Effects of soil moisture parameterization on a real-time flood forecasting system based on rainfall thresholds

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Abstract The rainfall threshold is the cumulated rainfall depth required to cause flooding flow at the basin outlet. Thresholds are used in operational flood forecasting systems as a means to provide flood warnings based on the comparison with rainfall amounts (either observed or forecast). This approach results in a simple system that can also be used by non expert technicians; it is a complementary tool to "classical" rainfall–runoff modelling systems. Despite the simple usage, a flood forecasting system based on thresholds requires great accuracy in definition of the critical rainfall. Special attention is required in modelling the basin moisture condition. The aim of this paper is to assess a reliability analysis of a framework for the definition of rainfall thresholds using the distributed hydrological model FEST. The AMC value (antecedent moisture condition) of the conventional SCS-CN method is employed to describe the soil moisture initial condition. The case study is the Arno River basin located in Italy. A detailed investigation of the most recent flood events shows that precise accounting of the watershed wetness based on analysis of actual soil moisture can improve the prediction accuracy of flood forecasting systems.

Key words flood forecasting; rainfall threshold; antecedent moisture condition; reliability analysis

INTRODUCTION

In recent years the interest in the prediction and prevention of natural hazards related to hydrometeorological events has grown due to the increased frequency of extreme rainstorms. In the field of natural weather-related calamities, flood is the worst hazard, causing loss of life and excessive damage to property (Carpenter *et al*., 1999). In 2005, 171 large flood events were reported worldwide (Brakenridge *et al*., 2005) with the loss of 10 140 lives and damages of more than 82 thousand million US dollars.

To reduce flood losses, two strategies are required: structural protection measures like flood retention basins for the reduction of flood hazard, and real time flood forecasting systems for the reduction of flood risk by issuing warning in advance. The model to be employed for flood forecasting depends on the spatial scale. For basins with an area greater than 10 000 km^2, because the travel time is longer than the time required to put in practice actions for flood loss reduction, a river routing model can give sufficient accuracy in flood prediction. For basins smaller than 10 000 km^2, it is necessary to take advantage of the lag time between the onset of a rainstorm and the beginning of the hydrograph rise. When the lag time is very short (basins with area less than 1000 km^2), in order to extend the forecasting horizon, a rainfall predictor is required (Lardet & Obled, 1994; Brath *et al.*, 1988). In small to middle-sized basins, the usual approach is to transform the rainfall into runoff using hydrological models in online mode. For this purpose, in recent years sophisticated continuous hydrological models including complex land surface sub-models have been developed.

An alternative approach operates in offline mode with the *a priori* knowledge of the rainfall patterns which generate flood events. The flood forecasting system requires the definition of the rainfall thresholds, a means to provide warnings based on the comparison with rainfall amounts (either observed or forecast). The rainfall thresholds are commonly used for the prediction and prevention of natural hazards related to hydrometeorological events both in the context of landslide hazard forecasting (Crosta & Frattini, 2000) and of flood prediction (Carpenter *et al.*, 1999; Reed *et al.*, 2002; Martina *et al.*, 2006).

The goal of this paper is to assess a reliability analysis of a framework for the definition of rainfall thresholds for a flood forecasting system. The system's performance with different approaches to describe watershed wetness is evaluated. The case study is the River Arno, in Italy.

FRAMEWORK FOR THE RAINFALL THRESHOLDS ESTIMATION

The rainfall threshold for flood forecasting is defined as the cumulated rainfall depth causing flooding flow at the basin outlet. As a consequence, for the estimation of rainfall thresholds, solution of the inverse hydrological problem is needed. The traditional problem of hydrological research is the modelling of the transformation of rainfall into runoff; here the aim is, on the contrary, to define the amount of rainfall which produces a given flooding discharge.

For this work the distributed conceptual hydrological model FEST98 (Mancini, 1990; Montaldo *et al.*, 2002, 2004, 2007) was employed. The FEST98 model is composed of two modules. The first module computes the direct runoff (Q) for each cell according to the SCS-CN method (US Department of Agriculture Soil Conservation Service, 1985):

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{1}$$

where P is total precipitation, I_a is initial abstraction, and S is potential maximum retention. The second module computes the flow routing to the outlet using the Muskingum-Cunge method in its nonlinear form with the time-variable celerity (Ponce & Chaganti, 1994). For a detailed description of the model refer to Montaldo *et al.*, 2007.

