VALIDATION OF FEST-WB, A CONTINUOUS WATER BALANCE DISTRIBUTED MODEL FOR FLOOD SIMULATION

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ABSTRACT

The distributed event based hydrological model FEST, that adopts the classical SCS-CN method for abstractions, was extended for continuous simulation. The new FEST-WB model makes use of a simplified local water and energy balance scheme, accounting for soil, vegetation and atmosphere interactions, to provide Antecedent Moisture Condition (AMC) at rainfall beginning. In this work, particular care is focused on the understanding of the role that the AMC of soil plays in the run-off formation and on the flood hydrograph definition. The use of the FEST-WB model is analysed and the comparison between the two approaches showed that the 'water balance' approach, while needing calibration, gets more reliable showing that the simple estimation methods (based on antecedent precipitation) adopted in event-based simulations often proved to be inadequate.

1 INTRODUCTION

The problem of flood forecasting, and in general of the catchment response to heavy rainfall, is still an open field in hydrological researches. Moreover the growing impact of floods on human activities highlights the need of an urgent and deep analysis of numerical models able to forecast these phenomena as well as severe tests based on historical events.

In the last 30 years, starting from the first studies by *Freeze & Harlan* (1969), research activities focused on the importance of the time-space variability both of the soil characteristics and of the rainfall field combined with the processes governing catchment response to precipitation. The so-called distributed approach has become very common in the research field but it is still not widely diffused in the applications and in the operational tasks.

Furthermore in flood hydrology event based models are often preferred, thanks to their simple schemes, to complete models, nevertheless the antecedent soil moisture conditions play a crucial role in the run-off formation and on the flood hydrograph definition (*Montaldo et al.*, 2007). A good estimate of the soil moisture field and of its spatial variability still presents significant uncertainties so that the simple estimation methods adopted in event-based simulations often proved to be inadequate while direct observations of soil moisture are still far to be reliable for non point estimations. An interesting state-of-the-art method for soil moisture assessment is based on the numerical simulation of the local water balance representing water and energy fluxes between soil, vegetation and atmosphere.

In this paper, the evaluation of a forecasting operational system based on a distributed hydrological model is addressed. The FEST model (event based) and the new FEST-WB (continuous water balance model) are considered. The former adopts the classical SCS-CN (*Soil Conservation Service*, 1986) model for abstractions; the latter makes use of a simplified local water and energy balance scheme to provide AMC (Antecedent Moisture Condition) at rainfall beginning.

This study was part of the AMPHORE (Application des Methodologies de Previsions Hydrometeorologiques Orientees aux Risques Environnementaux) European Union research project whose objective regards the forecasting and the prevention of natural hazards, with particular reference to risks coming from severe hydro-meteorological events.

2 THE UPPER PO RIVER BASIN

The subject area is the upper Po River basin and covers 38000 km^2. This is predominantly an alpine region that is bounded on three sides by mountain chains covering 73% of its territory. While the north-east part of the basin is located in Switzerland, most of it is in the north-west of Italy. Piedmont, located in the Padana Plain, is the principal Italian region in the area while other Italian regions include Aosta Valley, Liguria and Lombardy.

Several flood events have occurred in the very last years, for example, September 1993, November 1994, November 1996, June and October 2000 and November 2002. On the basis of historical data that goes back to 1800, this region has been hit by severe meteorological events, on average, once every two years.

2.1 Physiographic basin characterization

Available digital cartographic data include: the Digital Elevation Model (DEM) available in raster format at 100 m x 100 m resolution; CORINE land cover maps for the Italian part updated in the year 2000 available in vector format and CORINE maps for the Switzerland part updated in the year 1990 available in raster format (spatial resolution of 250 m x 250 m); pedologic characteristics for soils available in vector format; Curve Number in raster format at 100 m x 100 m resolution. From the available basic thematic layers, basin parameters required for the application of the hydrological model have been derived at a spatial resolution of 1000 m x 1000 m. These include: flow direction, slope and aspect, residual and saturated soil moisture, albedo, pore size distribution index, saturated hydraulic conductivity, wilting point, field capacity and soil depth.

2.2 Hydrologic and meteorological data

For this study, meteorological and hydrologic ground measured data were collected by the telemetric monitoring system of the Regione Piemonte, Regione Lombardia and Switzerland. Data of rainfall, air temperature, incident short wave solar radiation and air relative humidity are available from 1 January 2000 to 31 December 2004 at hourly or sub-hourly time steps.

