for FLOOD Mitigation and prevEntion in the CADSES region

Flood Forecasting Issues for the Upper Tiber River Basin

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Contents

1 EXECUTIVE SUMMARY

The real-time hydro-meteorological monitoring, the rainfall spatial distribution, the initial wetness conditions of the basin are, here, investigated for getting an accurate flood forecasting assessment. The pilot area of the Upper Tiber river basin is considered at the purpose.

Specifically, besides to propose criteria for the hydro-meteorological network optimization, the monitoring approach to better catch the rainfall spatial distribution has been analyzed, emphasizing the reliability in estimating the rainfall field based on satellite data when heavy convective effects occur.

The characterization of soil moisture space-time variability is also addressed through an analysis of the Soil Conservation Service method applied to a small experimental basin of the Upper Tiber basin, where a plot for continuous soil moisture monitoring was settled up inside the catchment near the outlet. It was found that the well-known Antecedent Precipitation Index, API_5, is weakly correlated with the maximum potential retention, S, and used in a rainfall-runoff modeling could be cause of significant errors in representing the effective initial wetness conditions of the basin.

Finally, advantages in applying a Muskingum based stage forecasting model are shown for the pilot area in terms of both number of involved parameters and applied lead-time.

2 INTRODUCTION

Real-time hydrological forecasting is the prior action to minimize loss of life and injuries to people, loss and damage to property and disruption of normal activities caused by flooding. The steadily increasing of the damages due to flood and flash flood events, in terms of both number of casualties and economic costs, has led to heightened interest in flood forecasting systems.

A crucial component of these systems is the flood forecasting modeling which may include all or some parts of the following basic elements: observed meteorological data, hydro-meteorological analysis, meteorological forecast, rainfall-runoff modeling, hydraulic modeling and updating or error correction steps. As regards the possibility to provide a flood forecast useful for civil protection activities, two main factors are involved: lead-time and accuracy. The former, which represents the time between the time of forecast of an event and its occurrence, is fundamental for flood control and damage mitigation; the latter, represents the reliability of the forecasting in terms of magnitude and time of the flood peak and of the corresponding water level. Unfortunately, the need of greater lead-times is in conflict with the reliability of the forecast: longer lead-times, generally, imply forecasts of flood magnitude, location and timing less accurate. Since the amounts of data and the complexity of the modeling necessary to get a specific lead-time and accuracy is depending on the investigated basin, it is fundamental to analyze the adequacy of the real-time hydro-meteorological monitoring, the influence of the rainfall spatial distribution, the antecedent wetness conditions, the response time of the basin and river system.

The purpose of this paper is both to address the above issues for one of the pilot area of the FLOODMED project, the Upper Tiber basin in Central Italy, and to introduce a stage forecasting model for equipped river reaches.

3 THE UPPER TIBER RIVER BASIN

The pilot area is an inland basin, located in Central Italy, and characterized by a complex orography. The topography is mainly hilly with elevation above the mean sea level ranging from 200 to 800 m. The mountain peaks on a large portion of the boundary of the Upper Tiber basin, as well as on its sub-basin, range in elevation from 1000 to 1500 m above the mean sea level (see Figure 1). Mean annual precipitation over the basin ranges from 700 mm to 1600 mm. Higher monthly precipitation values generally occur during the autumn-winter period. It is this period during which floods, caused by widespread rainfall, normally occurred. The soil, overlying practically impervious rocks, is made up of clay and salty silt. The channel network of the basin has a regular structure, with Horton's numbers ranging within limits usually found in literature.

