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COMPARING DIFFERENT INFILTRATION METHODS OF THE HEC-HMS MODEL: THE CASE STUDY OF THE MÉSIMA TORRENT (SOUTHERN ITALY)

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COMPARING DIFFERENT INFILTRATION METHODS OF THE HEC-HMS MODEL: THE CASE STUDY OF THE MÉSIMA TORRENT (SOUTHERN ITALY)

INFILTRATION METHODS OF THE HEC-HMS MODEL IN TORRENTS OF SOUTH ITALY

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ABSTRACT

The HEC-HMS model has been widely applied for estimating hydrological variables at event scale. The choice of the most suitable infiltration method simplifies model's applicability under different environmental conditions. A proper case study for evaluating the runoff prediction capability of HEC-HMS by the available infiltration methods are the semi-arid torrents typical of Southern Italy as they are small and intermittent water courses, often subject to high-magnitude flash floods and erosive events. HEC-HMS performance of the "SCS-CN", "Green-Ampt" and "Initial and Constant" infiltration methods in predicting runoff volume and peak flow was evaluated at the outlet of the Mésima torrent, Calabria, Southern Italy. Fourteen rainfall-runoff events were simulated by HEC-HMS and compared with the corresponding observations by a quantitative approach. A good accuracy in predicting runoff volume was achieved using the "SCS-CN" method after calibration of the initial CNs. Peak flow was better estimated using the "Initial and Constant" method, also thanks to calibration of the "Constant Rate" parameter. The calibrated hydrographs were very similar to the

observations for both "SCS-CN" and "Initial and Constant" methods. Adopting the “Green-Ampt” equations, however, showed low reliability. The evaluation of the time to flood peak was in some cases inadequate.

KEYWORDS: HEC-HMS, semi-arid torrents, SCS-CN, Green-Ampt, Initial and Constant Loss.

INTRODUCTION

Negative impacts of surface runoff and, as a consequence, of soil erosion and pollutant transport can be predicted by computer models on different temporal and spatial scales (Keesstra, 2007; Keesstra et al., 2009; Bisantino et al., 2015; Gessesse et al., 2015; Zema et al., 2015). In spite of the availability of guidelines in reference manuals, the use of these models can be practically difficult, particularly in basins with peculiar climatic and geo-morphological characteristics, often different from the environments in which the hydrological models have been developed. In such contexts, the availability of previous studies, in which the models have been successfully used and verified, could simplify the analysis of hydrological processes and therefore provide guidelines for watershed management. For example, often the choice of the proper hydrological sub-model among methods of different nature (e.g. empirical, physically-based, conceptual) and complexity can be a time-consuming and difficult task (Keesstra, 2007; Lieskovský & Kenderessy, 2014; Cao et al., 2015), because reliability of runoff estimations is a prerequisite for predictions of other hydrological (e.g. soil loss and sediment yield) or environmental (e.g. pollutant loads) variables. This is the case of the conceptual model HEC-HMS (“Hydrologic Engineering Center - Hydrologic Modelling System”, USACE, 2000), widely used in hydrology, which provides eleven infiltration methods, called "loss methods" in the manual, for predicting surface runoff.

Beside the difficulty in choosing the most reliable infiltration method, HEC-HMS applicability outside the United States, in which the model was developed, is not completely defined and thus should be further experimented under other geomorphological and climatic conditions, in order to definitely assure its spatial transferability to different environmental contexts.

Concerning semi-arid conditions, Martìn-Rosales et al. (2007) applied the model to estimate groundwater recharge induced by check dams and gravel pits in Mediterranean mountains (the Campo de Dalìas basin, 320 km^2) of south-eastern Spain, demonstrating the high hydrogeological efficiency of gravel pits. In the City Creek basin (50.8 km^2), located in the San Bernardino Mountains (California), HEC-HMS was easily applied to support prediction of postfire floods (Cydzik and Hogue, 2009). Mashayekhi et al. (2009) calibrated HEC-HMS in the Bazoft torrent, a 2300-km^2 basin covered by sub-Mediterranean forests in Iran, and noticed the significant role of forest cover compared to likely alternative scenarios. The HEC-HMS model was used to simulate the impact of land-use changes on surface runoff by Ali et al. (2011), who found good consistency between the simulated and the measured hydrographs at the outlet of the Lai Nullah basin (235 km^2, Pakistan). More recently, Abushandi & Merkel (2013) calibrated the model in the Wadi Dhuliel catchment (2800 km^2, Jordan) and found that calibrated streamflows fit well with the observations.

However, its verification in the Mediterranean torrents typical of Southern Italy (the *fiumara*s of Calabria and Sicily regions) has never been carried out before. *Fiumara* is a local name used to describe seasonally-flowing streams which drain the mountain chains of Calabria and Sicily (Bombino et al., 2007). These streams, characterized by steep slopes and small catchments, have an intermittent regime; the response to the very intense rainfall events produces high-magnitude flash floods and erosive events, often causing hydrogeological instability and disruption (Zema et al., 2014).

This paper evaluates the ability of HEC-HMS to predict runoff volumes, peak flows, times to flood peaks and simulate hydrographs of rainfall-runoff events in the Mésima torrent, a *fiumara* of Calabria, Southern Italy, which helps to better define the boundary conditions under which the model may be successfully used in the experimental environmental conditions. By this study, three of the different infiltration methods of HEC-HMS are evaluated and guidelines about model parameterisation and performance for the experimental conditions are given.

MATERIALS AND METHODS

The studied basin

The Mésima torrent (Figure 1), whose basin, of ellipsoidal shape (Gravelius index of 1.5), has an area of 795 km^2 and a perimeter of 152 km, originates in the Serre mountain system at 1245 metres a.s.l. and flows 43 km into the Tyrrhenian Sea. The mean altitude is 395 m and the average slope steepness is 28.6%.

Land use and soil data of the studied basin were extracted from large-scale maps. The use of coarse resolution data is a deliberate choice, because this is widely available for watersheds of Southern Italy, whereas more detailed data is usually lacking.

According to the “Corine Land Cover” (scale 1:100000, 2007) classification (Figure 2a), the basin is predominantly agricultural (65.8% of the total area) with olive groves, intensive crops (mainly tomatoes, potatoes, beans and courgettes) and orchards (citrus, olive and kiwi fruit). Forest areas and artificial surfaces cover 31.1% and 3.1% of the remaining basin area (Figure 2a).

Soil data were derived from the “Soil Map of the Calabria Region” (scale 1:250000, ARSSA, 2003). The prevalent texture of the soils in the basin is sandy loam (50% of the basin area) with the presence of loam (19%) and clay loam (18%) zones (USDA, 1985). The soils were identified from texture data as prevalently hydrological group "A" (that is, soils with low runoff potential when thoroughly wet) (Figures 2b and 2c).

The climate is semi-arid, typical of the Mediterranean basin, with mild winters and hot summers (Csa type, according to Koppen-Geiger's classification, 2006). Precipitation (annual average of 900 mm) is distributed mainly in autumn and winter. The average minimum temperature is 4.2 °C, while the average maximum value is 31.8 °C (meteorological station of Arena, 38.5613°N, 16.2166°E).

Brief description of the HEC-HMS model

HEC-HMS is a hydrological model, developed since 1998 by the "US Army Corps of Engineers" (Feldman, 2000), capable of incorporating spatially varied land use by subdividing the watershed such that only subareas with homogeneous land use exist (Beighley et al., 2003). The model has been designed to simulate the rainfall-runoff processes and forecast streamflow of dendritic basin systems in a wide range of geographic areas such as large river basins and small urban or natural watersheds (Abushandi & Merkel, 2013; Verma et al., 2010).

The model provides a suite of hydrological modelling options, with the main components focusing on determining runoff hydrographs from sub-basins and routing the hydrographs through channels to the study outlet (Beighley et al., 2003; Beighley & Moglen, 2003). Users can select different methods based on existing data and local characteristics. Moreover, spatial data can be prepared in GIS platform and directly imported into HEC-HMS (Ali et al., 2011) (Figure 3).

The HEC-HMS model contains: i) an analytical model to calculate overland flow runoff as well as channel routing; ii) an advanced graphical user interface illustrating hydrologic system components with interactive features; iii) a system for storing and managing data, specifically large, time variable data sets; and iv) a means for displaying and reporting model outputs (Halwatura & Najim, 2013). Concerning its structure (Figure 3), the model consists of the following four "components" (U.S. Army Corps of Engineers, USACE, 2015):

- "*Basin Model"*, which estimates hydrologic losses (as infiltration), rainfall-runoff transformation, baseflow, routing, and specifies the general characteristics of the basin (Kamali et al., 2013);

- "*Meteorological Model"*, which calculates the precipitation input required by a sub-basin element (Ali et al., 2011);

- "*Control Specification",* specifying the time step, the inception and the simulation period (Kamali et al., 2013);

- *"Input Data",* to provide the observed hydrological variables to the model, as *Time-Series Data, Gridded Data* and/or *Paired Data* (U.S. Army Corps of Engineers, USACE, 2015).