Hydrometric observations at 30 minutes time step are available at 40 locations from 1 January 2000 to 31 December 2003. In the present analysis, only medium-sized basins with areas ranging from 422 to 3976 km^2 are considered (Table 1). Locations characterized by lack of meteorological observations have been intentionally excluded from analysis.

Cross-section	River	Drained Area [km^2]
Bellinzona	Ticino	1624
Candoglia	Toce	1531
Carignano	Po	3976
Casalcermelli	Orba	798
Cassine	Bormida	1521
Castelnuovo Belbo	Belbo	422
Cuorgnè	Orco	630
Farigliano	Tanaro	1508
Fossano	Stura di Demonte	1249
Palestro	Sesia	2587
Serravalle	Scrivia	619

Table 1. List of catchments involved in the analysis and drained area.

3 DISTRIBUTED HYDROLOGIC MODELS

For this work FEST-WB, a distributed hydrological water balance model, was developed based on the event based model FEST (*Mancini*, 1990; *Montaldo et al.*, 2002), acronym of Flash–flood Event–based Spatially–distributed rainfall–runoff Transformation.

Four main components can be identified in both models: 1) the flow paths and channel network definition, 2) the spazialization of site measured meteorological forcings, 3) the runoff computation and 4) the overland flow routing.

The first and the fourth components are common to the two models.

In the first component the flow path network is automatically derived from the DEM using a least-cost path algorithm (*Ehlschlaeger*, 1989). It assigns flow from each pixel to one of its eight neighbours, without the necessity to remove pits in the elevation data. For hillslope and channel network definition the models use the constant minimum support area concept. It consists of selecting a constant critical support area that defines the minimum drainage area required to initiate a channel (*Montgomery & Foufoula–Georgiou*, 1993).

In the second component, the spatial interpolation of ground measured meteorological forcings is performed. The FEST model needs only rainfall as input. The FEST-WB needs rainfall, solar radiation, air relative humidity and temperature. The rain and relative humidity data are interpolated using the inverse distance weighting algorithm. Solar radiation and temperature interpolation is described in the following subsections.

In the third component, the runoff is computed for each elementary cell. The two models use different methods for runoff estimation. The methods are described in the following subsections.

The fourth component performs the runoff routing throughout the hillslope and the river network. It is performed via a diffusion wave scheme based on the Muskingum-Cunge method in its non-linear form with the time variable celerity. Details are given by *Montaldo et al.* (2007).

3.1 The FEST model

The FEST model, designed for operating on a single-event basis, computes the surface runoff for each elementary cell using the CN method of the Soil Conservation Service (1986) in its differential form (*Mancini & Rosso*, 1989).

The SCS-CN method distinguishes three levels of antecedent moisture condition (AMC I, AMC II, and AMC III), depending on the total rainfall in the 5 days preceding a high rainfall event. The values of *CN* for the AMC II condition are tabulated by the Soil Conservation Service on the basis of soil type and land use. The values of *CN* for AMC I and AMC III are expressed in terms of the values of *CN* for AMC II through empirical relationships (*Montaldo et al.*, 2004). In this way, different values of *CN* (i.e., soil retention capacity) can be assigned to the cells of the basin according to the antecedent moisture conditions.

3.2 The FEST-WB model

FEST-WB computes the main processes of the hydrological cycle: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamics.

Spatial distribution of air temperature local measurements have to consider the reduction of temperature with altitude. In the model a constant lapse rate adjusts temperature for elevation (-0.0065 °C m^{-1}). Thermal inversion phenomena are neglected.

The snow module of FEST-WB includes snow melt and snow accumulation dynamics (*Tarboton et al.*, 1994). The snow melt simulation is based on the degree day concept (*Martinec et al.*, 1960).

The terrain covered by snow is supposed to be frozen, and hence the melted water is prevented from infiltrating into the soil. On the contrary, the liquid fraction of snow water equivalent, R_s, sum of melted water and liquid precipitation, is supposed to flow cell by cell trough the snow pack with a linear reservoir routing scheme (*Ponce*, 1989) with a celerity of 1.67 10^{-3} m/s (*Salandin et al.*, 2004). When R_s reaches a cell not covered by snow, it is added to the liquid precipitation of that cell.