For the solution of the inverse hydrological problem, different sources of variability are considered. The first source of variability can be found in the rainfall rate, considered as varying among three characteristic hyetographs: constant, linear increasing and linear decreasing rate. The second source of variability is the soil moisture condition prior to the storm event (AMC). Following USDA-SCS guidelines, AMC is categorized into three levels according to the five-day antecedent rainfall: AMC I (dry), AMC II (normal) and AMC III (wet).

Soil moisture condition is the most sensitive factor in estimating thresholds. It is recognized to have a key role in the field of flood prediction (Rosso, 1994; Montaldo *et al.*, 2007). An alternative to the classical SCS approach is to use the actual soil moisture as a watershed wetness index. Such a method has been implemented in the AnnAGNPS model (Bingner & Theurer, 2005). It is possible to continue to use equation (1) for runoff evaluation where S becomes a continuous function of the actual soil moisture:

$$S = S_I \cdot \left\{ 1 - \left[\frac{\varepsilon}{\varepsilon + \exp(W_I - W_{II} \cdot \varepsilon)} \right] \right\} \tag{2}$$

with:

$$W_{II} = 2 \cdot \left[\ln\left(\frac{0.5}{1 - \frac{S_{II}}{S_I}} - 0.5 \right) - \ln\left(\frac{1}{1 - \frac{S_{III}}{S_I}} - 1 \right) \right] \tag{3}$$

$$W_I = \ln\left[\frac{1}{1 - \left(\frac{S_{III}}{S_I} \right)} - 1 \right] + W_{II} \tag{4}$$

where S_I is S evaluated for AMC I, S_{II} is S evaluated for AMC II, S_{III} is S evaluated for AMC III, and ε *is* degree of saturation.

After FEST98 is calibrated on the observed runoff data, for each moisture condition, hyetograph type and duration, the threshold value is estimated. The solution (critical rainfall) is found according to an iterative trial and error procedure based on a numerical optimization method (Brent, 1973). Figure 1 shows an example of the resulting thresholds with constant rainfall rate for a section of the River Arno. The different thresholds of AMC I, AMC II, AMC III and ε = 0.2, 0.4, 0.6, 0.8 are represented. The AMC I corresponds to $\varepsilon = 0$ and the AMC III corresponds to $\varepsilon = 1$.

THE CASE STUDY: THE ARNO RIVER BASIN

The framework for the estimation of rainfall thresholds was applied to the Arno River basin in Italy. The greater part of this basin (98%) is located in the Tuscany Region, the remainder in the Umbria Region. The total drainage area is 8 228 km^2. The Arno River originates from the Falterona Mountain at 1385 m a.m.s.l. After flowing for 60 km generally in a northwesterly direction, the river receives its first important tributary, the Chiana channel. It then changes course and takes a path to the Tirrenian Sea. The total flow path is 241 km. The climate is temperate and generally characterized by extreme rainfall events in spring and autumn. On 4 November 1966, one of the major flood events was recorded: at the section of Nave di Rosano a discharge of 3540 m^3/s was observed (recurrence interval greater than 200 years). The high rainfall intensity was positioned on the north part of the basin, the Sieve River and the upper Arno River. The cumulative rainfall in 24 hours was 130 mm over the

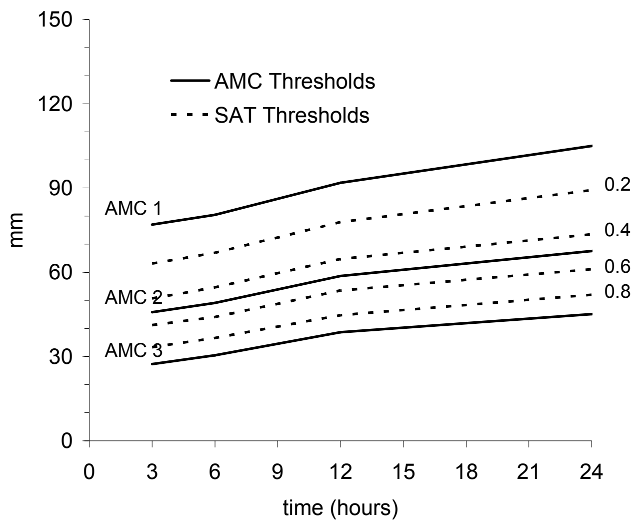

Fig. 1 Rainfall thresholds computed for the Rignano cross-section, on the River Arno, Italy. Solid lines show thresholds estimated for the three levels of AMC following classical SCS-CN guidelines. Dotted lines show thresholds estimated according to the alternative approach as a function of the 0.2, 0.4, 0.6, 0.8 soil degree of saturation.

