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On the Lateral Inflows Assessment Within a Real-Time Stage Monitoring Addressed to Flood Forecasting

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Abstract: The role of the lateral inflows component for an on-line stage forecasting model Muskingum based is investigated. In particular, the original empirical formulation is replaced by a physically based approach incorporating the error on lateral contribution that is updated using the stage observations available in real-time. The updating procedure for lateral inflows assessment is different depending on the weight of the lateral contribution in the downstream flood evolution. The model requires the estimation of four parameters if the downstream rating curve is unknown, otherwise only two parameters have to be determined. The accuracy of the new model formulation is tested by its application to different flood events observed along an equipped river reach of the Upper Tiber River basin, in Central Italy, characterized by a significant intermediate drainage area. Assuming the rating curve known at the downstream site, the forecast stage hydrographs are found in good agreement with the observed ones for all the investigated events and more accurate than those provided by the original model. A preliminary analysis has highlighted that the forecast reliability is not significantly affected by the rainfall spatial variability in the intermediate basin, whereas it is strictly linked to the ratio between the rainfall depth in the upstream and intermediate drainage area (RRI). Moreover, a threshold of RRI has been defined in order to identify the forecast stages which could be affected by a not negligible degree of uncertainty. On this basis, the proposed model can be conveniently employed as part of a real-time flood forecasting system involving the RRI continuous monitoring during critical storm events.

Keywords: real-time flood forecasting; lateral inflows; Muskingum method; rainfall spatial variability.

1. INTRODUCTION

Short-term (or real-time) forecasting is fundamental for both minimizing the effects of forthcoming flood events in flood-prone regions and optimizing water resources management where dam safety is also of concern. Models within a flood forecasting system aim at producing future estimates of hydrological variables, based on the present state and the past behavior of the investigated catchment or river reach, thus allowing to reduce the uncertainty in decision making for the evolution of the flood event. The mathematical models applied at the purpose generally belong to either conceptual or black-box approaches. For medium-sized catchments (drainage area of the order of 10^3 km^2) conceptual rainfall-runoff models of the semi-distributed type seem to be most reliable for operational activities provided that an updating procedure is adopted [Michaud & Sorooshian, 1994; Boyle et al., 2001].

To reduce the complexity of the flood forecasting system, simplified models based only on flood routing have been also used [O'Connell & Clarke, 1981; Lamberti & Pilati, 1996] for flood-prone sites located downstream of a gauged station and at a distance allowing an appropriate forecasting lead-time. Moreover, this type of models reduces the level of forecast uncertainty since the water level measurements are definitely more accurate than the rainfall ones. In this context, the Muskingum model can be a useful tool. However, critical points in hydrological routing are the representation of lateral inflows contribution and the knowledge of stage-discharge relationships. As regards the former, O'Donnell [1985] proposed a three-parameter Muskingum procedure assuming the lateral inflows proportional to the contribution entering upstream. Using this approach, Franchini and Lamberti [1994] presented a simple model Muskingum type to provide forecast water levels at the downstream end by selecting a routing time interval and, hence, a forecasting lead-time which allows to express the forecast stage as a function of only observed quantities. Moramarco et al. [2006] enhanced the modeling scheme by Franchini and Lamberti [1994] incorporating a procedure for adapting the parameter linked to lateral inflows. This last model, called STAFOM (STage FOrecasting Model), was successively extended by Moramarco et al. [2006] to a two connected river branches schematization in order to improve significantly the forecasting lead-time. The STAFOM model provided satisfactory results for most of the analysed flood events in each investigated river reach in the Upper-Middle Tiber River basin in Central Italy. However, the updating procedure for the parameter linked to the lateral contribution was based on empirical assumptions.

This might be questionable for floods with characteristics different from those there employed for model calibration and evaluation phase. On this basis, the STAFOM model has been modified by incorporating a physically based simplified approach for lateral inflows representation.

The objective of the paper is, then, to describe the general features of the modified stage forecasting model and to test its performance along a river reach selected in the Upper Tiber River basin, in Central Italy. A preliminary analysis has been also carried out to assess the effect of the rainfall field on the intermediate basin on the accuracy of the forecast stage hydrographs. For this aim, two indexes have been used. The first addresses the rainfall field variability on the basin and the second one represents the significance of the intermediate drainage area contribution.

