Improvement of the integration of Soil Moisture Accounting into the NRCS-CN Model

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ABSTRACT

Rainfall-runoff quantification is one of the most important tasks in both engineering and watershed management as it allows the identification, forecast and explanation of the watershed response. This non-linear process depends on the watershed antecedent conditions, which are commonly related to the initial soil moisture content. Although several studies have highlighted the relevance of soil moisture measures to improve flood modelling, the discussion is still open in the literature about the approach to use in lumped model. The integration of these previous conditions in the widely used rainfall-runoff models NRCS-CN (e.g. National Resources Conservation Service - Curve Number model) could be handled in two ways: using the Antecedent Precipitation Index (API) concept to modify the model parameter; or alternatively, using a Soil Moisture Accounting (SMA) procedure into the NRCS-CN, being the soil moisture a state variable. For this second option, the state variable does not have a direct physical representation. This make difficult the estimation of the initial soil moisture store level. This paper presents a new formulation that overcomes such issue, the rainfall-runoff model called RSS_a . Its suitability is evaluated by comparing the RSS_a model with the original NRCS-CN model and alternatives SMA procedures in 12 watersheds located in six different countries, with different climatic conditions, from Mediterranean to Semi-arid regions. The analysis shows that the

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new model, RSS_a , performs better when compared with previously proposed CN-based models. Finally, an assessment is made of the influence of the soil moisture parameter for each watershed and the relative weight of scale effects over model parameterization.

Keywords: NRCS CN model; rainfall-runoff modelling; ARC; antecedent soil moisture; Soil Moisture Accounting;

1. INTRODUCTION

The rainfall-runoff process is affected by several physical factors and their interactions: from the predominant climatic scenarios, to the runoff mechanism, passing through the interaction between surface and subsurface layers, the vegetation canopy or soil characterization. For this reason, the development of reliable predictions of surface runoff in ungauged watersheds are difficult and time-consuming (Fan et al., 2013). Thus, the development of models which make easier the watershed management purposes, constitutes a relevant step in hydrologic applications such as design flood or water resources assessment (Soulis and Valiantzas, 2012).

Many hydrologic models offer a high goodness-of-fit of the rainfall-runoff process for gauged watersheds. However, its suitability of each of them is conditioned by its requirements in terms of both input data and calibration (Shi et al., 2009). In balancing complexity and efficiency, the National Resources Conservation Service Curve Number method (NRCS-CN), previously called the Soil Conservation Service Curve number, was proposed. The method was developed to reduce the uncertainty and simplify the estimation of peak runoff. The widespread application of the NRCS-CN model is based on its simplicity and its applicability, together with the fact that it combines most relevant factors affecting surface runoff such as soil type, land use and treatment and surface condition, in a single parameter (NRCS, 2009). Furthermore, it is the only methodology that features readily available and reasonably well-documented environmental inputs, being a well-established and worldwide accepted procedure (Soulis et al., 2009). The key parameter of the method, the Curve Number (CN), was developed from an empirical study of runoff in a limited number of small catchments and hillslope plots located in the United States Southwest. To facilitate its use, the CN parameter was tabulated for different combinations of affecting factors. These values were originally defined from annual maximum rainfall and runoff information; however, they are used in hydrologic simulation models such as CREAMS (Knisel, 1980) and AGNPS (Young et al., 1987) to estimate direct runoff from daily rainfall events.

Nonetheless, the NRCS-CN model has limitations related to its lack of representation of the spatio-temporal rainfall distribution, its suitability for different runoff mechanisms (Schneiderman et al., 2007), scale effects, and above all, the soil initial water state before the rainfall-runoff process begins. Other factors were neglected despite their well-recognized relevancy in the initial version of the model but were considered in later versions. In the initial versions of the NRCS-CN model, the conditions prior to rainfall were related to the soil moisture content, establishing three levels called Antecedent Moisture Conditions (AMC), linked to dry conditions (AMCI), average conditions (AMCII) and wet conditions (AMCIII). In the latest versions, the AMC are no longer considered as a part of the NRCS-CN model, and are now named the Antecedent Runoff Conditions (ARC), which integrate all the significant factors (NRCS, 2009): rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature. Frequently, the soil moisture content is one of the most important factors, but not the only one (Cao et al., 2011). Moreover, the relevance of the initial soil moisture to the runoff generation is stated in many process-based studies (Bronstert and Bárdossy, 1999; Castillo et al., 2003; Cerdà, 1996; Cerdà, 1997; Merz and Bárdossy, 1998; Meyles et al., 2003; Ruggenthaler et al., 2015; Ziadat and Taimeh, 2013). The behavior of ARC is based on “error bands” (Hawkins et al., 2009), where AMCI and AMCIII correlate well with the Weibull exceedance probabilities of 10 and 90 percent, respectively. Therefore, ARC and AMC can be considered as intrinsically equivalent in their use.