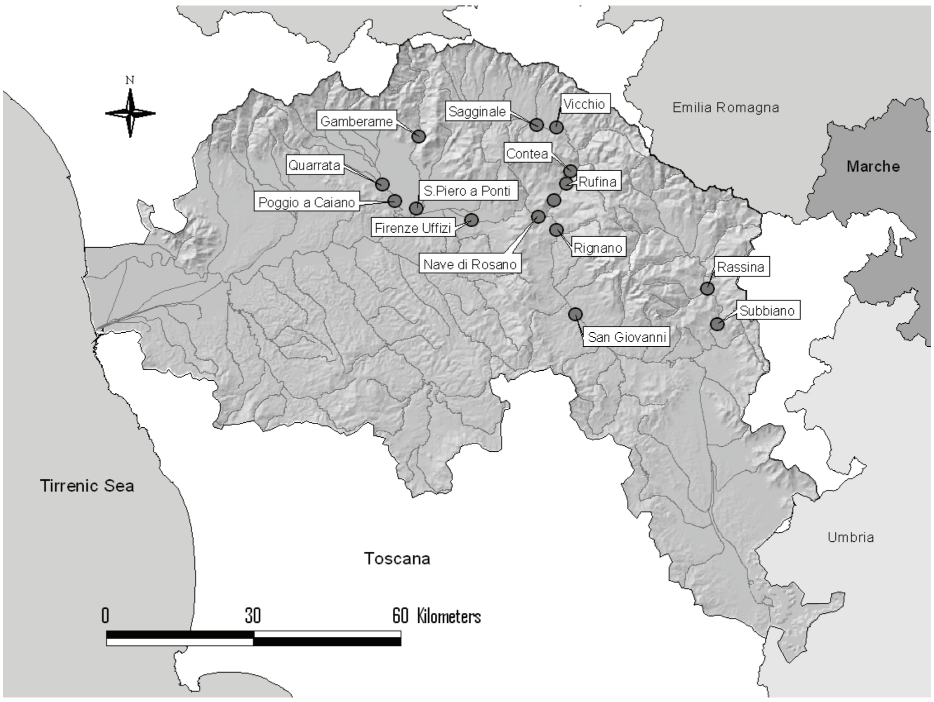

Fig. 2 Location of the 15 sections on the River Arno basin, in Italy, where rainfall thresholds have been estimated.

sub-basin of Nave di Rosano, 180 mm over Subbiano and 200 mm over Pontassieve. With the aim of flood risk reduction, the *Autorità di Bacino del fiume Arno* (the River Basin Authority), has started the development of a real-time flood forecasting system called ARTU. In this framework, rainfall thresholds were evaluated for 15 sections located on the Arno River and its tributaries Sieve, Ombrone and Bisenzio (Fig. 2).

The flooding discharge at the critical sections is characterized by a recurrence interval of two years. The area of the sub-basins varies from a minimum of 151 km^2 for Gamberame to a maximum of 4267 km^2 for Firenze. The time of concentration varies in the range 4–35 hours.

For this study, rainfall and river discharge observations with an hourly step were available for nine years from 1992 to 2000. Measures of discharge were available for the section of Subbiano, Nave di Rosano, Pontassieve, S. Piero a Ponti and Poggio a Caiano. For the other sections, discharge data were not available or they were not validated. For the period from June to September 2006 hourly temperature observations were also available.

RELIABILITY ANALYSIS

For this work the thresholds based on the classical AMC concept with three categories (called AMC thresholds in the following) were investigated. The reliability analysis was based on the hourly time series of observed rainfall and river discharge data. Rainfall data were averaged over the sub-basins with the Thiessen polygon method. From the rainfall–discharge continuous time series, only the events which overtopped a significant discharge were extracted. For each event, the AMC class was evaluated by summing the rainfall of the prior five days. Cumulated rainfall was compared to the threshold which, for a given AMC class, is variable as a function of time and hyetograph type.