2. THE STAGE FORECASTING MODEL STAFOM

2.1 Modelling Scheme

For a river reach bounded by two hydrometric sites with not negligible lateral inflows the Muskingum approach is expressed as:

$$Q_d(t+\Delta t) = C_0 I(t+\Delta t) + C_1 I(t) + C_2 Q_d(t) \tag{1}$$

where Q_d is the discharge at the downstream end. C_0, C_1 and C_2 are the Muskingum parameters depending only on K and x coefficients value and on the time interval, Δt. The term I in equation (1) is the total discharge entering into the selected river reach defined by the upstream contribution, Q_u, and the lateral inflows, Q_l:

$$I(t) = Q_u(t) + Q_l(t) \tag{2}$$

In particular, the lateral inflows are mainly due to the tributaries contribution which is determined by the overland flow formation and propagation process during the flood event.

In order to get the formulation for a real-time forecasting model, the term $C_0 I(t+\Delta t)$ in equation (1) has to be eliminated and this can be achieved by assuming a time interval $\Delta t = \Delta t^* = 2Kx$ for which $C_0 = 0$ [Franchini & Lamberti, 1994]. For each time of forecast, t_f, the estimation of the downstream discharge carried out Δt^* hours in advance is then given by:

$$Q_d(t_f + \Delta t^*) = C_1^* \left[Q_u(t_f) + Q_l(t_f) \right] + C_2^* Q_d(t_f) \tag{3}$$

where C_1^* and $C_2^* = 1 - C_1^*$ are now referred to the Muskingum parameters K and x with the constrain $\Delta t^* = 2Kx$ [Moramarco et al., 2006]. The term in equation (3) linked to the lateral inflows, $Q_l(t_f)$, can be assessed by considering the continuity equation written in the characteristic form. Following Moramarco et al. [2005] the lateral contribution per unit channel length, q, is expressed as a function of the upstream and downstream flow area, A, and of the wave travel time, T_L, which is the time shift to match the rising limb and the peak region of the upstream and downstream dimensionless stage hydrographs:

$$q(t)=\left(A_d(t)-A_u(t-T_L)\right)/T_L \tag{4}$$

Assuming $T_L=\Delta t^*$, $Q_l(t_f)$ is given by:

$$Q_l(t_f)=q(t_f)L=\left[\left(A_d(t_f)-A_u(t_f-\Delta t^*)\right)/\Delta t^*\right]L \tag{5}$$

where L is the channel length.

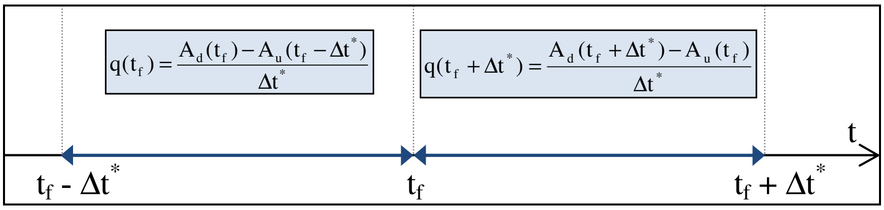

Figure 1. Lateral contribution per unit channel length, q, referred to different time intervals (for symbols see text).

In order to determine the downstream discharge at time ($t_f+\Delta t^*$), in the model formulation the q value referred to the time interval [t_f; $t_f+\Delta t^*$] should be employed (see Figure 1). However, it is an unknown quantity and, hence, the lateral contribution has to be assumed invariant over the forecasting lead-time, Δt^*, and equal to $q(t_f)$. However, for floods characterized by a short duration, the lateral inflows can be expected to be highly varying in time. Moreover, considering the simplified approach adopted for lateral inflow representation an additive error, ε, for q is introduced, so that equation (3) is rewritten as:

$$Q_d(t_f+\Delta t^*)=C_1^*Q_u(t_f)+C_1^*\left[q(t_f)+\varepsilon\right]L+C_2^*Q_d(t_f) \tag{6}$$

Assuming a kinematic relationship, $Q=\lambda h^\delta$, for the rating curve at the downstream section, the general formulation for the STAFOM model can be obtained from equation (6):

$$h_d(t_f+\Delta t^*)=\left\{(1/\lambda)\left[C_1^*\left(Q_u(t_f)+q(t_f)L+\varepsilon L\right)+C_2^*\lambda h_d^\delta(t_f)\right]\right\}^{1/\delta} \tag{7}$$

where h_d is the water level at the channel outlet and λ and δ are parameters to be estimated.