The first step in the application of HEC-HMS is defining the basin area and sub-basins, a stream network, and diversions and junctions. HEC-HMS simulates most of the key hydrologic processes at watershed scale (Abushandi & Merkel, 2013) and uses separate methods to represent each component of the runoff process, including methods that compute runoff volume, methods of direct runoff and methods of baseflow. Firstly, runoff volume is calculated by an infiltration method; it implicitly combines the subsurface flow and overland flow and models this as direct runoff. Precipitation on the pervious surfaces is subject to losses, which is found by the different methods for each computation time interval and subtracted from the mean areal precipitation depth for that interval; the remaining depth is referred to as precipitation excess and is considered uniformly distributed over a watershed, so it represents a volume of runoff. Then, HEC-HMS transforms the rainfall excess into direct surface runoff through a rainfall-runoff transformation method. Finally, the baseflow method is applied both at the start of simulation of a storm event and later in the event as the delayed subsurface flow reaches the watershed channels (Verma et al., 2010).

HEC-HMS model implementation and evaluation

The hydrological database ("Regional Agency for Environmental Protection of Calabria") used for model verification contains the following data related to the period of January 2008 – May 2011:

- hourly rainfall, collected at 16 rain gauging stations, of which 5 are located inside the basin and 9 within a maximum distance of 15 km from the basin perimeter (Figure 4);
- surface water discharge, measured at a time step of 20 minutes by an ultrasonic flow meter at the basin outlet, close to the municipality of Rosarno (38.5006°N, 15.9875°E) (Figures 2 and 4). Baseflow was identified in the observed hydrograph by the "straight-line" method.

In order to spatially scale the rainfall input, Thiessen's polygon method (Thiessen, 1911) was applied: 15 polygons were drawn covering the entire basin area (Figure 4).

In the hourly rainfall series of the experimental database, two consecutive events were considered separate, if no rainfall was recorded for six hours or more (Wischmeier & Smith, 1978). For model evaluation, all the events with a peak flow higher than 100 m^3/s were selected, resulting in a sample of 14 rainfall/runoff events. Each event had rainfall up to 125 mm with an intensity of up to 15.1 mm/h and duration from 45 to 132 hours. The maximum observed peak flow was 451 m^3/s (Table I).

Preliminarily, possible correlations between the rainfall and the runoff attributes were analysed. The matrix reported in Table II highlights significant correlations between rainfall duration and total runoff volume (r^2 = 0.68), rainfall intensity and runoff coefficient (r^2 = - 0.70) and maximum rainfall intensity and peak discharge (r^2 = 0.80). No correlation was found instead between total precipitation and runoff (r^2 = 0.45). These preliminary outcomes suggest the use of hydrological models to achieve reliable predictions of total runoff or to improve estimations of peak flow.

Prior to using HEC-HMS, a 20-m resolution Digital Elevation Model (DEM) was used to divide the basin into three interconnected sub-basins and simulate the stream network by a GIS software (QuantumGIS version 2.6 “Brighton”). A more detailed discretisation was not made given the available low-resolution land use and soil texture maps.

Using the GIS software, the map of the homogenous response units (HRUs) was built (Figure 2d). To this end, the maps of land use and soil type were overlaid, identifying the HRUs with a given land use and soil type. Therefore, each HRU is characterized by a specific land use and soil type on which its hydrological behaviour depends.

Among the eleven infiltration methods of the HEC-HMS model, “SCS-CN” (USDA-SCS, 1972), “Green-Ampt” (Rawls et al., 1983) and “Initial and constant” methods (USDA-NRCS, 1986) were chosen. More details about equations simulating infiltration losses can be found for "SCS-CN" and "Initial and Constant" methods in the HEC-HMS Technical Manual (Feldman, 2000), and for "Green-Ampt" method in the papers of Jin et al. (2015) as well as Ficklin and Zhang (2013).

The three infiltration methods analysed in this study were selected, because the required input parameters were available or could be easily estimated by the experimental database of the studied basin. Moreover, previous studies have shown that the "Initial and Constant" and "SCS-CN" methods have been used successfully to model flooding (Jin et al., 2015), being conceptually simple models. The more complex “Green-Ampt" method was applied to assess its performance in the present case of scarcity of soil data, but availability of sub-daily precipitations. Even though the Green-Ampt model is physically based, Wilcox et al. (1990) showed that the many regression equations that are needed to parameterize it may dilute much of the “physically based” aspect of the model (Ficklin & Zhang, 2013).

In relation to the "SCS-CN” method, the average value of the initial Curve Number (CN) was calculated for each identified sub-basin: the CN, identified for each HRU of the sub-basins according to the USDA-SCS guidelines (1972), was weighted by its area. Furthermore, the initial CN was updated to the Antecedent Moisture Condition (AMC) of the soils prior to each rainfall event. AMC was determined by the total rainfall in the 5-day period preceding a storm (USDA-SCS, 1972). Thus, the “Initial Abstraction” and the “Lag time” (for the SCS-UH transform method), which depend on CN, were calculated for each sub-basin (Table III).

In relation to the "Green-Ampt” method, the input parameters (“Saturated water content”, “Initial water content”, “Wetting front suction” and “Hydraulic conductivity”) were estimated as functions of the prevalent hydrological group and texture of soils of the three studied sub-basins, adopting the values suggested by the HEC-HMS Manual (Feldman, 2000) (Table III).

The "Initial and Constant" method requires two input parameters: the "Initial loss" (IL) and the “Constant Rate” (CR). For the estimation of IL, the range suggested by the HEC-HMS manual was initially used. In more detail, the values of 12.7 mm (AMC I, dry soil), 25.4 mm (AMC II, medium water content) and 38.1 mm (AMC III, wet soil) were adopted for agricultural and forested areas, while the values of 2.54 (AMC I), 3.81 (AMC II) and 5.08 (AMC III) mm were input for urban areas. IL was spatially scaled according to the land use distribution, in order to identify a lumped value for each of the three sub-basins. The lack of the measured values of CR for the modelled sub-basins forced an initial use of the range suggested by the HEC-HMS manual or a Pedo-Transfer Function (PTF) (Table III).

A total of seven different rainfall-runoff transformation methods are provided in HEC-HMS. Some of these methods are unsuitable because they require more inputs which are not available for most of the ungauged catchments (Halwatura & Najim, 2013). In this study the "SCS unit hydrograph" (SCS-UH) method was selected, because it requires only the input of lag time. Moreover, Jin et al. (2015) have reported good performance in basin hydrological modelling using the SCS-UH for the direct runoff.

Concerning model evaluation procedure, the total volume of surface runoff and the peak flow were simulated at the torrent outlet for each of the 14 rainfall events by using the three selected methods. Due to its simplicity, the "Constant baseflow" method was selected to represent storm baseflow and estimated by the observed streamflow at the beginning of each storm. Baseflow was allocated to specific sub-basins by the relative area (%) in the basin (Cydzik & Hogue, 2009).

The “Green-Ampt” method was simply verified without calibration, being a physically-based model (Rawls et al., 1983; Damodhara Rao et al., 2006; Ying et al., 2010), while the "SCS-CN" and "Initial and Constant" methods were calibrated/validated taking into account the most sensitive inputs (CNs for "SCS-CN" method, USDA, 1975; Kamali et al., 2013; Initial Loss and Constant Rate for "Initial and Constant" method, Jin et al., 2015). Nine events (three for each AMC) were used for calibration and five (the remaining events of the hydrological database) for validation.

For the "SCS-CN" method the calibration/validation process was carried out by modifying the "default" initial CN for each sub-basin and AMC. CN represents a key factor in obtaining accurate prediction of runoff and sediment yield (Yuan et al., 2001; Shrestha et al., 2006) and the most important input parameter to which the runoff is sensitive (Yuan et al., 2001; Baginska et al., 2003). The separate calibration for each AMC depends on the importance of the soil water content as a factor controlling modelled runoff from the medium to low intensity storms, as in the present study;

in other words, runoff from less intense storms on soils of high permeability, such as sandy soils (more than 50% of the basin area), is controlled by the surface water content and is more dependent on initial conditions compared to the events following high rain intensities or less permeable soils (Castillo et al., 2003; Zhang et al., 2011).

For the "Initial and Constant" method, we tried to identify a possible correlation among the input parameter CR and the maximum intensity of each rainfall event in the calibration phase. The calibrated model was thus evaluated in the case of IL input parameter taken from the reference manual (indicated in the following by the letter "I") or by estimating IL by the "SCS-CN" method (letter "II").