In order to test the reliability of rainfall thresholds for flood prediction on the Arno River basin, following the meteorological practice (Mason & Graham, 1999), a framework based on contingency tables was used. These contingency tables indicate the quality of a forecast system by considering its ability to anticipate correctly the occurrence or non-occurrence of predefined events that are expressed in binary terms. A warning, W, is defined as a forecast of an occurring event, E (Table 1). The number, n, of total observations consists of the occurred events e, and the non-events e'; the total number of warnings is w, and the number of no-warnings is w'. The following outcomes are defined: (1) a hit, if an event occurred and the warning was provided (h is the number of hits); (2) a false alarm, if an event did not occur but the warning was provided (f is the number of false alarms); (3) a miss, if an event occurred but the warning was not provided (m is the number of misses); (4) a correct rejection, if an event did not occur and the warning was not provided (c is the number of correct rejections); (5) a delayed hit, if an event occurred and a warning was provided later (d is the number of delayed hits).

Table 1 Two-by-two contingency table for verification of a threshold-based forecasting system.

	Forecasts		
Observations	Warning (W)	No warning (W')	Total
Event (E)	h	m	e
Non-event (E')	f	c	e'
Total	w	w'	n

Table 2 Results for reliability analysis at the main river sections on the River Arno basin.

Outcome	River section: Nave di Rosano	Subbiano	Pontassieve	S. Piero a Ponti	Poggio a Caiano
Hit (*h*)	2	2	4	0	1
False alarm (*f*)	1	3	1	1	0
Miss (*m*)	1	1	1	0	0
Correct reject. (*c*)	8	9	15	3	11
Delayed hit (*d*)	0	2	2	0	0
Total (*n*)	12	17	23	4	12

Table 3 indexes for the evaluation of the skill of the forecasting system for the River Arno basin based on rainfall thresholds.

Index	River section: Nave di Rosano	Subbiano	Pontassieve	S. Piero a Ponti	Poggio a Caiano
POD	0.667	0.667	0.800	-	1
FAR	0.111	0.250	0.063	0.250	0
CSI	0.615	0.545	0.759	-	1
CPI	0.833	0.647	0.826	0.750	1

The skill of the forecasting system can be represented on the basis of the probability of detection (POD) defined as $h/(h + m)$, the false alarm ratio (FAR) defined as $f/(f + c)$, the critical success index (CSI) defined as $1/[1/(1 - \text{FAR}) + (1/\text{POD}) - 1]$ and the correct performance index (CPI) defined as $(c + h)/n$.

The results of the reliability analysis are shown in Table 2. In nine years the total number of observations (significant occurrences) is greater than 10, except for the Poggio a Caiano section where the number of significant events is four. Table 3 shows the system performs quiet well on all five river sections. The POD results are greater than FAR, except for the S. Piero a Ponti section. In fact, because of the lack of events exceeding the critical discharge, in that section FAR is not definable. Also the result for Poggio a Caiano is a bit distorted, as only one event has exceeded the critical discharge. The correct performance index, a measure of the overall performance of the system, gives results greater than 75%, except for the Subbiano section where CPI = 0.647. But, if we consider that the system receives rainfall forecasts 48–72 hours in advance, it is logical to suppose that the delayed hits reduce to zero in real time operational configuration. As a consequence, the CPI becomes 0.765 for the Subbiano section and 0.913 for Pontassieve.

THE 17 SEPTEMBER 2006 FLOOD EVENT

Flood events usually occur on the River Arno basin in spring and more frequently in autumn. One of the most recent floods was reported during September 2006. The summer of 2006 was dry. It was characterized by some rare and localized convective phenomena with a total precipitation of 110 mm observed from June to 14 September 2006. During the night between Saturday 16 September 2006 and Sunday 17

September 2006, heavy rainfall was recorded over the entire Arno River basin. The greater intensity was on the southeast part, the Chiana tributary. The raingauge at Pratomagno, Chiana sub basin, recorded a 15-hour rainfall of 180 mm. The cumulative rainfall measured in 20 hours on the basin of Nave di Rosano was 73 mm (recurrence interval estimated to be about 10 years). As a result of the intense rainfall, flooding occurred in a less severe way than expected. The observed peak flow of the Arno River at Rignano was 600 m^3/s (the flood warning is 900 m^3/s) with a recurrence time interval less than two years. Actually some responsibility for peak reduction was due to two flood retention basins, Levane and La Penna, located just upstream of the S. Giovanni Valdarno section; at the time of writing, data for the two reservoirs are not available, so a quantitative analysis of their effects on the hydrograph is impossible.