2.2 Updating Procedure

If the rating curves at the ends are accurate, the main uncertainty can be assumed to be linked to the lateral inflows assessment. Therefore, the error on the lateral contribution estimate, that is the ε term, is updated through an automatic procedure which, obviously, is based on the last measurements carried out by the monitoring network operating on-line. In particular, for each time of forecast, t_f, ε is estimated assuming that the model furnishes the optimal forecast at t_f when the lateral inflows in the forecasting period is considered. This means that the error on lateral contribution is given by the difference between the discharge observed at the downstream section, $Q_{d\_obs}(t_f)$, and the discharge forecasted by the model Δt^* hours before using the lateral contribution per unit channel length, q, at time t_f or ($t_f-\Delta t^*$) for events characterized by predominant upstream or lateral inflows, respectively:

$$\varepsilon(t_f)=\left(Q_{d\_obs}(t_f)-C_1^*Q_u(t_f-\Delta t^*)-C_2^*Q_d(t_f-\Delta t^*)\right)/\left(C_1^*L\right)-q \tag{8}$$

The different approaches for the q estimate are necessary for taking the lateral inflows underestimation into account occurring during the rising limb when the intermediate contribution is predominant in the downstream flood wave formation. The choice of the approach to be applied is based on the real-time stage observations at the two channel ends which allow to assess the significance of the lateral inflows.

2.3 Model Parameters Evaluation

In order to employ the stage forecasting model expressed by equation (7), all the involved parameters have to be defined. In particular, beside the adaptive parameter, ε, the values of λ, δ and C_1^* have to be assessed. As far as the rating curve coefficients, λ and δ, are concerned they are easily inferred when an accurate stage-discharge relationship is available at the downstream site. Otherwise, they can be derived through the Rating Curve Model (RCM) proposed by Moramarco et al. [2005] which also takes the lateral inflows contribution into account along the selected river reach. The C_1^* value depends only on the Muskingum coefficients, K and x. In particular, K is evaluated considering that in the classical Muskingum formulation it represents the mean wave travel time along the investigated river branch. Therefore, it can be estimated through few observed flood events. For each event the wave travel time, T_L, is computed as the time shift necessary to overlap the rising limb and the peak region of the normalized stage hydrographs [Moramarco et al., 2005]. Finally, K is obtained as the average of the T_L values. It represents a characteristic of the selected reach and the value of the forecasting lead-time, Δt^*. The assumption $\Delta t^*=K$ implies that x has to be set equal to 0.5 which, however, is in the typical range of the parameter values [Chow et al., 1988] and, hence, C_1^* and C_2^* are set equal to 1 and 0, respectively, in the model formulation. This means that the Muskingum approach follows the kinematic wave dynamic [Kundzewicz & Strupczewski, 1982].

3. MODEL APPLICATION AND RESULTS

The accuracy of the modified forecasting model was verified considering some flood events occurred along one equipped river reach in the Upper Tiber River basin bounded by the hydrometric sites of Pierantonio and Ponte Nuovo, whose location is shown in Figure 2 along with the main sub-basins and the existing raingauge network operating in real-time. The main geomorphological properties of the reach are summarized in Table 1. As can be seen, the reach is characterized by a significant intermediate drainage area, equal to 2340 km^2, which is about 56% of the total basin and, hence, the lateral inflows contribution can be fundamental in flood wave formation process. Moreover, an artificial reservoir (Montedoglio dam) is located in the upper part of the basin subtending a drainage area of about 275 km^2 (see Figure 2). An accurate stage-discharge relationship was available for both the upstream section and the downstream one. Significant flood events observed during the last decade were selected for the analysis and their main characteristics are summarized in Table 2. As can be seen, they are characterized by different values of the percentage lateral inflow contribution, LC. In particular, the events with LC<50% are considered 'Prevalent Upstream Contribution' (PUC) events, while the others 'Prevalent Lateral Contribution' (PLC) ones. For each water level the flow areas in equation (5) were estimated by the sections geometry defined through accurate topographical surveys. The model parameters λ and δ were derived from the knowledge of Ponte Nuovo rating curve, while K was assessed considering the mean