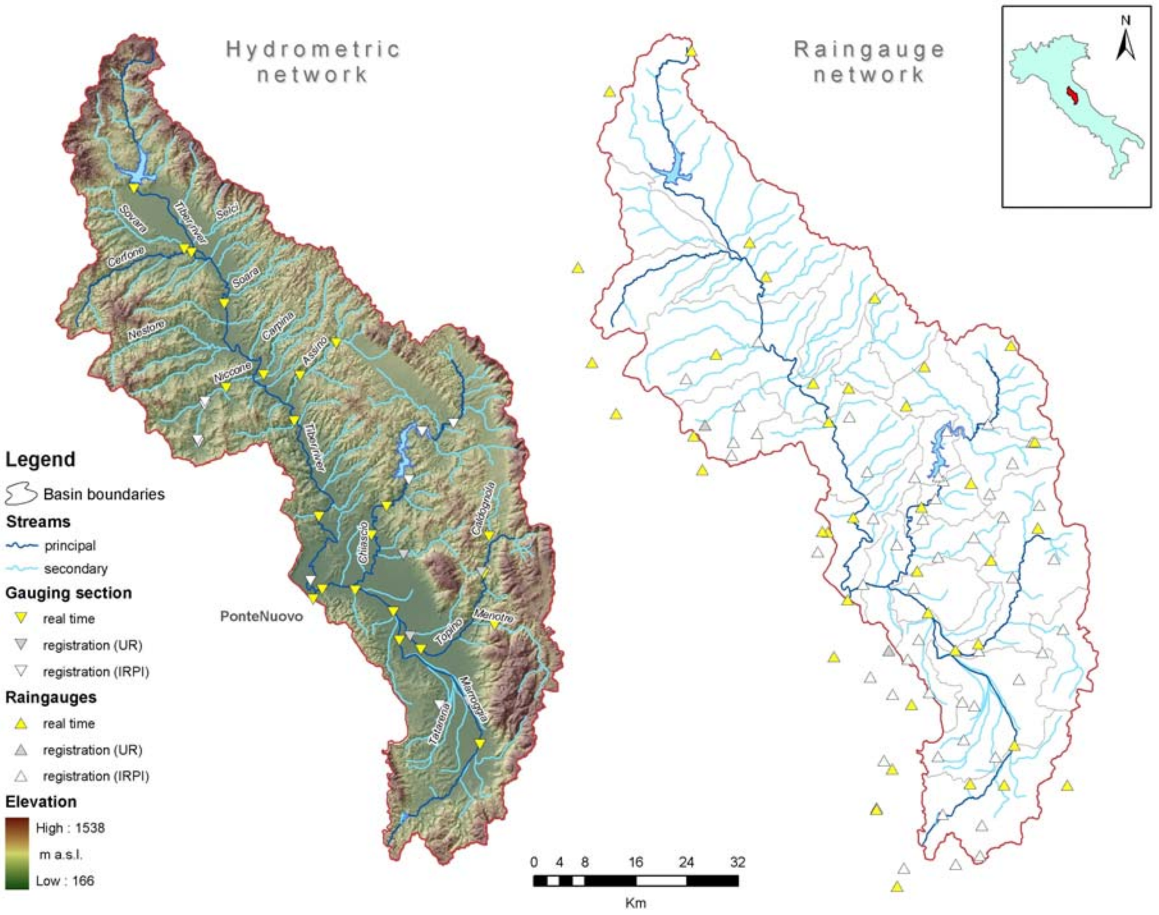

Figure 1 – Upper Tiber river basin: morphology and hydro-meteorological network.

In the pilot area of the Upper Tiber Basin a telemetering hydro-meteorological network has been operating since 1985. It is Umbria Region's property and, after successive integrations, at present is constituted by 22 hydrometers, 39 raingauges, 32 thermometers and 12 meteorological stations (see Figure 1).

A local-recording network of 9 hydrometers, 52 raingauges and 4 meteorological stations belonging to the Research Institute for Geo-Hydrological Protection (IRPI) has also been operating since 1987 with the aim to study the orographic effects on rainfall and the rainfall-runoff transformation at different scales. In particular, the raingauges and the meteorological stations were set up mainly in a portion of the Upper Tiber river basin of about 2000 km^2 characterized by a complex orography.

4 HYDRO-METEOROLOGICAL NETWORK OPTIMIZATION

Recently, an activity concerning the optimization of the telemetering hydro-meteorological network for the whole territory of the Umbria Region was performed, with the main purpose of flood warning and forecasting. The analysis was subdivided for sensor type: hydrometer, raingauge and thermometer, with particular attention on the streamgauge and raingauge network.

As regards the streamgauge network, different criteria were adopted. The first one guarantees the monitoring in real-time of the flood evolution for each of the main tributaries of the Tiber river. To this end, a hydrometric station for each tributary draining an area greater than 100 km^2 was fixed. Moreover, the flood damages historical archive (Guzzetti et al., 1994) has been considered to identify the portion of the river branches mainly subject to flooding in the past and, hence, that need to be integrated by a direct stage control. Finally, the monitoring of the inflows and outflows for the principal artificial reservoirs included in the basin was guaranteed in accordance with their significative role for the development of a flood warning system.

The raingauge network was deeply investigated analyzing the spatial variability of the precipitation pattern for various temporal aggregation scales (annual, monthly and daily). In particular, considering the monthly data, the use of the geostatistical techniques (Matheron, 1969; Goovaerts, 1998) along with the historical data let us to identify basin areas where the spatial precipitation field is poorly represented by the actual network. By way of example, Figure 2 shows the comparison between the errors obtained by the operating and the design raingauge network. In particular, the optimal network density different for the three considered topographic regions (mountain, hilly and plain) was obtained through the analysis of corresponding semivariograms. The verification of the network at the daily time scale was carried out for a specific area (Chiascio Basin) for which data were available. In terms of the error spatial distribution, the results were found analogous to those obtained at the monthly time scale.