Once the optimization process was completed with the selected rainfall events for the calibration phase, the optimized parameters ("Initial CNs" for "SCS-CN" and "Constant Rate" for "Initial and Constant" methods) were taken as input for model validation by the remaining rainfall events.

HEC-HMS performance was evaluated at the event scale by qualitative and quantitative approaches. The qualitative procedure consisted of visually comparing observed and simulated values of the simulated hydrological variables. For quantitative evaluation the set of summary and difference measures as well as coefficients of model efficiency reported by Licciardello et al. (2007) and Zema et al. (2012; 2016) were used: mean, standard deviation, minimum and maximum values of observed and simulated values; coefficient of determination (r^2); Nash & Sutcliffe (1970) coefficient of efficiency (E) and its modified form (E_1); Root Mean Square Error (RMSE) and Coefficient of Residual Mass (CRM). Model performance is optimal if RMSE and CRM = 0 and r^2, E and E_1 = 1, good if E ≥ 0.75, satisfactory if 0.36 ≤ E ≤ 0.75 and unsatisfactory if E ≤ 0.36 (Van Liew & Garbrecht, 2003).

Finally, the model accuracy in estimating the times to peak of the modelled floods was evaluated for the 14 flood events by comparing the observed and simulated values using the three selected methods.

RESULTS AND DISCUSSIONS

"SCS-CN" method

A low accuracy in predicting surface runoff was shown by HEC-HMS using the same initial CN for all AMCs, given the high differences among the observed and simulated mean values of total runoff (up to +110%) and peak flow (+96%). Then, in successive model runs different CNs were input for each sub-basin and AMC.

Model predictions with default input parameters were not reliable, as shown by the under-estimation of total runoff (on the average by 33%) and peak flow (by 44%) (see also the positive value of CRM); the maximum differences between observed and simulated values of the hydrological variables were 76.7% for total runoff and 92.3% for peak flow. Moreover, model efficiency was very low, as shown by the negative values of E and E_1 coefficients (Table IV). Also, trials with a basin discretisation in more than three sub-basins did not improve runoff prediction capability of HEC-HMS.

The model was then calibrated by increasing the initial CNs on average by 20% in order to increase the aptitude to produce runoff; after calibration, the values of the hydrological variables simulated by HEC-HMS were noticeably closer to the corresponding observations. These differences were lower than ±20% both for total runoff and peak flow and, as expected, slightly higher in the validation phase (Table IV). In general, total runoff volume was estimated with a higher accuracy than peak flow; 13 of the 14 modelled simulated hydrological variables fall very close to the identity (1:1) line (Figure 5). However, for the event recorded on 1-3 November 2010, total runoff and peak flow simulated by the model were very different from the corresponding observations in spite of calibration. For this event a relatively high rainfall intensity was observed, up to 15.1 mm/h, which produced noticeable surface runoff on a soil wetted by previous low rainfalls. The model adopted the driest AMC, thus hypothesizing a dry soil; as a consequence of the low initial CN, it simulated a high infiltration capacity of soils, thus determining an unrealistic low capacity of runoff production.

On the whole, the calibration process allowed (Table IV): i) a decrease in the model's tendency to underestimate runoff (CRM = 0.10-0.12), found for the default model; ii) closer statistics between the predictions and the corresponding observations of total runoff and peak flow (average and maximum differences not higher than 12% and 20% respectively); iii) a noticeable reduction (-77%) of the RMSE; iv) a higher model efficiency (maximum E = 0.30 for peak flow and 0.74 for total runoff).

According to Van Liew & Garbrecht (2003), the model's efficiency, measured by E, in predicting peak flow is considered unsatisfactory. If the event recorded on 1-3 November 2010 is excluded from the analysis, the values of E increase up to 0.93 for peak flow and 0.96 for total runoff and the model performance can be considered good. The prediction capability of the hydrological variables shown by HEC-HMS in the Mésima torrent can be considered even better if we take into account the low spatial resolution of input soil data. The values of model efficiency found in the studied basin are close to the maximum E (0.92, 0.88 and 0.96) found in other HEC-HMS calibrations in semi-arid basins by El Hassan et al. (2013), Abushandi & Merkel (2013) and Ali et al. (2011) respectively. Jin et al. (2015) achieved a model efficiency always higher than 0.70 in applying HEC-HMS in a semi-arid region of Northern China. Concerning the difference measures, El Hassan et al. (2013) after model calibration reported errors not higher than 27-30% for both total runoff and peak flow, thus with model performances only slightly worse than our findings. Deviations between observed and calibrated runoff volumes and peak flows were found by Ali et al. (2011) to be lower than 12% and 4% respectively. In their study basin Cydzik & Hogue (2009) noticed differences up to 50% in predicting runoff volumes before prefire storms and lower than 8% in simulating peak flows.

"Green-Ampt" method

Predicting the water infiltration by the "Green-Ampt" method, the HEC-HMS model showed low accuracy in estimating both the modelled hydrological variables (Figure 6): underprediction was on average 49% for peak flow and 78% for total runoff (see also the positive value of CRM). Maximum differences of 81% for total runoff and 92% for peak flow were found. Moreover, a very low model efficiency was detected, as shown by the negative values of E and E_1 (Table V).

Even though physically-based models theoretically do not require calibration due to their conceptual nature (Guinot & Gourbesville, 2003; Merritt et al., 2003), we did try to improve runoff prediction capability of the "Green-Ampt" method, tuning the soil hydraulic conductivity (K_s) by the values suggested in the literature for sandy-loamy soils. After this attempt, HEC-HMS predictions slightly improved only when we used unrealistic values of K_s; in other words, we were forced to input very low K_s, typical of other soil textures.

This low model accuracy may be attributable to a series of factors. First of all, the Green-Ampt equation is sensitive to the effective hydraulic conductivity of soils and thus its accurate estimation is important for runoff prediction capacity. In our study, the lack of soil measurements forced the modellers to estimate the soil hydraulic properties by means of a PTF or regression equations, as suggested also by the HEC-HMS manual. Moreover, the physically-based Green-Ampt model predicts surface runoff only when the precipitation intensity is greater than the soil infiltration rate. The 14 rainfall events used for model evaluation are characterized by long durations and low intensities (on the average 1-2 mm/h, Table V), often much lower than the soil infiltration capacity (20-27 mm/h). This may be one of the reasons for the high model underestimation of the observed runoff and peak flow (see the values of CRM, Table V). This is also confirmed by the findings of Ficklin & Zhang (2013), who compared the Curve Number and Green-Ampt models in modelling an agricultural basin (San Joaquin Torrent, California, USA); these authors noticed that the Green-Ampt model has the ability to predict large storm events better than the curve number model, while this latter may better predict normal flow events. Finally, the physically-based nature of the Green-Ampt model would require a higher discretisation of the modelled basin, to take into account the variability in soil properties and thus the different runoff production capacities of the different areas of the basin. For example, Lane et al. (1978) reported that significant errors in estimating runoff are possible if it is assumed that a basin contributes runoff uniformly over the entire area when only a small area within the basin is actually contributing all of the runoff. Even adopting a basin discretisation of more than three sub-units, as also carried out when the "SCS-CN" method was chosen as model, runoff was not correctly reproduced by the HEC-HMS model using the "Green-Ampt" method.

"Initial and Constant" method

Using the "Initial and Constant" method, HEC-HMS predictions of the hydrological variables with default input parameters were basically poor (Table VI). Since model accuracy did not improve by estimating the values of "Constant Rate" using the common PTF of Saxton et al. (1986), the model was calibrated.

As mentioned before, in the calibration/validation procedures the "Initial Loss" was estimated by two methods. Using the IL values provided by the HEC-HMS manual, we found an appreciable correlation (r^2 = 0.64), between CR and the maximum rainfall intensity (I) of the nine rainfall events used for calibration, each one spatially scaled in each sub-basin. This equation has the following expression:

$$CR = 0.384\ I + 1.066 \qquad [1]$$

Calculating CR by equation [1], model performance noticeably improved. The total runoff predictions were satisfactory with an average underestimation of 11% and E equal to 0.73. HEC-HMS performed better for predicting peak flow, as shown by the very low differences between the observed and simulated values, on the average less than 2%, and good model efficiency, as shown by E and E_1 (Table VI and Figure 7).

Estimating the "Initial Loss" by the SCS-CN method, the value of r^2 in the equation [2] increased to 0.88:

$$CR = 0.423\ I + 0.878 \qquad [2]$$

Total runoff predictions were slightly worse than for the previous calibration strategy (i.e. by estimating IL from the manual), even though still satisfactory, with an average underestimation of 19% and E equal to 0.68. For peak flow the differences between the observed and simulated values remained very low (on average 4%) and the model efficiency very good (E and E_1 > 0.76) (Table VI and Figure 7). Therefore, under these experimental conditions this method could be suitable in HEC-HMS applications requiring a high reliability in predicting peak flow, as for example the construction of hydraulic works.