Soil moisture, θ, evolution for the cell not covered by snow, is described by water balance equation:

$$\frac{\partial \theta}{\partial t} = \frac{1}{Z}\left(P_l - R - D - ET\right) \tag{1}$$

where P_l is liquid precipitation, R is surface runoff flux, D is drainage flux, ET is evapotranspiration rate and Z is the soil depth. Soil moisture in cells covered by snow is assumed not varying with time.

The actual evapotranspiration, *ET*, is computed as a fraction of the potential rate tuned by a function that, in turn, depends on soil moisture content (*Montaldo et al.*, 2003). Potential evapotranspiration is computed with a radiation-based equation (*Priestley & Taylor*, 1972).

Shortwave net radiation involved in evaporative processes is calculated considering the effect of topography (*Mancini et al.*, 2005). Longwave net radiation is evaluated as a function of air temperature (*Goudriaan*, 1977).

Runoff is computed according to a modified SCS-CN method extended for continuous simulation (*Ravazzani et al.*, 2007) where the potential maximum retention, *S*, is updated cell by cell at the beginning of rainfall as a linear function of the degree of saturation, ε.

$$S = S_1 \cdot (1 - \varepsilon) \tag{2}$$

where S_1 is the maximum value of *S* when the soil is dry (AMC 1).

Subsurface flow routing, computed on those cells not covered by snow, is computed with a linear reservoir routing scheme.

4 MODEL CALIBRATION

The FEST-WB model was subjected to a rigorous process of calibration and validation by comparison of simulated and observed discharge. Thanks to discharge time series availability, eleven locations could be chosen for this study. 57 flood events from 2000 were used for calibration, while 77 additional flood events from 2001-2003 were exploited for verification. In the calibration set, the peak flow per unit basin area ranges from 0.07 $m^3s^{-1}km^{-2}$ to 2.2 $m^3s^{-1}km^{-2}$, and the volume of the hydrograph per unit basin area from 0.01 10^6 m^3km^{-2} to 0.52 10^6 m^3km^{-2}. In the verification set, the peak flow per unit basin area ranges from 0.06 $m^3s^{-1}km^{-2}$ to 2.67 $m^3s^{-1}km^{-2}$, and the volume of the hydrograph per unit basin area from 0.01 10^6 m^3km^{-2} to 0.65 10^6 m^3km^{-2}.

Simulated hydrographs were extracted from the hourly time step continuous simulation for the period 2000-2003. Flood events in those locations where widespread inundation was observed were excluded from calibration and validation process as well, as the hydrologic distributed model cannot simulate this.

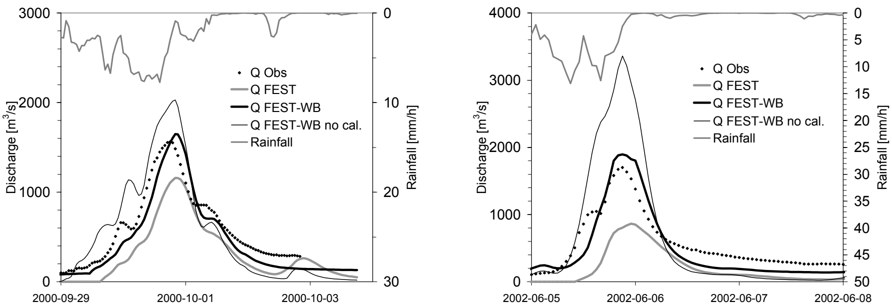

Figure 1. Comparison of observations, FEST, FEST-WB and FEST-WB not calibrated simulation results for a calibration event (left) and a validation event (right) for the river Toce at Candoglia

The main calibration activity, based on the "trial and error" approach, was primarily focused on flood volumes, which are strongly dependent on the infiltration process. The parameters subjected to calibration were the soil hydraulic conductivity, regulating saturation dynamics and, undirectly, 'Hortonian' infiltration excess, and soil depth, regulating ‘Dunnian’ saturation excess. To this aim, observed discharge hydrograph was subdivided into its superficial and deep flow components. The deep soil hydraulic conductivity, responsible for hypodermic flow velocity, was calibrated as well. The deep soil conductivity was checked comparing observed and modelled hypodermic flow and taking into account that an increase of deep soil conductivity implies an increase of hypodermic flow. The CN map and parameters required for surface flow routing (roughness coefficient and section width), adopted also for simulations with FEST, were not modified in calibration process.