The analysis of the thermometric network, which is useful for the long-time hydrological and climatic studies, was also carried out. For the temperature data, for which the spatial pattern was found more identifiable, the analysis based on the Kriging with external drift approach allowed to eliminate the trend linked to the strong correlation found between the temperature and the altitude. A cross-correlation analysis at the hourly time-scale was also performed to identify the redundant stations not useful for the definition of the spatial temperature field.

Finally, a verification of the historical stations operating in the region since 1929 was made to preserve their hydrological time series which were most important in reconstructing the rainfall-runoff characteristics of higher floods occurred in the basin.

The result of the above mentioned analysis might be considered a suitable and modular proposal for the network rationalization and extension in view of the development of a reliable flood forecasting and warning system addressed to Civil Protection purposes and hydraulic risk mitigation.

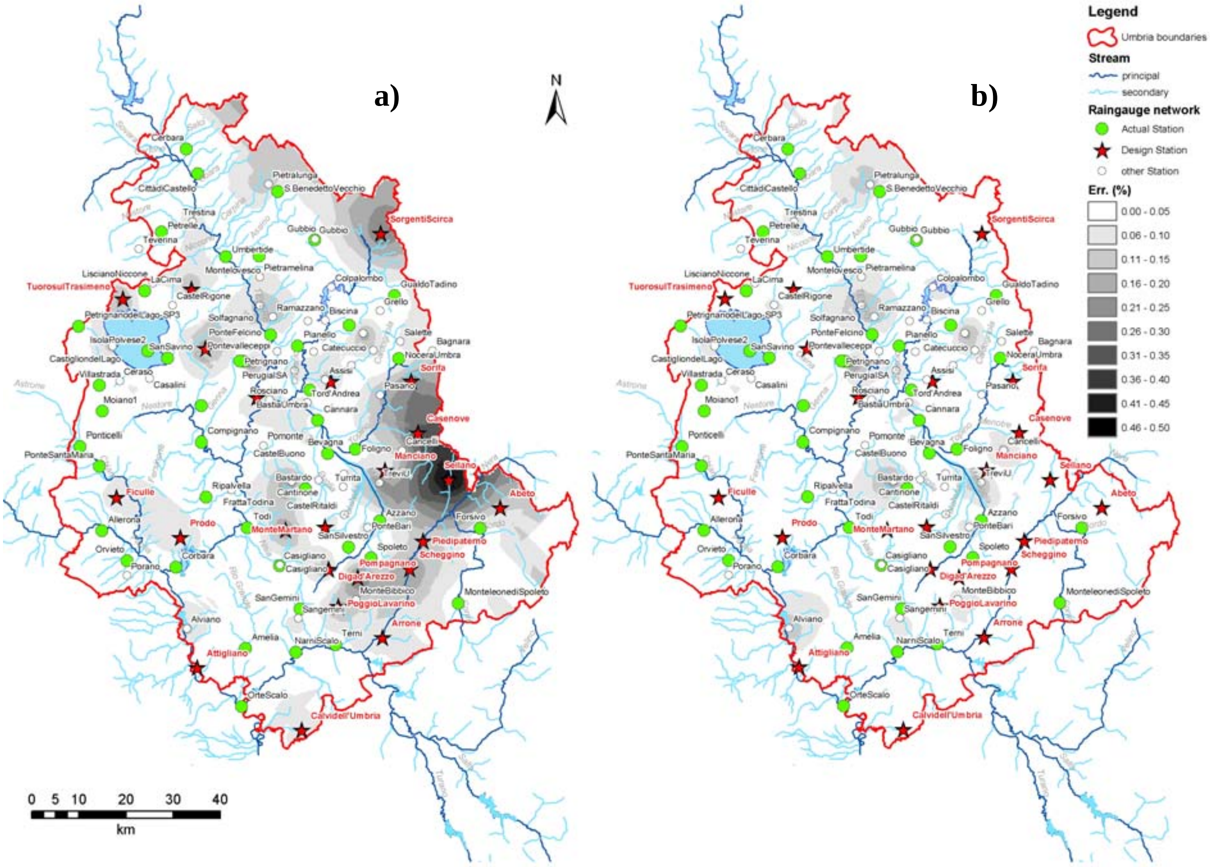

Figure 2 – Errors map obtained by: a) the operating raingauges network; b) the design raingauge network.