Once the ARC levels were established, it was necessary to determine the most appropriate CN value for each level. In early versions of the National Engineering Handbook, NEH (NRCS, 2009), AMC/ARC levels were correlated with 5-day antecedent precipitation (Antecedent Precipitation Index, API_5), adding a correction factor for growing and dormant seasons. The API_5 assumes a temporal decay process to estimate the soil moisture loss rates (Jacobs et al., 2003). Although API_5 is commonly evaluated in different hydrologic models, it is neither supported nor recognized by the NRCS that discourages any approach to change the established AMC/ARC levels as stated in Table 7 in Hawkins et al. (2009). Furthermore, several studies have shown poor results when ARC are characterized by API_5 (Brocca et al., 2008; Huang et al., 2007; Longobardi et al., 2003; Melone et al.,

2001; Soulis et al., 2009; Trambly et al., 2010). Singh et al. (1989). These references expose the lack of a physical basis for the relationship between the API₅ and ARC.

Michel et al. (2005) developed an alternative to the use of AMC/ARC conditions, based on the incorporation of a Soil Moisture Account procedure (SMA) into the original formulation. This work proposed a simple methodology that eliminated the dependency on previously fixed levels. Based on the conceptual independence between initial watershed condition and initial abstraction, Michel et al. (2005) developed a model combining the initial soil moisture content and the rainfall. One issue, still not addressed and essential for its integration into a continuous hydrologic model is the quantification of the antecedent conditions. Since the release of this model, it has been the leitmotif of several attempts. Due to difficulties in characterizing the initial soil moisture content, most of the previous works have linked the antecedent conditions to API₅ (Durbude et al., 2011; Jain et al., 2012; Sahu et al., 2010; Sahu et al., 2007; Singh et al., 2015; Suresh Babu and Mishra, 2012). However, as previously shown, the use of this variable could lead to poor results. Indeed, most of them depend on more than two parameters, and the calibration procedure is more complex and more information may be required. Alternative approaches based on the NRCS-CN model, but not on the SMA procedure, have been proposed to overcome this challenge. These approaches obtained a relationship between the antecedent conditions and the initial soil moisture content, which was estimated by local measurements, remote sensing or modelled data (Beck et al., 2009; Brocca et al., 2009a; Brocca et al., 2009b; Huang et al., 2007; Jacobs et al., 2003; Massari et al., 2014b; Meyles et al., 2003; Zehe et al., 2010).

In case of semi-arid watersheds, the estimation of the initial soil moisture content is particularly significant, where runoff during medium and low intensity storm events is controlled by antecedent soil moisture content (Castillo et al., 2003), generating substantial errors in runoff predictions if not examined. In humid climates, it also plays a crucial role when evaluating runoff from heavy rainfall (Ruggenthaler et al., 2015). Among the variables involved in runoff generation, rainfall and antecedent runoff conditions are the most significant in any hydrological model. By combining the influence of

rainfall variability and prior conditions, particularized by initial soil moisture content, it is possible to explain most of the variability in runoff predictions. The evaluation of the sensitivity of the runoff response to these variables is an issue well recognized and studied (Nikolopoulos et al., 2011). However, although the streamflow is conditioned by initial conditions, most studies have focused on the sensitivity of each variable independently, and only a few have analysed the combination of both in runoff generation (Noto et al., 2008; Zehe et al., 2005).

The first objective of this paper is therefore to examine the relationship of both rainfall variability and initial soil moisture with runoff for several watersheds with different characteristics, both climatological and soil. The second objective is to propose a new approach based on the SMA procedure to include soil moisture content in an explicit manner in the NRCS-CN model. The third objective is to analyse the advantages of the proposed model over previous proposed CN-based models and the influence of scale effects on model parameterization in 12 watersheds.