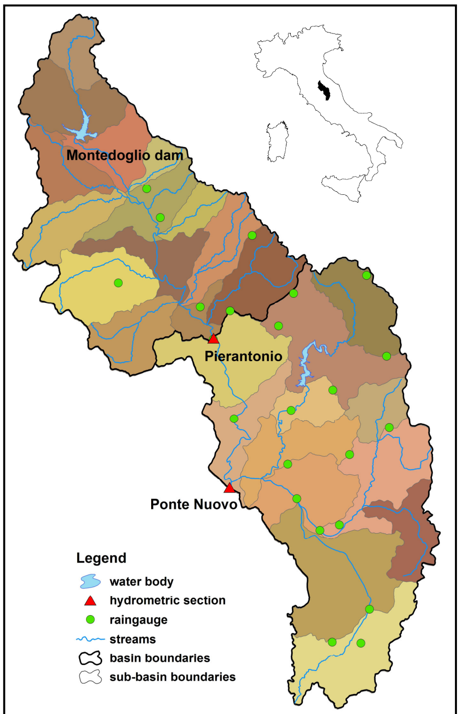

Figure 2. Location of the selected sections in the Upper Tiber River basin. The existing raingauge network and the main sub-basins are also shown.

wave travel time, T_L, of the selected river reach. T_L values are shown in Table 2 and an average can be surmised equal to 4.5 hours. Therefore, K can be assumed equal to 5 hours considering also the need to adopt a lead-time as high as possible.

Table 1. Main geomorphological properties of the selected reach: area subtended by each section, A_b, channel length, L, mean channel slope, S_0, mean section width, B.

Sections	A_b [km^2]	L [km]	S_0	B [m]
Pierantonio	1805	40.23	0.0013	46
Ponte Nuovo	4145			

Table 2. Main floods characteristics (peak stage, h_p, peak flow, Q_p, wave travel time, T_L) and model results (percentage error on peak stage, e_{hp}, and time to peak, e_{tp}; coefficient of persistence for the event, E_v, and the rising limb, E_r; Nash-Sutcliffe coefficient, NS). The Spatial Deviation Index, SDI, and the Rainfall Ratio Index, RRI, are also shown along with the percentage lateral inflows contribution, LC.

Date	Pierantonio		P.Nuovo		T_L [h]	LC [%]	e_{hp} [%]	e_{tp} [h]	E_v [%]	E_r [%]	NS [%]	SDI	RRI
	h_p [m]	Q_p [m^3/s]	h_p [m]	Q_p [m^3/s]									
Dec. 96,13	4.32	378	6.43	728	4.5	47	-1.3	2.0	77.9	78.0	91.5	0.200	0.99
Apr. 97, 20	4.67	429	5.16	502	5.5	18	-2.2	-3.0	95.3	96.5	98.9	0.154	0.80
Nov. 97, 22	3.82	308	4.56	409	3.5	36	6.6	4.0	83.4	83.3	95.4	0.131	0.85
Dec. 97, 26	2.17	121	3.0	189	3.0	44	5.6	1.0	80.4	79.0	93.8	0.112	1.04
Jan. 98, 19	3.12	221	3.79	302	4.5	33	1.7	1.0	96.4	96.2	98.1	0.215	1.00
Feb. 98, 3	1.56	70	2.91	177	2.5	63	12.7	3.0	43.0	75.7	86.2	0.116	1.44
Apr. 98, 15	3.12	221	4.77	441	7.0	51	10.7	4.0	33.8	79.6	90.0	0.176	1.62
Oct. 98, 5	1.84	92	4.85	453	0.0	78	16.6	2.0	39.7	58.6	86.8	0.161	1.65
Dec. 98, 3	3.24	235	6.37	717	3.5	62	22.6	3.0	23.4	59.1	56.8	0.127	1.87
Feb. 99, 9	4.66	428	6.61	764	6.0	45	-5.4	2.0	85.6	89.2	94.5	0.093	0.85
Dec. 99, 14	2.31	134	6.62	766	2.0	80	8.4	-2.0	60.4	62.5	93.3	0.169	2.03
Dec. 00, 25	5.52	552	7.17	879	8.0	36	8.7	1.0	66.9	70.4	95.3	0.125	0.65
Mar. 01, 1	2.83	188	4.26	367	4.0	50	2.4	3.0	73.0	76.8	91.5	0.348	0.80
Apr. 01, 7	3.28	240	3.78	300	5.5	30	3.3	-1.0	96.9	97.1	97.0	0.118	0.96
Nov. 05, 25	6.70	779	8.19	1110	6.0	39	-2.6	5.0	79.2	92.5	96.4	0.085	0.99
Dec. 05, 2	4.70	434	5.91	631	5.5	35	2.9	2.0	86.2	86.2	92.6	0.233	0.77
Dec. 05, 5	5.09	495	7.13	871	4.0	47	-2.4	2.0	81.3	80.5	93.1	0.104	1.26
Dec. 05, 30	4.59	417	6.04	655	7.0	41	-2.2	1.0	86.8	85.1	98.2	0.139	1.06
Feb. 06, 20	1.88	96	4.19	357	2.0	74	8.2	3.0	34.5	37.8	85.3	0.107	1.74