5 RAINFALL SPATIAL DISTRIBUTION EFFECTS ON FLOOD FORMATION

Spatial and temporal distribution of rainfall is one of the main factors affecting watershed runoff. For example, Michaud and Sorooshian (1994) showed that the error on the estimation of peak discharge may increase up to 58% for an inadequate raingauge network. Moreover, for real-time applications, mechanisms which produce flood-causing precipitation in a given basin determine the maximum forecast lead-time and dictate the data collection and modelling requirements necessary to achieve it.

In this context, it is important to take account of the many different types of precipitation which can occur in the basin of interest. Convective precipitations, very intense and localized, can cause flash flooding in very short times. Frontal or widespread precipitations, prolonged but usually not very intense, are associated with large flood in large river basins. The two precipitation types may also be combined into the stratiform precipitation pattern, with embedded convective cells. Moreover, in mountains areas the precipitation can be triggered or enhanced by the relief, causing the orographic precipitation. For cold front systems in an inland region (2000 km^2) of the Mediterranean area, the effects of hilly orography may cause an enhancement in storm depth up to a factor of 2.5 (Corradini and Melone, 1989).

Real-time monitoring of the convective and orographic precipitation is generally difficult through conventional ground based raingauge networks ought to their limitations related to their sparse and spot-like data distribution. Satellites on larger scale and weather radars on smaller scales are very useful tools offering fresh information each 5 and 15 minutes, respectively. The radar system besides being technically and economically onerous, may be unusable in areas characterized by a complex orography where the radar signal may be obscured. On the contrary, a potentially useful measurement system is based upon the analysis of clouds shown by geo-stationary satellites. In particular, with the Meteosat second generation sensors a potential exists for improved instantaneous rainfall measurements from space (Levizzani and Turk, 2002) by combining infrared (IR) observations with data of a limited number of raingauges. Moreover, the spatial resolution of satellite data guarantees, in principle, the detection of mesoscale convective systems and the localization of convective rainstorms responsible of most of the flash-flood events produced in the Mediterranean area (Llasat and Rigo, 2004).

The reliability of the estimation of the rainfall spatial distribution through IR-satellite imagery was analyzed indirectly by using a distributed rainfall-runoff model of conceptual type (Vélez et al., 2005). The model was implemented for an Italian basin covering an area of about 1000 km^2 and often interested by severe floods (Gabriele et al., 2006). Six 15-min time measuring raingauges and one 30-min hydrometer are available. Specifically, the flooding event occurred on November 2005 was simulated by the model with parameters estimated in advance through some flood events, characterized by a precipitation almost uniform in space, and with boundary forcing conditions represented by the rainfall field estimated through all the raingauges or through the satellite observations. In particular, the data of three raingauges were used for converting brightness temperatures into precipitation. As can be seen in Figure 3, the model with satellite derived precipitation estimated accurately the rising limb of the observed stage hydrograph whereas a delay of about four hours was obtained by using the raingauge network. The difference in accuracy can only be ascribed to the different rainfall fields. In fact, Figure 4 shows that satellite data exhibit a portion of the basin interested by heavy rainfall and located near the outlet determining a faster response. Unfortunately, the comparison of the two methods to estimate the spatial rainfall is limited to the rising limb because the hydrometer did not work in the peak region because of the distance between the water level and the ultrasonic sensor position which was less than 1 m, being it the minimum allowed.