2. METHODS

In this section, the current NRCS-CN model as well as similar ones inspired on it were analysed. Those models were selected because the ARC can be evaluated based on the initial soil moisture content. Although in the literature there are models based on different variables to represent the ARC, such as the Antecedent Precipitation Index (Beck et al., 2009; Huang et al., 2007), base flow (Longobardi et al., 2003; Shaw and Walter, 2009; Trambly et al., 2010) or water table elevation (Epps et al., 2013), our work is focused on ISMC as it is the best indicator of the antecedent conditions (Trambly et al., 2010). Thus, the models analysed in this section are: the SMA procedure over the NRCS-CN model developed by Michel et al. (2005), called SS_a model, the adaptation of the CN parameter depending on ISMC exposed in Brocca et al. (2009a) and Brocca et al. (2009b), called $S_f(\theta)$ model, and a new model based on a reinterpretation of the parameters involved in Michel (2005) to evaluate the initial conditions, called RSS_a model. All these models are dependent in only two parameters, being consistent with the number of parameters of the NRCS-CN model

2.1 NRCS-CN Model

The Natural Resources Conservation Service Curve Number (SCS-CN) model (NRCS, 2009) is a rainfall-runoff model originally developed by the Soil Conservation Service of the US Department of Agriculture. It was derived from different studies based on the relationship between direct runoff and rainfall events for small rural watersheds in the USA (Ponce and Hawkins, 1996).

This model is based on the water balance equation, Eq. (1), and the conceptual hypotheses of equality of the ratio of direct runoff to potential maximum runoff with the ratio of actual retention to potential maximum retention, Eq. (2). To reduce the number of parameters in the model, an empirical relationship was proposed to quantify the initial abstraction I_a as a proportion of the potential maximum retention S by a coefficient λ . The value of λ is frequently fixed at 0.2, Eq. (3), although it is recognized that this value is not the most appropriate. Furthermore, a value of 0.05 was proposed by Woodward et al. (2003), as well as another relationship with S (Elhakeem and Papanicolaou, 2009)

$$P = I_a + Q + F \quad (1)$$

$$\frac{P - I_a}{Q} = \frac{S}{F} \quad (2)$$

where P is the cumulative rainfall depth, I_a is the initial abstraction including surface storage, interception and infiltration prior to runoff, F is the actual retention, Q is the direct surface runoff or rainfall excess, and S is the potential maximum retention. The combination of Eqs. (1) and (2) yields the common form of the NRCS-CN model, Eq. (4):

$$I_a \approx 0.2 S \quad (3)$$

$$Q = \frac{(P - I_a)^2}{S + P - I_a} \quad (4)$$

For convenience and simplification, parameter S was transformed into a new dimensionless parameter (curve number CN) that represents the average soil type, cover and hydrological conditions, Eq. (5), with S expressed in mm.

$$CN = \frac{25400}{S + 254} \quad (5)$$

The variability of CN values was initially attributed to antecedent soil moisture content by the Antecedent Moisture Content (AMC) Index, which establishes three levels linked to average (AMC

II), dry (AMC I) or wet (AMC III) conditions, with sudden jumps in the CN-variation (Jain et al., 2006). This index was based on rainfall totals for five days prior to a storm event (API_5), which is not nowadays supported by the NRCS (Hawkins et al., 2009). The presence of another source of variability such as spatial and temporal variability of the storm, or scale effects were not considered. The Antecedent Runoff Conditions (ARC), acknowledges these other factors. Hence in the definition of the ARC the probabilistic upper and lower limits for runoff generation for a given site based on frequency analysis are considered (Grabau et al., 2009; Hjelmfelt, 1991).

2.2 SS_a Model (Michel et al., 2005)

Michel et al. (2005) proposed a reformulation of the NRCS-CN model to include the impact of the initial soil moisture content on an explicit form, avoiding the mixing it with the surface storage and vegetation interception process. Based on the SMA (Soil Moisture Accounting) methodology, that model eliminates sudden jumps in estimated runoff (Wang et al., 2012), avoiding the only three steps suggested by ARC. Hence, the initial soil moisture is represented by a variable named V_0 .