These model performances agree with the results achieved by Jin et al. (2015), which found that the "SCS-CN" method performed better than the "Initial and Constant" method in estimating runoff generation in semi-arid and sub-humid regions of northern China, particularly when the flood runoff is dominated by combined infiltration- and saturation-excess during long-lasting rainfall of various intensities, as in the case of the present study. Conversely, Halwatura & Najim (2013), testing HEC-HMS for runoff simulations in the tropical Attanagalu Oya catchment of Sri Lanka, noticed better performance using the "Initial and Constant" method compared to the "SCS-CN". These authors found that the standard "SCS-CN" method used to find the average CN for the basins failed to estimate excess rainfalls correctly, resulting in unacceptably large deviations of predicted peak flows from those observed; they concluded that the use of standard SCS tables of runoff CN in a tropical climate may lead to large errors in runoff estimates.

Analysis of the simulated hydrographs

In our study, thanks to calibration, the simulated hydrographs were very similar to the observations for both "SCS-CN" and "Initial and Constant" methods (e.g. for the events recorded on 30 January - 4 February 2011 and 17-22 October 2010, Figure 8); conversely, estimation of infiltration performed by "Green-Ampt" method gave noticeable discrepancies in the shape of the simulated and observed hydrographs. Therefore, calibration gave an accurate simulation of the time variability of peak flow for thirteen of the fourteen modelled events, with the exception of the event on 1-3 November 2010 (Figures 5 and 8), although some relative maximum values of the peak flow were not adequately reproduced by HEC-HMS, for example the events recorded on 17-22 October 2010 and 9-12 November 2009 (Figures 7a and 7c). As observed also by Cydzik & Hogue (2009), the volume differences in the simulated and observed hydrographs may be attributed to inclusion of discontinuous rainfall events in the experimental database. Moreover, in accordance with the same authors, it can be argued that when rainfall events are simulated over longer storm periods and the precipitation contains a variety of sustained periods of light rainfall coupled with brief periods of intense rainfall, the subsequent runoff is highly variable and can result in rapid and extreme peaks that were somewhat difficult to model with the selected HEC-HMS algorithms ("loss" and "transform" methods).

Model accuracy in estimating the times to flood peak

The time to flood peak is a fundamental parameter for emergency planners. Its reliable estimation in occasion of floods is essential in order to warn the population about the occurrence of extreme events without giving false alarms or, vice versa, dangerous underestimations.

The application of the three studied infiltration methods in estimating the time to flood peak showed the highest reliability was for "SCS-CN" method with mean differences among observed and simulated times of 5% and a coefficient of efficiency of 0.54. Using the "Green-Ampt" and "Initial and Constant" methods the mean differences were 10% and -18% and E was equal to 0.23 and 0.44 respectively. The maximum Δt, that is the difference between the simulated and observed times to flood peak, was eight hours for "SCS-CN" and "Green-Ampt" methods and six hours for the "Initial and Constant" method. This latter gave the higher number of predictions lower than two hours, 50%

of the modeled events (Table VII). Cydzik & Hogue (2009), who found errors in predicting the time to flood peak up to 14.6 hours, consider a threshold value of four hours as reasonable.

Therefore, planning emergency procedures in occasion of extreme floods, which need the maximum accuracy in predictions of times to flood peak, should be done with care when using the HEC-HMS model, since estimations are not always adequate.

Summarising the results of the HEC-HMS verification in the Mèsima torrent, the rainfall-runoff transformation was reproduced with a satisfactory accuracy in this Mediterranean basin, in spite of the low spatial resolution of input soil data. Thanks to model calibration, simulations of total runoff, not well predicted by linear correlation with rainfall, were reliable and peak flow estimations was improved compared to correlation method. These results suggest that HEC-HMS can be successfully applied to *fiumara*s of Southern Italy for hydrological predictions; in such contexts, due to the peculiar characteristics of water courses (Zema et al., 2014), hydrological model applicability is not always presumed. Conversely, HEC-HMS seems to be inadvisable for planning emergency procedures when the maximum accuracy in predictions of times to flood peak are needed.

From this modeling experience, some simple recommendations arose for HEC-HMS model developers, in order to increase the reliability of the hydrological predictions: (i) for "SCS-CN" method, the improvement of procedures tuning CNs in the case of dry AMCs; (ii) in "Green-Ampt" method, the introduction of PTFs or regression equations to estimate directly the soil hydraulic properties; (iii) for "Initial and Constant" method, the application of regression equations between the Constant Rate and the maximum rainfall intensity, as reported above; (iv) finally, a higher discretisation of long storm periods to avoid highly variable runoff, with peaks difficult to be modelled by HEC-HMS.

The comparison of the different infiltration methods available in the HEC-HMS model showed that "SCS-CN" is preferable for simulating surface runoff volumes, while "Initial and Constant" is suggested for estimating peak flow. Predictions of infiltration losses by "Green-Ampt" method are generally poor for the modelled events, characterized by long durations and low intensities. These outcomes can be also useful in modelling watersheds with similar environmental conditions by other prediction models using the same algorithms for simulating surface runoff, for example SCS-CN in AnnAGNPS and CREAMS models, Green-Ampt in WEPP, CREAMS and ANSWERS models (Merritt et al., 2003).

On the whole, thanks to the guidelines provided in this study about the choice of the most suitable infiltration method, HEC-HMS model can be used more easily and with lower effort by the modellers; thereby, this model becomes a powerful and reliable tool in future land management options and regulation of in-stream processes (Merritt et al., 2005), for example to evaluate the hydrological response of basins under different land use scenarios or future climate changes. As a matter of fact, standardized guidelines increase accountability and public acceptance of models to support scientific research and to guide policy, regulatory and management decision making. These models also facilitate the simulation of various conservation program effects and aid policy design to mitigate water and soil quality degradation by determining suitable conservation programs for particular watersheds and agronomic settings (Moriasi et al., 2007).

CONCLUSIONS

Comparison of three infiltration methods available in HEC-HMS model in a typical torrent of Calabria showed, after calibration, satisfactory-to-good accuracy in simulating total runoff and peak flow by the "SCS-CN" method, while a good model reliability was noticed by using the "Initial and Constant" method for estimating peak flow and satisfactory for runoff volume. Conversely, low HEC-HMS performance was found using "Green-Ampt" equations for simulating infiltration. Estimation of the times to flood peak was in some cases inadequate and thus HEC-HMS seems to be inadvisable for planning emergency procedures. The results of this study support the transferability of HEC-HMS model in the Mediterranean environment as a practical tool in approaching land use analysis and planning.

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REFERENCES

Abushandi E, Merkel B. 2013. Modelling Rainfall Runoff relations Using HEC-HMS and IHACRES for a Single Rain Event in an Arid Region of Jordan. Water Resource Management **27**: 2391-2409. DOI: 10.1007/s11269-013-0293-4.

Ali M, Khan SJ, Aslam I, Khan Z. 2011. Simulation of the impacts of land-use change on surface runoff of Lai Nullah Basin in Islamabad, Pakistan. Landscape and Urban Planning **102**: 271-279. DOI:10.1016/j.landurbplan.2011.05.006.

ARSSA Calabria (Regional Agency for Development and Services in Agriculture). 2003. Pedological map scale 1:250.000. Agenzia Regionale per lo Sviluppo ed i Servizi in Agricoltura della Calabria. Catanzaro (Italy) (in Italian).

Baginska B, Milne-Home W, Cornish PS. 2003. Modelling nutrient transport in Currency Creek, NSW, with AnnAGNPS and PEST. Environmental Modelling and Software **18(8)**: 801-808. DOI:10.1016/S1364-8152(03)00079-3.

Beighley RE, Moglen GE. 2003. Adjusting measured peak discharges from an urbanized watershed to reflect a stationary land use signal. Water Resources Research **39**: 1093–1104. DOI:10.1029/2002WR001846

Beighley RE, Melack M, Dunne T. 2003. Impacts of California's climatic regimes and coastal land use change on streamflow characteristics. Journal of the American Water Resources Association **39**: 1419–1433.