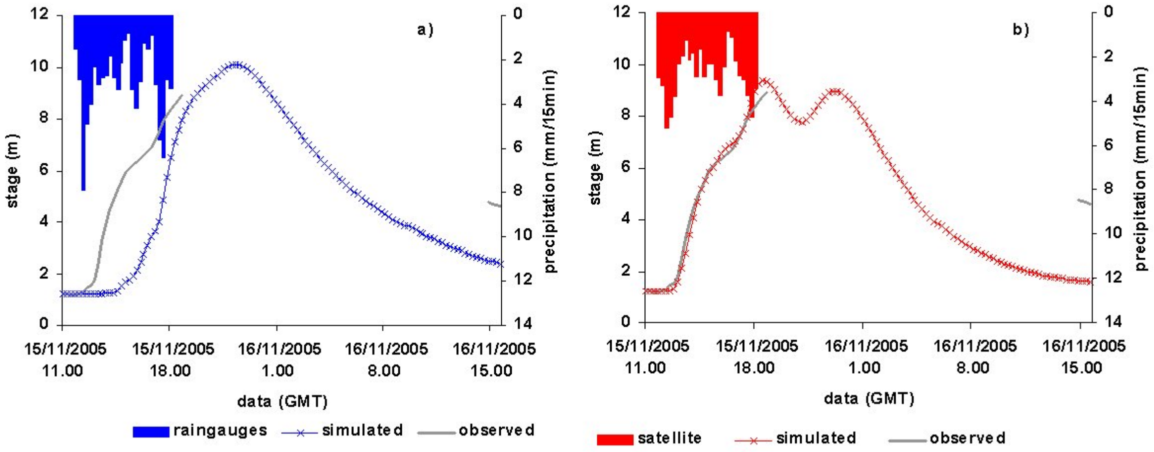

Figure 3 – Comparison of observed and simulated water level hydrographs for the events occurred on November 2005 with precipitation estimated by: a) remote sensing data; b) raingauge network.

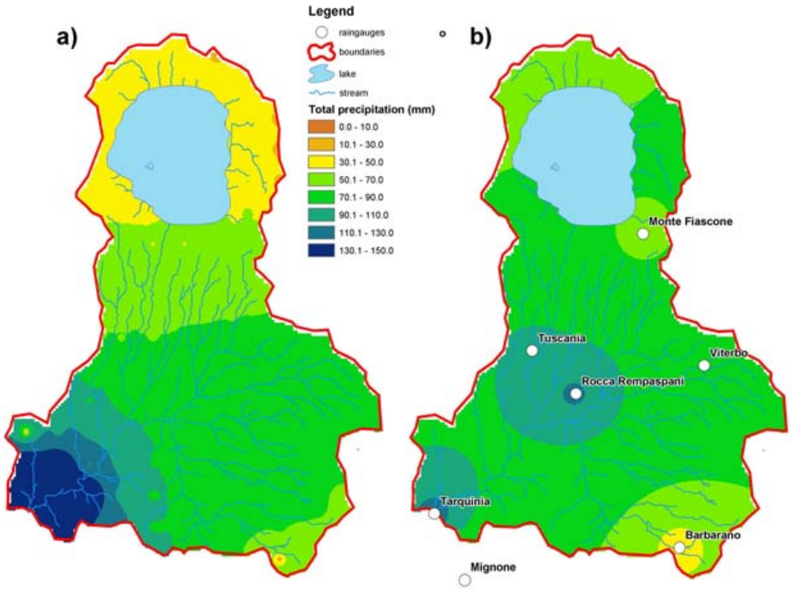

Figure 4 – Total precipitation map for the November 2005 event estimated by: a) remote sensing data; b) raingauge network.

6 ANTECEDENT WETNESS CONDITIONS ASSESSMENT

The characterization of soil moisture space-time variability is a fundamental issue in modeling the hydrological response of a basin and land-atmosphere interactions. In fact, root-zone soil moisture is addressed as a key-variable controlling surface water (evapotranspiration, infiltration and surface runoff) and energy exchange between the land surface and the first layer of the atmosphere. In particular, soil moisture is fundamental for real-time flood forecasting modeling (Kitanidis and Bras, 1980) and for the precipitation prediction at local scale (Entekhabi et al., 1996). Many studies pointed out that for Mediterranean catchments the soil moisture conditions before a given storm event is the main factor affecting the flood formation process (Aronica and Candela, 2004). The soil wetness conditions are frequently addressed through an index based on the cumulated rainfall within a small period preceding the event, the Antecedent Precipitation Index (API). In particular, the index adopted in the American Soil Conservation Service method (SCS-CN) uses the precipitation depth of the previous five days, API_5 (Chow et al., 1988). The initial soil wetness conditions and the effective precipitation depth are defined through the API_5 and the parameter CN (curve number) based on the geolithological characteristics of the basin coupled with land-use information. A particular analysis of this parameter has been carried out for the Upper Tiber basin considering the flood event occurred in November 2005, which caused significant damages for flooding. Table 1 shows the values of the runoff coefficient and the corresponding curve number estimated for the basins subtended by the hydrometric stations and where a reliable rating curve is available. As can be seen, a coherence in representing global losses through the CN approach can be found. This aspect is better emphasized in Figure 5 where runoff coefficient values are plotted against the CN values corresponding to intermediate antecedent wetness conditions.

Table 1 - Principal features of the November 2005 flood event (Vol=runoff volume; Q_{max}=peak discharge; C_d=runoff coefficient; CN(II)=curve number for intermediate soil wetness conditions).