The conceptual representation of the soil response is composed of two connected reservoirs (Figure 1). The lower reservoir represents the minimum soil moisture content required to start runoff generation, and it is characterized by the storage parameter S_a . This parameter is represented by the surface storage and vegetation interception ($S_a = I_a + V_0$). The upper reservoir accounts for the additional soil moisture storage capacity, the capacity of the second reservoir (S) being assessed as the difference between the soil water content linked to saturation conditions and the runoff threshold S_a . This second parameter is identical to the parameter S in the original SCS-CN model, because the potential maximum retention when runoff starts, S , is the soil moisture capacity not accounting for the ponding threshold. By analysing the S and S_a parameters obtained in several French watersheds, Michel et al. (2005) established a dependency between S and S_a , reducing the model to a single parameter S . However, to add an extra degree of freedom to this model, in the present work, no relationship between parameters is fixed.

The proposed computation procedure begins with the comparison between the antecedent soil water content, V_0 , plus the rainfall depth (available water) against S_a . Runoff (Q) will only be produced if there is a precipitation depth ($P > 0$) and the available water (initial soil moisture plus precipitation) is larger than S_a ($V_0 + P > S_a$). However, its magnitude depends on the relative value of V_0 with respect to the threshold S_a :

- $V_0 < S_a$: a proportion of the rainfall depth will contribute to supply the soil moisture deficit just up to the S_a level, and the remainder will be divided into two: one portion will result in runoff, and the other will increase the soil moisture content. The calculation of the corresponding runoff, Eq. (8), and infiltration depths is estimated with the SCS-CN model hypothesis, Eq. (6) and (7), where F is the accumulated soil moisture content after infiltration takes place.

$$\frac{P + V_0 - S_a}{Q} = \frac{S}{F - S_a} \quad (6)$$

$$P = V_0 + Q + F \quad (7)$$

$$Q = \frac{(P + V_0 - S_a)^2}{S + P + V_0 - S_a} \quad (8)$$

- $V_0 > S_a$: the soil moisture difference between V_0 and S_a results in an initial soil moisture content (ΔF) larger than S_a coming from antecedent precipitations (ΔP), which according to the SCS conceptual model, Eqs. (9) and (10), produced a previous runoff amount (ΔQ). ΔP corresponds to the precipitation that generates a runoff (ΔQ), which increases the soil moisture from S_a to the actual point V_0 . The runoff produced by a new rainfall (P) must be computed cumulatively, applying the SCS hypothesis to accumulated variables. Therefore, the effective runoff is the difference between the total runoff linked to the total water availability (current precipitation - P -, precipitation which generates previous runoff - ΔP - and initial soil moisture content positioned at S_a) and the runoff previously generated (ΔQ), which produces the current initial soil moisture larger than S_a , Eq. (11).

$$\frac{\Delta P}{\Delta Q} = \frac{\Delta S}{\Delta F} \quad (9)$$

$$\Delta P = \Delta E + \Delta F \quad (10)$$

$$Q = Q'|_{V_0=S_a, P+\Delta P} - \Delta Q = \frac{\left(P + \frac{\Delta F \cdot S}{S - \Delta F}\right)^2}{S - P + \frac{\Delta F \cdot S}{S - \Delta F}} - \left(P + \frac{\Delta F \cdot S}{S - \Delta F} - \Delta F\right) \quad (11)$$

where $Q'|_{V_0=S_a}$ is the cumulative runoff after a precipitation depth $P+\Delta P$ (i.e., total rainfall from runoff starts), and initial soil moisture filling the lower reservoir (i.e., on the limit to the runoff start).

The main limitation of this model is that requires the estimation of V_0 , which does not have an explicit form to do the evaluation. Several procedures have been proposed to try to address this and most of the procedures include a relationship with the variable on API_5 and the resulting runoff (Q_5). Wang et al. (2012) examined this approach by using V_0 as the product of the initial soil moisture content by the depth of the soil horizon (z_s). This value is not related to any physical property and it is also calibrated as an additional parameter, increasing the number of parameters from two (S, S_a) to three (S, S_a, z_s). Furthermore, the range of variation of z_s is fixed from 50 to 2000 mm, having a mean value equal to 847 mm, is large and it is in conflict with the effective soil depth above the impeding layer. This is similar z_s , obtained in Mishra et al. (2004), where for 55 sets of laboratory infiltration data on soils varying from Plainfield sand to Yolo light clay, the effective soil depth fluctuates between 19.7 and 72 mm. Thus, there is not clear physical meaning of this parameter is questioned and a new parameter without any relationship to the other parameters or the soil characteristics is added.