Figure 3 shows the behaviour of the thresholds-based flood forecasting system at the Nave di Rosano, Rignano and S. Giovanni Valdarno sections. The jumps in the threshold are due to the change in hyetograph type. During the antecedent days, the rainfall was enough to set the AMC to wet condition. The cumulated rainfall met the AMC threshold so issuing a warning. In all the other sections, where the cumulated rainfall was less, no warning was issued. The results in the three sections mentioned above can be regarded as false alarms, as the peak discharge remained less than the flood warning flow.

Better results can be obtained by using the thresholds based on soil saturation (called SAT thresholds in the following). In fact, the rainfall of the previous days was not enough to actually saturate the soil moisture as indicated by AMC, because of the scarcity of precipitation in the preceding dry season and the significant evaporation rate due to high temperatures recorded in September.

To use the SAT thresholds, a method to estimate average basin soil moisture is required. One possible solution is to retrieve information from satellite observations (Caschili *et al.*, 2003). In this work we estimated the soil moisture by simulating the hydrological balance of the Arno River basin for the period from June 2006 to the beginning of the flood event. The period is considered long enough to remove the influence of the initial condition. The distributed model FEST was modified to

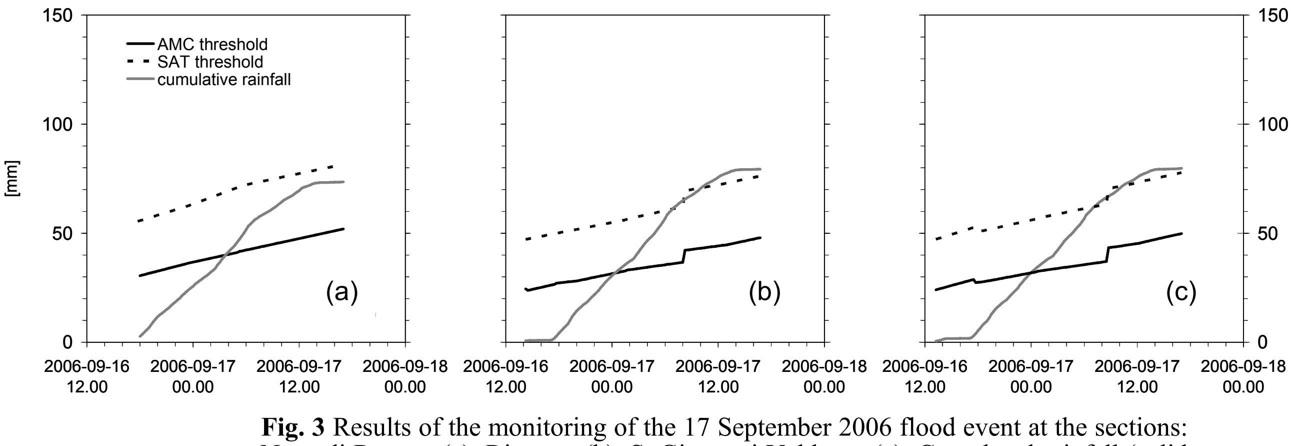

Fig. 3 Results of the monitoring of the 17 September 2006 flood event at the sections: Nave di Rosano (a), Rignano (b), S. Giovanni Valdarno (c). Cumulated rainfall (solid grey line) is compared to AMC threshold (solid black line) and SAT threshold (dotted black line).