Bisantino T, Bingner R, Chouaib W, Gentile F, Trisorio Liuzzi G. 2015. Estimation of runoff, peak discharge and sediment load at the event scale in a medium-size Mediterranean watershed using the annagnps model. Land Degradation & Development **26 (4):** 340-355. DOI: 10.1002/ldr.2213

Bombino G, Gurnell AM, Tamburino V, Zema DA, Zimbone SM. 2007. A method for assessing channelization effects on riparian vegetation in a Mediterranean environment. River Research and Applications **23(6)**: 613-630. DOI: 10.1002/rra.1004

Cao L, Zhang K, Dai H, Liang Y. 2015. Modeling Interrill Erosion on Unpaved Roads in the Loess Plateau of China. Land Degradation & Development **26(8)**: 825-832. DOI: 10. 1002/ldr. 2253

Castillo VM, Gomez-Plaza A, Martinez-Mena M. 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. Journal of Hydrology **284:** 114–130. DOI:10.1016/S0022-1694(03)00264-6

Cydzik K, Hogue TS. 2009. Modelling postfire response and recovery using the Hydrologic Engineering Center Hydrologic Modelling System (HEC-HMS). Journal of the American Water Resource Association **45(3):**702-714. DOI: 10.1111⁄j.1752-1688.2009.00317.x

Damodhara Rao M, Raghuwanshi NS, Singh R. 2006. Development of a physically based 1D infiltration model for irrigated soils. Agricultural Water Management **85(1)**: 165-174. DOI:10.1016/j.agwat.2006.04.009

El Hassan AA, Sharif HO, Jackson T, Chintalapudi S. 2013. Performance of a conceptual and physically based model in simulating the response of a semi-urbanized watershed in San Antonio, Texas. Hydrological Processes **27**: 3394–3408. DOI: 10.1002/hyp.9443

Feldman AD. 2000. Hydrologic Modelling System HEC-HMS, Technical Reference Manual. U.S. Army Corps of Engineers, Hydrologic Engineering Center, HEC, Davis, CA, USA.

Ficklin DL, Zhang M. 2013. A comparison of the curve number and Green-Ampt models in an agricultural watershed. Transactions of the ASABE 56(1): 61-69. DOI: 10.13031/2013.42590

Gessesse B, Bewket W, Bräuning A. 2015. Model-Based Characterization and Monitoring of Runoff and Soil Erosion in Response to Land Use/land Cover Changes in the Modjo Watershed, Ethiopia. Land Degradation & Development **26 (7)**: 711-724. DOI: 10.1002/ldr.2276.

Guinot V, Gourbesville P. 2003. Calibration of physically based models: back to basics? Journal of Hydroinformatics **5(4)**: 233-244.

Halwatura D, Najim MMM. 2013. Application of the HEC-HMS model for runoff simulation in a tropical catchment. Environmental Modelling and Software **46**: 155-162. DOI: 10.1016/j.envsoft.2013.03.006

Jin H, Liang R, Wang Y, Tumula P. 2015. Flood-Runoff in Semi-Arid and Sub-Humid Regions, a Case Study: A Simulation of Jianghe Watershed in Northern China. Water **7**: 5155-5172. DOI:10.3390/w7095155

Kamali B, Jamshid SM, Abbaspour KC. 2013. Automatic calibration of HEC-HMS using single-objective and multi-objective PSO algorithms. Hydrological Processes **27**: 4028–4042. DOI: 10.1002/hyp.9510

Keesstra SD. 2007. Impact of natural reforestation on floodplain sedimentation in the Dragonja basin, SW Slovenia. Earth Surface Processes and Landforms **32(1)**: 49-65. DOI: 10.1002/esp.1360

Keesstra SD, Bruijnzeel LA, van Huissteden J. 2009. Meso-scale catchment sediment budgets: combining field surveys and modeling in the Dragonja catchment, southwest Slovenia Earth Surface Processes and Landforms **34**: 1547-1561. DOI: 10.1002/esp.1846

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. 2006. World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift **15**: 259-263. DOI: 10.1127/0941-2948/2006/0130

Lane LJ, Diskin MH, Wallace DE, Dixon R.M. 1978. Partial area response on small semiarid watersheds. Water Resource Bulletin **14**: 1143-1158. DOI: 10.1111/j.1752-1688.1978.tb02253.x

Licciardello F, Zema DA, Zimbone SM, Bingner RL. 2007. Runoff and soil erosion evaluation by the AnnAGNPS model in a small Mediterranean watershed. Transactions of the ASABE **50(5)**: 1585-1593. DOI:10.13031/2013.23972

Lieskovský J, Kenderessy P. 2014. Modelling the effect of vegetation cover and different tillage practices on soil erosion in: A case study in vráble (Slovakia) using WATEM/SEDEM. Land Degradation & Development **25(3):** 288-296. DOI: 10.1002/ldr.2162

Martìn-Rosales W, Gisbert J, Pulido-Bosch A, Vallejos A, Fernàndez-Cortés A. 2007. Estimating groundwater recharge induced by engineering systems in a semiarid area (southeastern Spain). Environmental Geology **52**: 985-995. DOI 10.1007/s00254-006-0541-5

Mashayekhi Z, Panahi M, Karami M, Khalighi S, Malekian A. 2010. Economic evaluation of water storage function of forest eco system (case study: Zagros Forests, Iran). Journal of Forestry Research **21(3)**: 293-300. DOI 10.1007/s11676-010-0074-3

Merritt WS, Letcher RA, Jakeman AJ. 2003. A review of erosion and sediment transport models. Environmental Modelling & Software **18**: 761–799. DOI:10.1016/S1364-8152(03)00078-1

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. 2007. Model valuation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE **50(3)**: 885-900. DOI: 10.13031/2013.23153

Nash JE, Sutcliffe JV. 1970. Torrent flow forecasting through conceptual models. Part I. A discussion of principles. Journal of Hydrology **10**: 282-290. DOI:10.1016/0022-1694(70)90255-6

Rawls WJ, Brakensiek DL, Miller N. 1983. Green-Ampt Infiltration parameters from Soils Data. Journal of Hydraulic Engineering **109(1)**: 62-70.

Saxton KE, Rawls WJ, Romberger JS, Papendick RI. 1986. Estimating generalized soil-water characteristics from texture. Soil Science Society of America Journal **50**: 1031–1036. DOI:10.2136/sssaj2005.0117

Shrestha S, Mukand SB, Das Gupta A, Kazama F. 2006. Evaluation of annualized agricultural nonpoint source model for a watershed in the Siwalik Hills of Nepal. Environ. Modelling and Software **21(7)**: 961-975. DOI:10.1016/j.envsoft.2005.04.007

Thiessen AH. 1911. Precipitation Averages for Large Areas. Monthly Weather Review **39**: 1082 – 1089. DOI: 10.4236/jgis.2014.64026

U.S. Army Corps of Engineers (USACE). 2015. Hydrologic Engineering Center, Hydrologic Modelling System HEC-HMS. User's Manual (version 4.1, July 2015). Available at URL: www.hec.usace.army.mil/software/hec-hms/documentation.aspx. Last access: 1 September 2015.

USDA. 1975. USDA Soil Survey Staff, Soil Survey Manual. United States Department of Agriculture, USA.

USDA-NRCS. 1986. Urban Hydrology for Small Watersheds. Conservation Engineering, Technical Release 55. Washington, DC, USA.

USDA-SCS. 1972. National Engineering Handbook. Section 4: Hydrology. US Government Printing Office: Washington, DC, USA.

Van Liew MW, Garbrecht J. 2003. Hydrologic simulation of the little Washita torrent esperimental watershed using SWAT. Journal of the American Water Resources Association **39(2)**: 413-426. DOI: 10.1111/j.1752-1688.2003.tb04395.x

Verma AK, Jha MK, Mahana RK. 2010. Evaluation of HEC-HMS and WEPP for simulating watershed runoff using remote sensing and geographical information system. Paddy and Water Environment **8:** 131-144. DOI 10.1007/s10333-009-0192-8

Wilcox BP, Rawls WJ, Brakensiek DL, Wright JR. 1990. Predicting runoff from rangeland catchments: A comparison of two models. Water Resources Res. 26(10): 2401-2410. DOI: 10.1029/WR026i010p02401

Wischmeier WH, Smith DD. 1978. Prediction rainfall erosion losses. Handbook No. 537. Washington D.C.: USDA.

Ying M, Feng S, Su D, Gao G, Huo Z. 2010. Modelling water infiltration in a large layered soil column with a modified Green–Ampt model and HYDRUS-1D. Computers and Electronics in Agriculture **71**: S40-S47. DOI:10.1016/j.compag.2009.07.006

Yuan Y, Bingner RL, Rebich RA. 2001. Evaluation of AnnAGNPS on Mississippi Delta MSEA watershed. Transactions of the ASAE **44(5)**: 1183-1190.

Zema DA, Bombino G, Boix-Fayos C, Tamburino V, Zimbone SM, Fortugno D. 2014. Evaluation and modelling of erosion and sedimentation around check dams in a Mediterranean torrent (Calabria, Southern Italy). Journal of Soil and Water Conservation **69(4)**: 316-329. DOI: 10.2489/jswc.69.4.316

Zema DA, Denisi P, Taguas Ruiz EV, Gómez JA, Bombino G, Fortugno D. 2016. Evaluation of Surface Runoff Prediction by AnnAGNPS Model in a Large Mediterranean Watershed Covered by Olive Groves. Land Degradation & Development **27:** 811–822. DOI: 10.1002/ldr.2390

Zhang Y, Wei H, Nearing MA. 2011. Effects of antecedent soil moisture on runoff modelling in small semiarid watersheds of southeastern Arizona. Hydrology Earth System Science **15**: 3171–3179. DOI:10.5194/hess-15-3171-2011

TABLES

Table I - Hydrological characterisation of the 14 rainfall events used for HEC-HMS verification in the Mésima torrent, Calabria, Southern Italy.