The results provided by the model are summarized in Table 2 in terms of error on peak stage and time to peak along with the coefficient of persistence (E) [Kitanidis & Bras, 1981] and the Nash-Sutcliffe efficiency coefficient (NS) [Nash & Sutcliffe, 1970]. In particular, the coefficient E compares the prediction of the model against the obtained one by the no-model, which assumes the steady state over the forecasting lead-time. It has been computed for the rising limb (E_r) and up to the time in the recession limb when the dimensionless stage becomes equal to 0.5 (E_v). Considering the PUC events (LC<50%) the model was found very accurate in terms of error on peak stage which was less than 10% with a mean absolute error equal to 3.6%. On the contrary, this last error goes up to 13.2% for the PLC floods. As regards the error on time to peak, it has to be underlined that for events with a wide peak region the difference between the observed and the forecast peak time is not adequate to assess the model reliability in capturing flood-peak timing. In general, the model provides forecast peak stage with a mean absolute time error equal to 2.1 and 2.8 hours for the PUC and the PLC floods set, respectively. The coefficients of persistence, E_v and E_r, show that the proposed model is very useful, particularly during the rising limb period, for most of the selected flood events. In particular, for the PUC events set the values of E_v and E_r are greater than 70% with a mean value of about 85%. Moreover, the NS coefficient shows that the stage hydrograph shape is well simulated with a value always greater than 90% and equal on average to 95.1%. As regards the other flood events, the model performance can be still considered satisfactory even if the E_v and E_r assume lower values on average equal to 39.2% and 62.2%, respectively. Figure 3 shows the comparison between the observed and the forecast stage hydrograph for the floods occurred on April 97 and November 05, belonging to the PUC floods set, and those observed on December 99 and February 06 characterized by prevalent intermediate basin contribution.