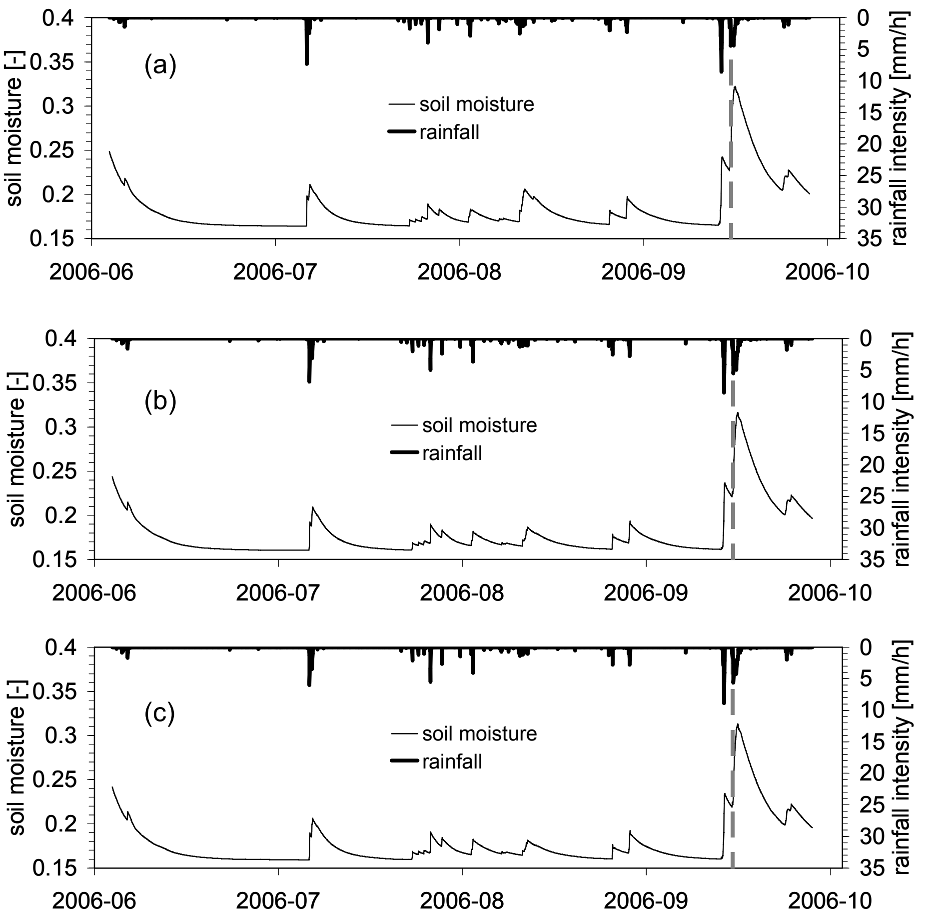

Fig. 4 Soil moisture dynamic (thin black line) simulated by means of FEST for the sub-basins of Nave di Rosano (a), Rignano (b), and S. Giovanni Valdarno (c). Vertical dotted grey line points out the beginning of the event.

simulate the soil moisture of each cell at an hourly time step, starting from an initial condition, by computing the mass conservation law for a single fixed soil layer:

$$\theta_{t+1} = \theta_t + \frac{(P - Q_{S_t} - D - ET)}{Z} \tag{5}$$

where θ_{t+1} and θ_t are the soil moisture at $t + 1$ and t time, respectively, P = precipitation, Q_{S_t} = runoff estimated from equation (1) on the basis of S calculated as function of θ_t, D = downward drainage, ET = evapotranspiration, and Z = soil depth. Drainage is evaluated as actual hydraulic conductivity, a function of soil moisture (Brooks & Corey, 1966). Evapotranspiration is evaluated from the potential rate (Hargreaves & Samani, 1982) as a linear function of soil moisture (details in Montaldo *et al.*, 2003).

The basin soil moisture dynamics are shown in Fig. 4. The average degree of soil saturation at the beginning of the rainstorm approximates the value of 0.4–0.5 in all the three sub-basins. Rainfall thresholds for that value are closer to the AMC II than the AMC III condition (Fig. 2). In fact, from Fig. 3 it is seen that, when using SAT thresholds, warning are not issued at Nave di Rosano, while, at the sections of Rignano and S. Giovanni Valdarno, cumulated rainfall is just enough to intercept the SAT threshold.

CONCLUSIONS

The paper presents a method for the estimation of rainfall thresholds based on the solution of the inverse hydrological problem. Application of the warning system to the historical flood events on the Arno River basin showed a high degree of reliability. However, in the most recent flood event on the Arno River basin, a false alarm was issued at three sections. The error is due to an incorrect estimation of the basin wetness index. The SCS method, which distinguishes three AMC categories only on the basis of past precipitation, is unsuitable if evapotranspiration has a key role in the soil moisture dynamics. The use of actual soil moisture as a basin wetness index, in conjunction with a method for estimation of soil moisture at the beginning of the rainstorm, leads to an improved result.

The next step will be to extend the reliability analysis of the SAT thresholds to the historical events of the River Arno basin.

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