Rainfall/runoff event	Rainfall				Runoff			
	Total precipitation (mm)	Duration (h)	Intensity (mm/h)		Total volume (mm)	Runoff coefficient (-)	Peak (m^3/s)	Time to peak (h)
			average	max				
10-15 January 2009	125	119	1.0	9.9	21.1	0.17	267	8
24-26 January 2009	36	58	0.6	2.4	12.4	0.34	100	10
26-30 January 2009	44	83	0.6	3.3	19.8	0.45	125	7
01-02 February 2009	38.4	91	1.2	6.8	11.8	0.31	199	6
09-12 November 2009	61.5	87	0.7	9.4	20.3	0.33	240	13
26-28 January 2010	92.8	45	2.1	6.1	16.2	0.17	217	17
09-13 February 2010	78.2	108	0.7	4.8	42.5	0.54	169	7
06-11 March 2010	97.4	109	0.9	7.4	34.2	0.35	323	8
17-22 October 2010	123.3	124	1.0	9.3	53.7	0.44	434	27
01-03 November 2010	76.1	67	1.1	15.1	33.6	0.44	451	7
26-28 January 2011	43.7	54	0.8	6.8	16.1	0.37	185	8
30 January-04 February 2011	43.1	132	0.3	4.5	38.2	0.89	178	13
28 February-03 March 2011	58.5	73	0.8	13.1	27.3	0.47	278	11
03-08 March 2011	51.9	121	0.4	8.4	37.6	0.73	192	5

Table II - Correlations between rainfall and runoff attributes of the 14 events used for HEC-HMS verification in the Mésima torrent, Calabria, Southern Italy.

		Total precipitation (mm)	Duration (h)	Intensity (mm/h)		Total runoff volume (mm)	Runoff coefficient (-)	Peak (m^3/s)	Time to peak (h)
				average	max				
Total precipitation (mm)		-	0.32	0.45	0.37	0.45	-0.40	0.65	0.48
Duration (h)			-	-0.48	-0.01	**0.68**	0.52	0.16	0.10
Intensity (mm/h)	average			-	0.19	-0.28	**-0.70**	0.30	0.31
	max				-	0.24	-0.11	**0.80**	0.06
Total runoff volume (mm)						-	0.57	0.53	0.39
Runoff coefficient (-)							-	-0.13	-0.08
Peak (m^3/s)								-	0.41
Time to peak (h)									-

Note: values in bold are significant at $p < 0.05$ (Tukey's test).

Table III - Input parameters of different infiltration methods for HEC-HMS model verification in the Mésima torrent, Calabria, Southern Italy.

	Parameter	AMC	Sub-basin 1	Sub-basin 2	Sub-basin 3
	"SCS-CN" infiltration method				
Default model	*Average initial CN (-)*	I	34	33	29
		II	54	53	49
		III	73	73	69
	Lag time (h)	I	9.5	12.2	10.9
		II	5.5	7.1	6.2
		III	3.4	4.3	3.7
	Initial abstraction (mm)	I	99.5	102.0	124.1
		II	43.3	44.3	53.9
		III	18.6	19.1	23.2
Calibrated model	*Average initial CN (-)*	I	54	52	57
		II	66	65	64
		III	76	73	74
	Lag time (h)	I	5.5	7.4	5.0
		II	4.1	5.3	4.2
		III	3.1	4.3	3.2
	Initial abstraction (mm)	I	43.3	46.9	38.3
		II	26.2	27.4	28.6
		III	16.0	18.8	17.8
	"Green-Ampt" infiltration method				
	Saturated water content (cm^3/cm^3)		0.46	0.46	0.45
	Initial water content (cm^3/cm^3)	I	0.12	0.11	0.09
		II-III	0.24	0.23	0.19
	Wetting front suction (mm)		292	285	232
	Hydraulic conductivity (mm/h)		20.0	26.8	26.8
	"Initial and Constant" infiltration method				
Default model	Initial Loss (mm) (*)	I	36.4	37.2	37.0
		II	24.3	24.8	24.7
		III	12.2	12.4	12.4
	Constant Rate (mm/h) (*)			9.52	
Calibrated model (I)	Initial Loss (mm) (*)	I	36.4	37.2	37.0
		II	24.3	24.8	24.7
		III	12.2	12.4	12.4
	Constant Rate (mm/h)			equation [1]	
Calibrated model (II)	Initial Loss (mm) (**)	I	43.3	46.9	38.3
		II	26.2	27.4	28.6
		III	16.0	18.8	17.8
	Constant Rate (mm/h)			equation [2]	

Notes: (*) estimated by HEC-HMS manual; (**) estimated by the SCS-CN method.

Table IV - Evaluation criteria of HEC-HMS model performance ("SCS-CN" method) at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

Hydrological variables			Mean	Dev. Std.	Min	Max	r^2	E	E_1	RMSE	CRM
Total runoff (m^3)	observed		*6054*	2813	2593	11854	-	-	-	-	-
	simulated	(default model)	*4259*	3165	1081	10635	0.65	0.11	0.17	2560	0.29
		(calibrated model)	*5446*	2729	2184	9899	0.79	0.74	0.66	1378	0.10
Peak flow (m^3/s)	observed		*246*	120	100	541	-	-	-	-	-
	simulated	(default model)	*115*	84	21	316	<0.01	-1.75	0.78	191	0.53
		(calibrated model)	*217*	84	98	431	0.37	0.30	0.39	97	0.12

Notes: r^2: coefficient of determination; E: coefficient of efficiency of Nash & Sutcliffe (1970); E_1: modified coefficient of efficiency of Nash & Sutcliffe (1970); RMSE: Root Mean Square Error; CRM: Coefficient Residual Mass.

Table V - Evaluation criteria of HEC-HMS model performance ("Green-Ampt" method) at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

Hydrological variables		Mean	Dev. Std.	Min	Max	r^2	E	E_1	RMSE	CRM
Total runoff (m^3)	observed	6054	2813	2594	11854	-	-	-	-	-
	simulated	3134	2093	893	7175	0.48	-0.69	-0.24	3517	0.48
Peak flow (m^3/s)	observed	246	120	99.6	541	-	-	-	-	-
	simulated	46	13.5	21.9	63.4	<0.01	-3.03	-1.29	232	0.81

Notes: r^2: coefficient of determination; E: coefficient of efficiency of Nash & Sutcliffe (1970); E_1: modified coefficient of efficiency of Nash & Sutcliffe (1970); RMSE: Root Mean Square Error; CRM: Coefficient Residual Mass.

Table VI - Evaluation criteria of HEC-HMS model performance ("Initial and constant" method) at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

	Hydrological variables		Mean	Dev. Std.	Min	Max	r^2	E	E_1	RMSE	CRM
	observed		6054	2813	2594	11854	-	-	-	-	-
Total runoff		(default model)	3419	2070	985	7174	0.57	-0.38	-0.12	3176	0.44
(m^3)	simulated	(calibrated model I) (*)	5241	2084	2587	8177	0.86	0.73	0.62	1406	0.14
		(calibrated model II) (**)	4913	2163	2053	8216	0.88	0.68	0.51	1533	0.19
	observed		246	120	99.6	541	-	-	-	-	-
Peak flow		(default model)	81.5	80.7	33.3	323	0.52	-1.52	-0.89	183.17	0.67
(m^3/s)	simulated	(calibrated model I) (*)	245	125	99.4	534	0.96	0.95	0.83	24.48	0.01
		(calibrated model II) (**)	251	105	99.6	453	0.91	0.90	0.76	35.25	-0.02

Notes: r^2: coefficient of determination; E: coefficient of efficiency of Nash & Sutcliffe (1970); E_1: modified coefficient of efficiency of Nash & Sutcliffe (1970); RMSE: Root Mean Square Error; CRM: Coefficient Residual Mass; (*) Initial loss estimated from the HEC-HMS manual; (**) Initial loss estimated by the SCS-CN method.