Hydrometer	**River**	**Basin area (km^2)**	**Vol ($10^6 \cdot m^3$)**	**Q_{max} (m^3/s)**	**C_d()**	**CN(II)**
SLucia	Tevere	933.3	38.2	399.6	0.41	71.53
Pierantonio	Tevere	1805.2	87.5	779	0.5	72.16
PFelcino	Tevere	2039.8	87.8	879	0.43	72.19
PNuovo	Tevere	4145.3	141.3	1109.8	0.34	69.38
MMolino	Tevere	5279.3	158.6	1305	0.31	70.21
Branca	Chiascio	166.0	7.6	83.2	0.49	66.24
LaChiusa	Chiascio	403.7	15.3	296	0.39	71.09
Barcaccia	Chiascio	463.1	18	118.5	0.39	71.73
Pianello	Chiascio	525.1	17.8	142.7	0.34	72.37
Petrignano	Chiascio	547.0	21.3	151.4	0.4	72.59
Rosciano	Chiascio	1955.3	53.3	569	0.27	65.80
Azzano	Marroggia	257.9	6.1	113.1	0.2	52.08
Cantalupo	Timia	549.3	15	173.5	0.25	59.99
Bevagna	Topino	442.0	6.3	92.5	0.14	58.52
Cannara	Topino	1105.0	22	270.1	0.19	60.82
Bettona	Topino	1221.7	21.3	244	0.17	61.66

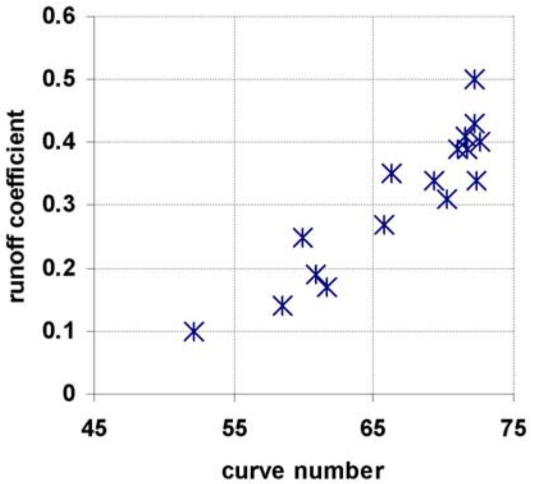

Figure 5 – Relationship between SCS Curve Number, for intermediate antecedent wetness conditions, and runoff coefficient estimated for sub-basins of the Upper Tiber river basin for the flood event occurred on November 2005.

Despite the good results in terms of losses, the initial wetness conditions estimated by the API_5 index were not equally satisfactory. Considering a rainfall-runoff model based on the geomorphological instantaneous unit hydrograph and using the API_5 for the initial conditions assessment, several flood events occurred on the basin subtended by the Migianella hydrometric section (250 km^2) were simulated. For each event, once estimated the API_5 value, the antecedent moisture class (AMC) and the corresponding CN value have been defined. As can be seen in Table 2, poor results were obtained with percentage errors in the runoff volume exceeding 90%, and with a mean of -73%.

Table 2 – Errors, E_{vol}, on flood volume estimation by the classical SCS-CN method for the basin subtended by Migianella hydrometric station (250 km^2) (P=rainfall depth; Q=runoff depth; API_5=Antecedent Precipitation Index of the previous 5 days; AMC=Antecedent Moisture Class).

Date	P (mm)	Q (mm)	API_5 (mm)	AMC	E_{vol} (%) λ=0.2
Nov 16, 96	89	25.12	0.5	1	-24
Nov 30, 96	20.7	6.97	20.3	2	-80
Dec 14, 96	21.8	8.1	14.5	2	-79
Dec 20, 96	23.3	7.54	0.7	1	-100
Apr 27, 97	27.7	11.21	6.9	1	-53
Nov 22, 97	66	17.86	5.9	1	-99
Jan 19, 98	26.6	8.45	20	2	-50
May 3, 98	28.3	10.49	20.7	1	-65
Feb 9, 99	38.9	14.12	6.7	1	-99
Nov 20, 99	18.2	6.92	22.6	2	-89
mean error					-73.1

Therefore, the API_5 index cannot be considered representative in estimating the antecedent wetness conditions. This insight was also proved through rainfall-runoff events observed on a small experimental catchment of the Upper Tiber basin, named Colorso, covering an area of 12.9 km^2. The lithology is a flysh formation and the land use is mainly forested and pasture. Based on these characteristics, the catchment curve number for average moisture conditions was estimated to be 78. Since July 2002, an experimental plot for continuous soil moisture monitoring was settled up inside the catchment (Brocca et al., 2005). In particular, the mean of the measurements carried out by the six-sensors buried at 10 cm depth are considered as the "observed" near-surface water content. Four raingauges and one hydrometric gauge were also located in the basin. Fifteen rainfall-runoff events were selected for the analysis. The relation between the maximum potential retention, S, of the SCS-CN method, computed for each observed event, and the antecedent moisture conditions is shown in Figure 6.