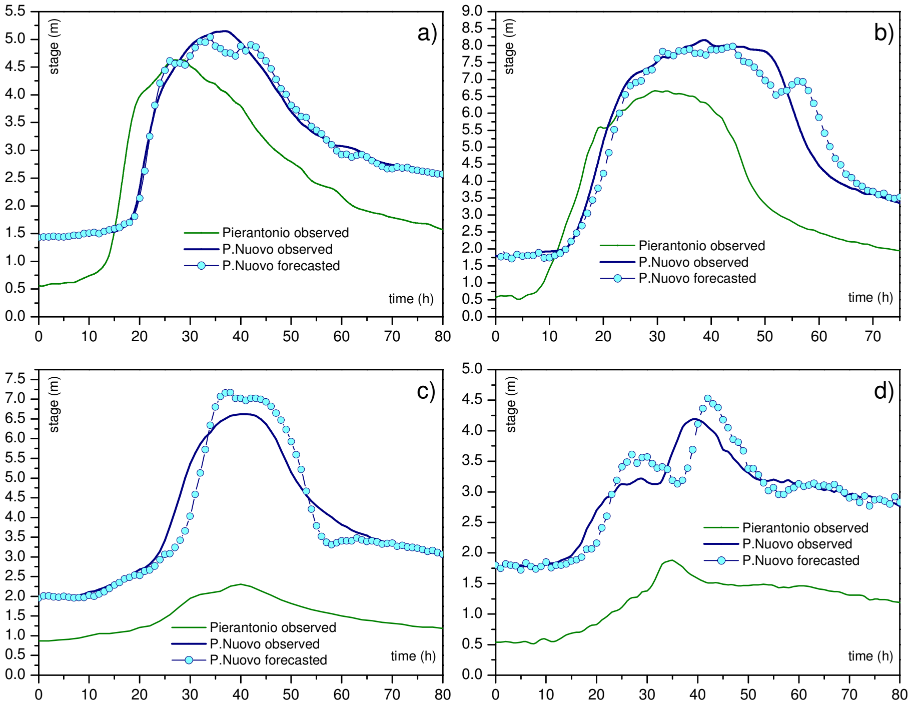

Figure 3. Comparison between observed and forecast stage hydrograph for the floods occurred on: a) April 97; b) November 05; c) December 99; d) February 06.

Considering that for the present case study the upstream drainage area and the intermediate one are equal to 44% and 56% of the total area, respectively, we can suppose that the model accuracy might be significantly influenced by the ratio between the contribution entering upstream and the lateral inflows as well as by the spatial rainfall distribution in the intermediate basin. Therefore, a preliminary analysis was carried out quantifying for each storm the rainfall field variability over the intermediate drainage area through the Spatial Deviation Index proposed by Segond et al. [2007]:

$$SDI = \left(1/N\right)\sum_{i=1}^{N}\left(\left|P_{ri}-P_{I}\right|/P_{I}\right) \tag{9}$$

where N is the number of sub-basins in which the intermediate basin is divided. P_{ri} and P_I is the Thiessen averaged areal rainfall for the i-th sub-basin and for the intermediate basin, respectively. In particular, the intermediate basin between Pierantonio and Ponte Nuovo sections was subdivided in 12 sub-basins shown in Figure 2 along with the raingauge network used for the analysis. Figure 4a shows the plot of E_v and E_r against the SDI index, (see Table 2) suggesting that a correlation does not exist. In principle, this result is affected by a sort of uncertainty linked to the representation of rainfall spatial variability through the existing raingauge network and the adopted spatial discretization. However, the different model accuracy for events characterized by an almost uniform rainfall (e.g. February 99 and February 06) suggests that this uncertainty can be considered negligible. In order to investigate this, the Rainfall Ratio Index (RRI) was computed for each storm as the ratio between P_I and the Thiessen averaged areal rainfall for the basin between Montedoglio dam and Pierantonio site, P_U, ($RRI=P_I/P_U$). Figure 4b shows that there is a linear relationship between E_r, more significant for flood forecasting purpose, and the RRI index. The floods occurred on April 98, December 00 and February 06, highlighted by red squares in Figure 4b, were not considered in the relationship assessment since they are characterized by a complex shape and multiple peaks. On the basis of the obtained results, it can be inferred that for the investigated river reach the accuracy of the proposed model is mainly influenced by the significance of the intermediate basin contribution in the flood wave formation process. In particular, for RRI less than 1.0÷1.2 the model results can be considered accurate being the coefficient of persistence greater than 80%. On the contrary, when RRI becomes greater than 1.4, which can be assumed as a preliminary threshold value, the provided forecast stages should be considered affected by a not negligible degree of uncertainty. However, it has to be emphasized that the NS coefficient was found greater than 85% for all the investigated events except for the flood occurred on December 98.