Table VII - Comparison among the time to flood peak (observed and simulated by different infiltration methods) simulated by HEC-HMS model at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

Rainfall event	Time to flood peak			
	Observed	Simulated		
		"SCS-CN"	"Green-Ampt"	"Initial and Constant"
10-15 January 2009	8	16	9	10
24-26 January 2009	10	9	7	6
26-30 January 2009	7	8	8	7
01-02 February 2009	6	7	6	6
9-12 November 2009	13	6	6	7
26-28 January 2010	17	13	20	14
09-13 February 2010	7	13	8	6
6-11 March 2010	8	15	16	8
17-22 October 2010	27	23	29	22
01-03 November 2010	7	8	12	7
26-28 January 2011	8	10	10	8
30 January-04 February 2011	13	9	17	8
28 February-03 March 2011	11	7	5	7
03-08 March 2011	5	11	9	5

FIGURE CAPTIONS

Figure 1 - Location and Digital Elevation Model of the Mésima torrent (Calabria, Southern Italy).

Figure 2 – Maps of land use (a, from Corine Land Cover, 2007), texture (b, ARSSA, 2003), hydrologic group (c) and homogenous hydrological units (HRU, d) in the Mésima torrent (Calabria, Southern Italy).

Figure 3 – HEC-HMS model structure and evaluation procedure (the symbol * indicates the method/component used in this work).

Figure 4 – Rainfall and water level gauging stations as well as Thiessen's polygons in the Mésima torrent (Calabria, Southern Italy).

Figure 5 – Comparison of total runoff (a, in m^3) and peak flow (b, in m^3/s) simulated by the HEC-HMS model ("SCS-CN" method) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

Figure 6 - Comparison of total runoff (a, m^3) and peak flow (b, m^3/s) simulated by the HEC-HMS model ("Green-Ampt" method) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

Figure 7 – Comparison of total runoff (a, m^3) and peak flow (b, m^3/s) simulated by the HEC-HMS model ("Initial and Constant" method) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

Figure 8 - Hydrographs simulated by the HEC-HMS model (different infiltration methods) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy).

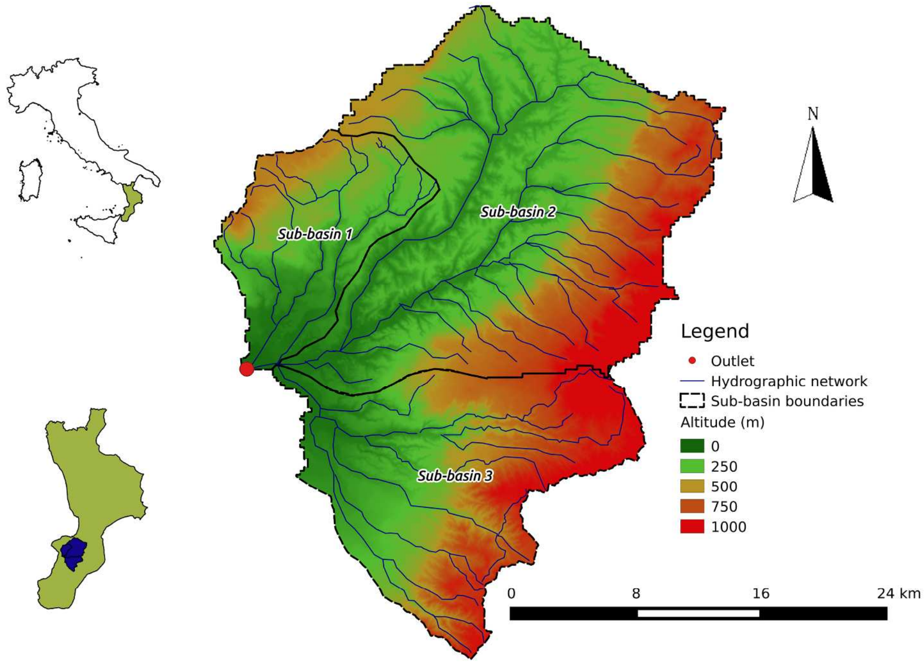

Figure 1 - Location and Digital Elevation Model of the Mésima torrent (Calabria, Southern Italy).

210x148mm (300 x 300 DPI)

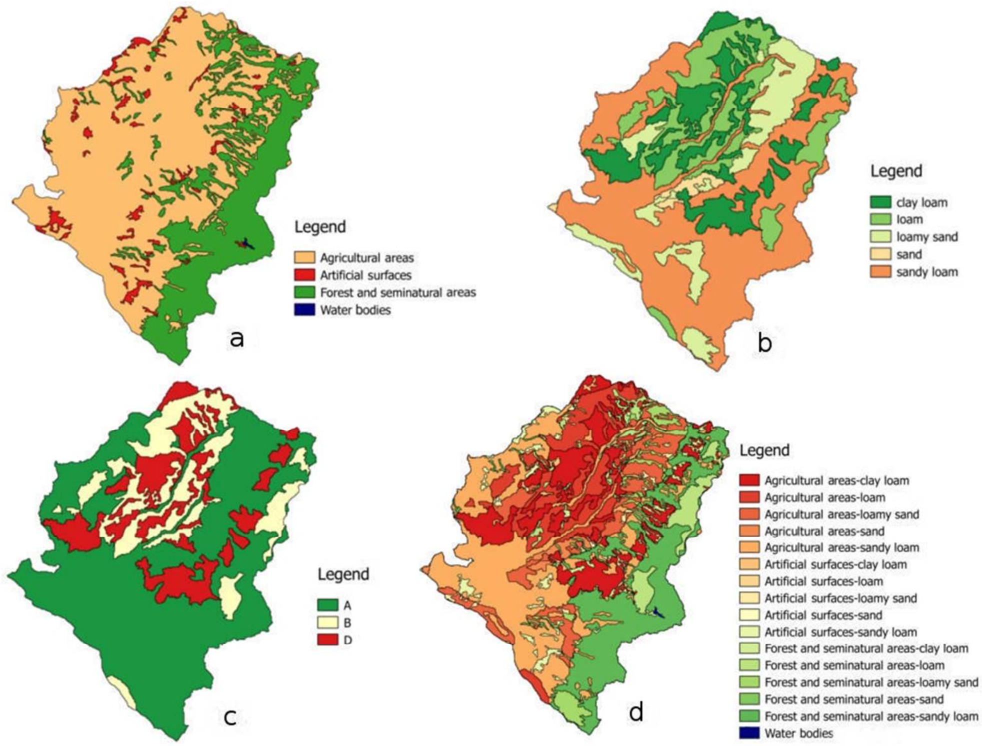

Figure 2 – Maps of land use (a, from Corine Land Cover, 2007), texture (b, ARSSA, 2003), hydrologic group (c) and homogenous hydrological units (HRU, d) in the Mésima torrent (Calabria, Southern Italy).

254x190mm (96 x 96 DPI)

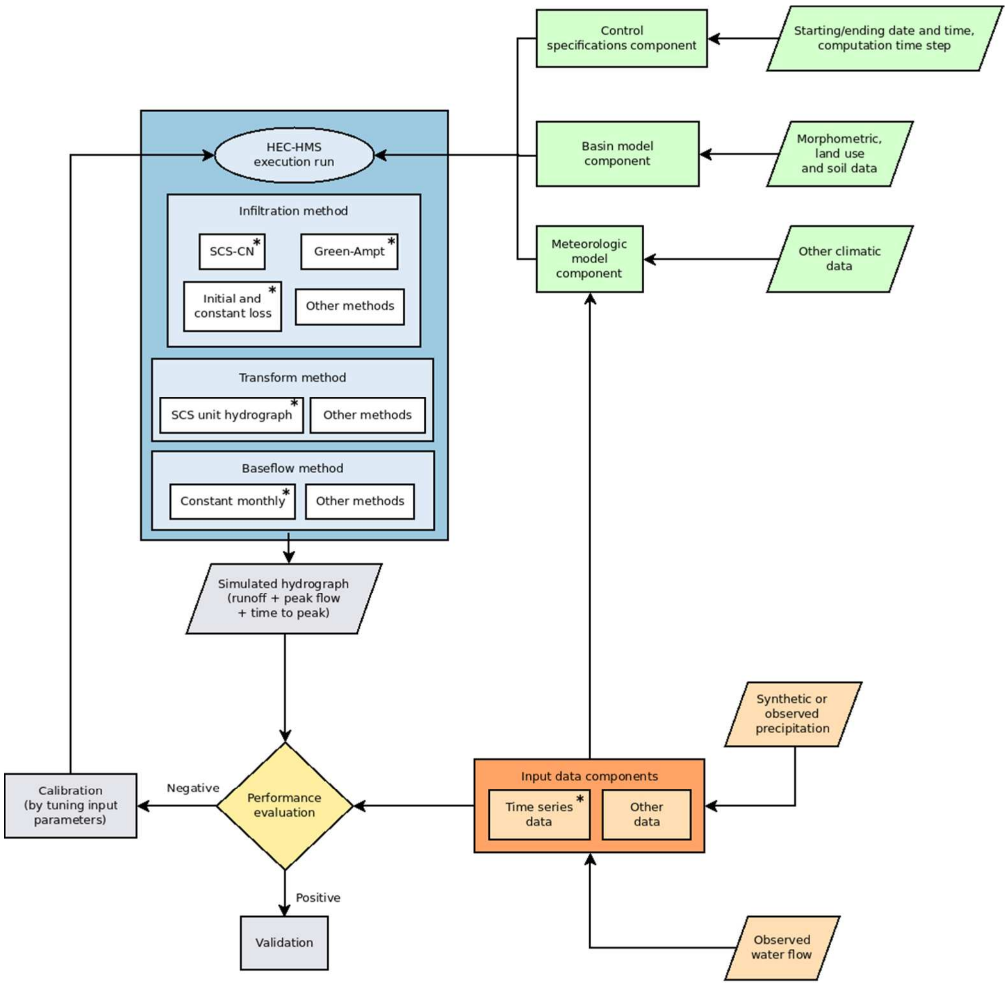

Figure 3 – HEC-HMS model structure and evaluation procedure (the symbol * indicates the method/component used in this work).