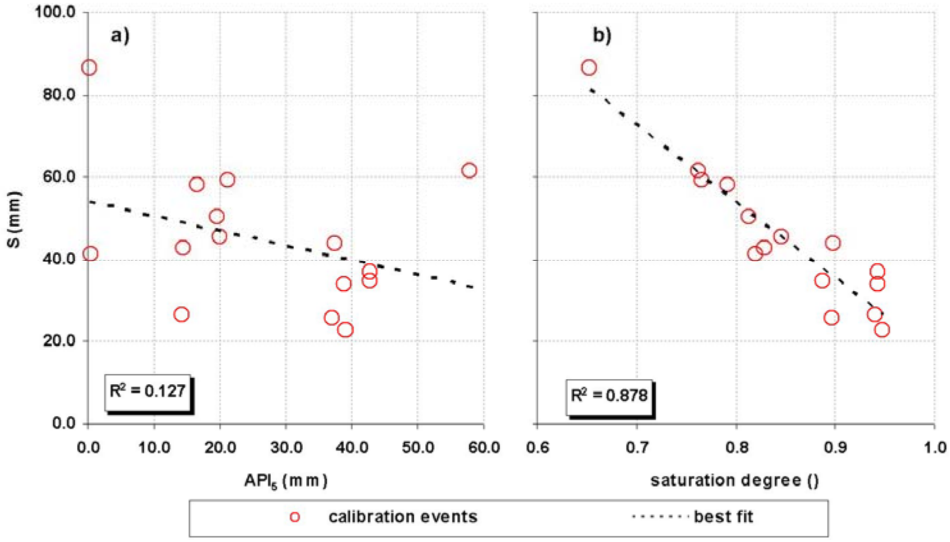

Figure 6 – Colorso basin: maximum calibrated potential retention, S, versus: a) the antecedent precipitation index, API_5, and b) the observed saturation degree at the experimental plot. The determination coefficient, R^2, of best fit line for the calibration events is also shown.

Specifically, the antecedent moisture conditions were estimated through the API_5 index and by the saturation degree obtained through the near-surface water content "observed" at the experimental plot before the storm event, θ_i, and expressed as $\theta_e = (\theta_i - \theta_r)/(\theta_s - \theta_r)$, where θ_r and θ_s were fixed from the extreme "observed" water content. As can be expected, a very weak relationship with the API_5 was observed (Melone et al., 2001), whereas with θ_i a determination coefficient of 0.879 was obtained (see Figure 6).

7 REAL-TIME STAGE FORECASTING MODEL

The very large number of parameters involved in rigorous flood forecasting models and the uncertainty in their estimation make many authors interested in simplified approaches based on flood routing along the river channel. In this case, the critical points are the representation of lateral inflow contributions and the knowledge of rating curve for sites where, for example, velocity measurements cannot be carried out. Franchini and Lamberti (1994), assuming the lateral inflows proportional to the contribution entering upstream, proposed a simple model based on the Muskingum approach and on water level data alone. Since the model performance was found poor for river reaches with medium-large intermediate basin area, Barbetta et al. (2004) enhanced it incorporating an adaptive procedure to take account of significant lateral inflows. Recently, in order to extend the forecasting lead-time a two-reach case in cascade was introduced (Moramarco et al., 2006).

7.1 General Features of the Model

Considering a river reach with the discharge known only at the upstream end, Q_u, and a kinematic relationship assumed for the downstream rating curve, $Q = \lambda h^{\delta}$, the forecast stage carried out at the time t_f for a lead-time Δt^* is computed as follows (Moramarco et al., 2006):

$$h(t_f + \Delta t^*) = \left\{ \frac{1}{\lambda} \left[(1+p) C_1^* Q_u(t_f) + C_2^* \lambda h^{\delta}(t_f) \right] \right\}^{1/\delta} \tag{1}$$

where h is the water level at the reach outlet, p is a parameter linked to lateral inflows, C_1^* and C_2^* refer to the well-known Muskingum parameters K and x and to Δt^* which is computed as 2Kx. The unknown quantities in equation (1) are Δt^*, C_1^*, C_2^*, λ, δ and p which reduce to K, x, λ, δ and p (Moramarco et al., 2006). They have to be estimated through some flood events applying the classical Muskingum approach in simulation mode with the following constrain on downstream peak discharge:

$$\lambda h^{\delta}(t_p) = Q_u(t_p - T_L) - Q^* + \frac{A_d(t_p) - A_u(t_p - T_L)}{T_L} L \tag{2}$$