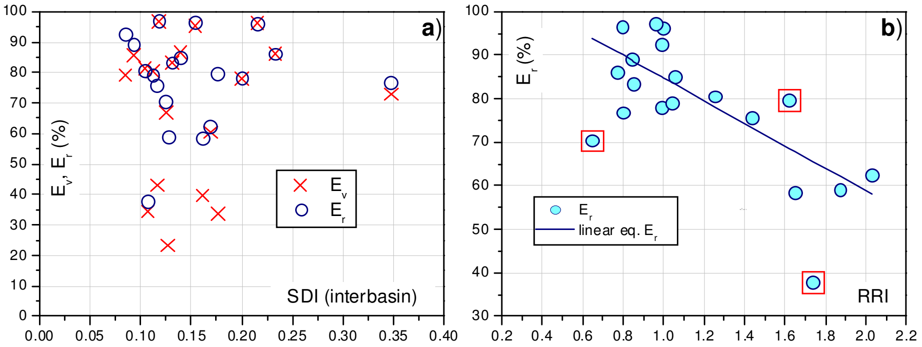

Figure 4. Relationships between coefficients of persistence E_v and E_r and a) SDI index; b) RRI index. Red square indicates floods characterized by a complex shape and multiple peaks (for symbols see text).

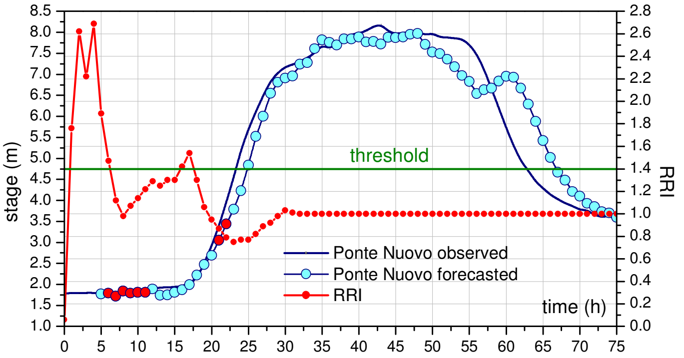

Figure 5. November 05: comparison between observed and forecast stage hydrograph along with the rainfall index, RRI. The red points indicate the forecast stages referring to RRI values greater than the fixed threshold.

However, these results refer to the total rainfall depth. In order to check the usefulness of the RRI index for having indications on the forecast stage reliability in real-time, it was computed at hourly time step considering the rainfall occurred up to the time of forecast. Specifically, the real-time RRI value monitoring at hourly time step has been simulated for the floods occurred on December 98, poorly forecast, and November 05, accurately forecast. As regards the former flood, the ratio P_I/P_U was found significantly greater than 1.4 for all the times of forecast, whereas for the second flood RRI overcomes slightly the fixed threshold just at eight forecast times whose corresponding forecast stages are shown as red points in Figure 5. As can be seen, they refer to periods before and at the beginning of the rising limb and, hence, are not fundamental for flood forecasting purposes.

4. CONCLUSIONS

The stage forecasting model proposed by Barbetta et al. [2003] for real-time applications was modified in the lateral inflows representation by introducing a physically based approach. In particular, two approaches were proposed for floods with prevalent upstream or lateral contribution, respectively. The accuracy of the modified model has been tested considering several floods occurred along the Pierantonio-Ponte Nuovo river reach, in the Upper Tiber River basin in Central Italy, characterized by a significant intermediate drainage area. Assuming the rating curve known at the downstream site, the forecast stage hydrographs were found in good agreement with those observed for all the investigated case studies even if a slightly lower model reliability characterized the floods affected by significant intermediate basin contribution. Moreover, the performance of the new formulation was found more accurate than that of the original one for all the investigated events. In particular, the new approach for lateral inflows assessment allowed to significantly reduce the error on peak stage, whose mean absolute value decreased from 13.5 to 6.6%, and to increase the coefficients of persistence, E_v and E_r, as well as the Nash-Sutcliffe. As far as the error on time to peak is concerned, it was found out that the two model formulations are characterized by similar accuracy. The analysis on spatial storm distribution has shown that the forecast stage reliability is mainly affected by the ratio between the intermediate basin contribution and the upstream one, defined by the RRI index. In particular, when this index is lower than 1.0÷1.2 the model results are expected to be accurate, while when it becomes greater than 1.4 the provided forecast stage might be characterized by a not negligible degree of uncertainty. On these bases, the proposed model can be a useful tool within a real-time flood forecasting system for the Pierantonio-Ponte Nuovo reach provided that RRI is monitored in continuous during critical storm events. Further investigations on other river reaches with different hydraulic and geometric properties should be carried out in order to verify the new model formulation reliability. Moreover, it could be interesting to analyze the effect of different representation of rainfall spatial variability on the model performance.

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