385x376mm (72 x 72 DPI)

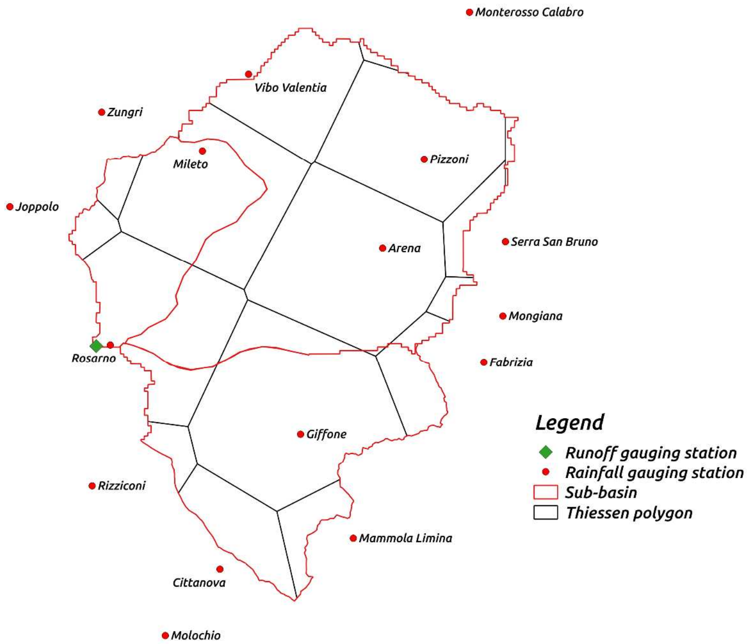

Figure 4 – Rainfall and water level gauging stations as well as Thiessen's polygons in the Mésima torrent (Calabria, Southern Italy).

297x210mm (299 x 299 DPI)

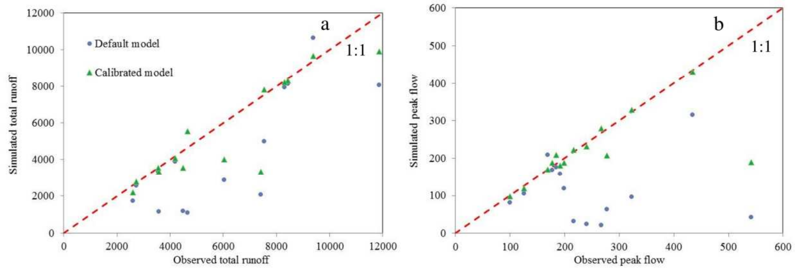

Figure 5 – Comparison of total runoff (a, in m3) and peak flow (b, in m3/s) simulated by the HEC-HMS model ("SCS-CN" method) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

102x50mm (600 x 600 DPI)

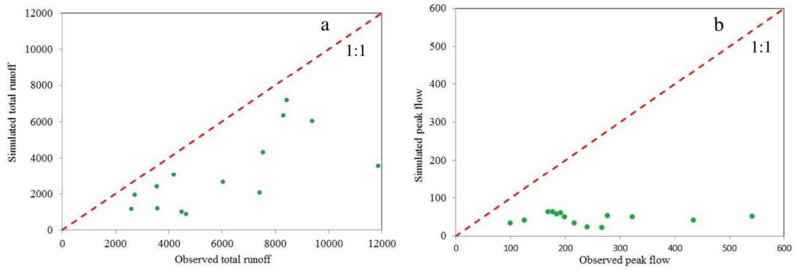

Figure 6 - Comparison of total runoff (a, m3) and peak flow (b, m3/s) simulated by the HEC-HMS model ("Green-Ampt" method) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

101x49mm (600 x 600 DPI)

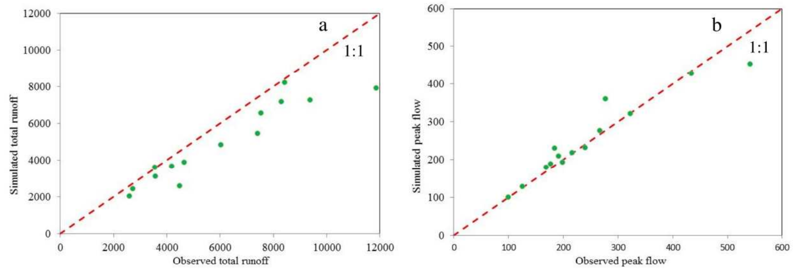

Figure 7 – Comparison of total runoff (a, m3) and peak flow (b, m3/s) simulated by the HEC-HMS model ("Initial and Constant" method) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy) (n = 14 rainfall-runoff events).

99x47mm (600 x 600 DPI)

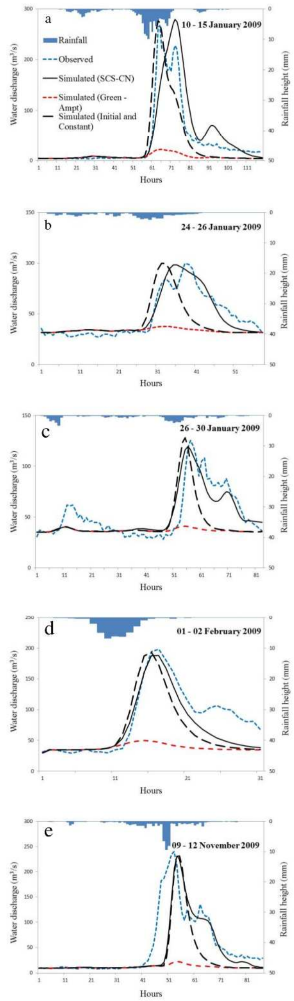

Figure 8 - Hydrographs simulated by the HEC-HMS model (different infiltration methods) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy). - part A

296x845mm (600 x 600 DPI)

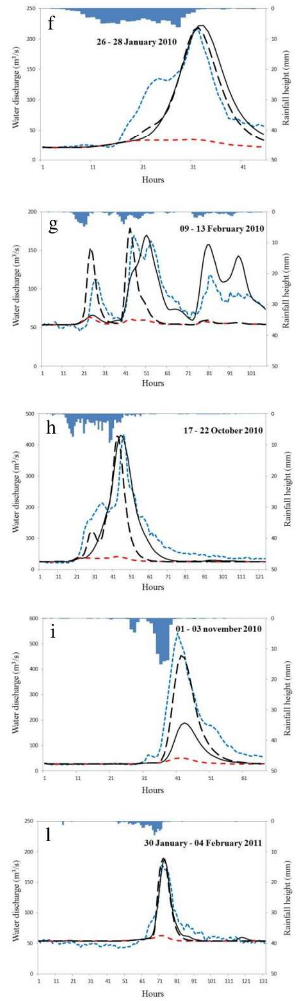

Figure 8 - Hydrographs simulated by the HEC-HMS model (different infiltration methods) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy). - part B

296x845mm (600 x 600 DPI)

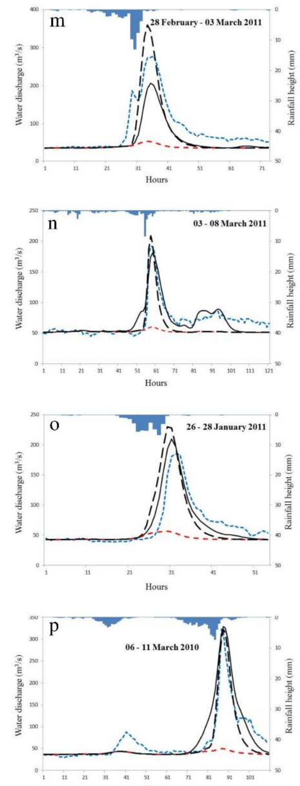

Figure 8 - Hydrographs simulated by the HEC-HMS model (different infiltration methods) and observed at the outlet of the Mésima torrent (Calabria, Southern Italy). - part C

296x845mm (600 x 600 DPI)