On the right side of equation (2) Q^* is the attenuation of Q_u expressed by the Price formula (1973) and the last term takes account of the lateral inflow contribution (Moramarco et al., 2005). Specifically, t_p is the time when peak stage occurs at the downstream section, T_L is the wave travel time along the reach, L is the river reach length and A is the channel flow area. The mean values of the parameters derived from the selected flood events are then adopted for forecasting application except the parameter p which is adapted on-line for each forecasting time, t_f, through a procedure based on new stage observations acquired at the reach ends. In order to extend the forecasting lead-time, the two-reach in cascade model was developed (Moramarco et al., 2006). In this case, the forecast estimate is carried out for each river reach separately and finally the case of two connected branches is considered employing the forecast output at the downstream end of the upstream reach as input for the forecast at the downstream one.

7.2 Model Applications

The real-time stage forecasting model was tested for some equipped river reaches in the Upper-Middle Tiber river basin (see Table 3).

By way of example, Figure 7 shows a comparison between the observed water-level hydrograph and the proposed model results for the event observed in November 2005 at MMolino section and which caused many damages for flooding. In this case, using a river schematization in cascade having PFelcino and MMolino sections as upstream and downstream end, respectively, and PNuovo as intermediate section, the estimated lead-time was 9 hours, which can be considered quite good for civil protection purposes. As can be seen, the forecasted stage shape well reproduces the observed one.

Table 3 - Main geomorphological characteristics of the selected river reaches: length, L, mean slope, S_0, and mean width, B. The drainage area of the subtended basin, A, is also reported.

Bounded Sections	**A [km^2]**	**L [km]**	**S_0**	**B [m]**
SLucia	935	44.6	0.0016	35
PFelcino	2035			
Pierantonio	1805	40.2	0.0013	46
PNuovo	4145			
PFelcino	2035	25.4	0.001	45
PNuovo	4145			
PNuovo	4145	30.8	0.0009	55
MMolino	5279			

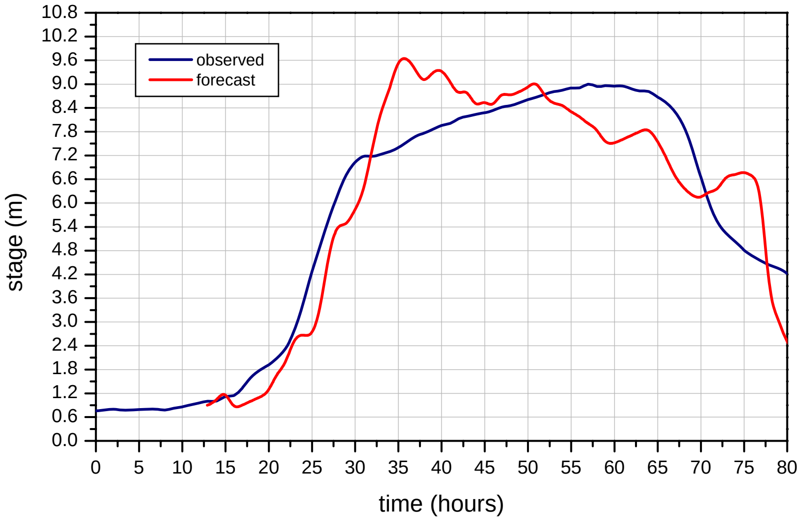

Figure 7 - MMolino section: comparison of observed and forecasted stage hydrograph for the event occurred on November 2005 and for a forecasting lead-time of 9 hours.

8 CONCLUSION

Based on the above contents, the following conclusions can be drawn:

a) the complexity to get an accurate flood forecasting is depending on the adequacy of the real-time hydro-meteorological monitoring which has to be able to provide an accurate representation of the rainfall spatial distribution as well as of the surface water in natural channel networks;
b) the coupling of ground rainfall measurements with satellite data can provide a better knowledge of the storm and its evolution enhancing the performances of the distributed rainfall-runoff modeling addressed for flood forecasting;
c) the characterization of the antecedent soil moisture conditions based on the API_5 index can mislead the flood forecasting hydrologic modeling;
d) the simple stage forecasting model, Muskingum based, here described is able to provide accurate forecast with a large lead-time also when significant lateral inflows occur.

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