A comparison of observations, FEST, FEST-WB and FEST-WB not calibrated simulation results for river Toce at Candoglia is reported in Figure 1.

5 MODELS VERIFICATION

For the entire set of selected events the hydrological simulations are run using both models. Each simulation is then compared with the observed discharge hydrograph calculating some quality index to classify the model reliability. These indexes are: relative error in peak discharge, relative error in flood volumes, time difference between simulated and observed peak time.

In this frame, negative relative error values for peak discharge and flood volumes show the model trend to underestimate while negative errors in time represent the model trend to anticipate flow routing. Actually these three indexes are not independent but can describe the most important feature to evaluate the reliability of the model focusing on its use in operational flood forecasting.

In Table 2, results for FEST runs are reported. The relative error statistics highlight the need of an improvement of the model reliability. Moreover, as shown in figure 2, there is a significant dependency of errors on AMC estimation. In particular the error is higher when the AMC is one, i.e. dry soil, and becomes acceptable as the AMC passes to 3, i.e. wet soil. This problem, linked to the intrinsic uncertainty in AMC estimates, show the difficulty in the operational use of the SCS-CN procedure in its classical formulation. As far as time errors are concerned, peaks are generally simulated late. Anyway, a more detailed analysis showed that high errors are often observed during multiple peaks floods where, even if the simulations catch the right phases, it can happen that the maximum observed discharge is linked to the first peak while in the simulation it occurs in one of the successive peaks.

In Tables 3 and 4, results for FEST-WB runs, respectively, before and after calibration, are reported. Mean, standard deviation and absolute mean, defined as the mean of the absolute value of errors, are reported. Before calibration, it seems that the FEST-WB tends to overestimate peak discharges and a model improvement, on respect to FEST runs, in relative peak discharge errors cannot be appreciated even if there’s no bias for flood volumes relative error. The calibration activity produced a generalised improvement of the model performance both in terms of flood volume and peak discharge errors.

	Flood peak relative error [%]	**Flood volume relative error [%]**	**Time to peak error [hours]**
Mean	-32.21	-45.59	6.7
Absolute Mean	61.00	57.93	8.5
Standard deviation	61.57	47.59	15.0

Table 2. Synthesis of the FEST runs: relative error statistics

	Flood peak relative error [%]	Flood volume relative error [%]	Time to peak error [hours]
Mean	30.07	1.69	0.3
Absolute Mean	69.23	50.18	4.7
Standard deviation	106.58	70.45	8.9

Table 3. Synthesis of the not calibrated FEST-WB runs: relative error statistics

	Flood peak relative error [%]	Flood volume relative error [%]	Time to peak error [hours]
Mean	7.41	-0.89	0.6
Absolute Mean	41.11	34.38	4.6
Standard deviation	64.96	46.70	8.7

Table 4. Synthesis of the calibrated FEST-WB runs: relative error statistics

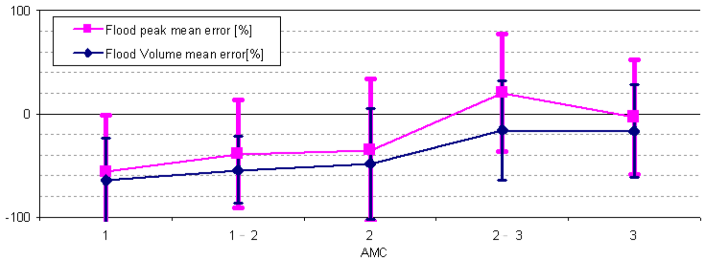

Figure 2. . Errors dependence on AMC

6 Conclusions

The FEST model, based on SCS-CN method and AMC concept for runoff estimation, denoted insufficient accuracy in flood simulation with significant underestimation of both peak and volume flow. Errors are mainly due to flood events characterized by dry soil at the beginning of the rainfall.

The FEST-WB, whose development is addressed to increase the number of processes considered involving a more careful physical description, showed a significant reduction in both peak and volume flow relative error. However, calibration of model parameters proved to be a crucial activity.

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