In our work, the parameter V_0 is obtained by multiplying the relative soil moisture (or degree of saturation) times the total soil storage ($V=S+S_a$), as stated in Michel et al. (2005) who stated “... *the correct solution should have been to try and identify typical situations where V_0 could be set in relation to the intrinsic parameters S and S_a ...*”

2.3 RSS_a Model (Reformulation of Michel model)

To address these inconsistencies, a new reformulation of that of Michel et al. (2005) is proposed in this paper. The SS_a model, which represents the first formulation that incorporates the SMA evaluation, while maintaining the original conceptualization and tractability, there are still some limitations in the model regarding the intrinsic parameters and the initial conditions. Moreover, the Soil Moisture Accounting (SMA) procedure is incorrectly used (Singh et al., 2015).

Another limitation of this model is the representation by the parameter S_a of two elements the initial abstraction I_a and the initial soil moisture volume V_0 , not unquestionable in defining the “*intrinsic parameter of soil moisture reservoir*” as $S_a = I_a + V_0$ (Wang et al., 2012). Nonetheless, V_0 could be greater than S_a and an inconsistent physical situation is generated. This exceedance is recognized as “bonus” runoff (Michel et al., 2005).

In the RSS_a model, the threshold parameters S_a is considered as a second parameter, independently from S . Additionally, a new formulation is proposed to account for the antecedent soil moisture conditions. The parameter S_a represents a threshold value for runoff generation (combining surface conditions, land use and vegetation), so it is considered independent of soil response. Therefore, the quantification of V_0 is only dependent variable on the parameter S , which actually controls the division of effective rainfall into runoff, once the previous threshold is exceeded. With this new hypothesis, the physical inconsistency of the rest of the models presented above is solved. It should be noted that this hypothesis underlies the Michel et al. (2005) model, when S_a is considered as a percentage of S (0.33S); hence V_0 is “only” dependent on S ranging from 0 to 1.33S. In other words, the establishment of a fixed relationship between parameters S and S_a not only affects the soil response but also the SMA procedure.

2.4 S_{f(0)} Model (Brocca et al., 2009a; Brocca et al., 2009b)

To compare the goodness of our proposal, the model presented in Brocca et al. (2009a) and Brocca et al. (2009b) is also analysed. In this model a new recognized dependency of the S parameter on ARC

appears. Based on the limitations and inability of API_5 to characterize the initial wetness of a watershed shown in different previous works, it is concluded that the best option should be performed by the observed linear behaviour between the wetness state of the soil and the parameter S , proposing the relationship exposed in Eq. (11)

$$S = a \cdot (1 - \theta_e) \quad (12)$$

where a is the maximum soil storage (to be calibrated) and θ_e is the relative soil moisture (or degree of saturation). Following the basis of the NRCS-CN model, the λ parameter is initially equal to 0.2, even though it could be evaluated as another parameter of the model.

3. VARIABLES AND DATABASES

The model presented in this paper is evaluated in 12 watersheds, located in different climate regions and exhibiting different soil characteristics (Figure 2). These scenarios can be classified into two groups by climatic type using the Köppen climate classification (Köppen, 1900) described in Table 1. The first group is a Mediterranean climate, with seven watersheds located in France, Italy and Greece with areas ranging from 3.83 to 137 km² and with sandy loam as the predominant soil texture. Within this set of watershed there are five watersheds belonging to a similar river basin called Niccone river basin, Italy (Colorso Pmarie, Vallaccia Pmarie, Vallaccia Molino, Niccone Reschio and Niccone Miglianella).

The second group with five watersheds with a preponderant semi-arid climate are located in US, Brazil and Spain. In this second case, the difference between smaller and higher watersheds is greater than for those in the first group, varying from 0.0146 to 109 km², also having different soil textures among them. Similarly, within this set of watershed there are five watersheds belonging to a similar river basin called Rillito river basin, US (WG Flume 102, WG Flume 103 and Walnut Gulch 4). The estimation of the initial soil moisture content is developed by different procedures: direct methods like the gravimetric method, or indirect methods using a Frequency Domain Reflectometry (FDR) sensor or Time Domain Reflectometry (TDR) sensors. When no measurements of antecedent soil moisture content were available, it was estimated using a Water Balance method.

4. RESULTS AND DISCUSSION

4.1. Joint analysis of rainfall, runoff and initial soil moisture content

The need to evaluate simultaneously the rainfall, runoff and initial soil moisture content is examined in one representative watershed from each group of watersheds depending on climatic type: the Valescure (France) and La Conchuela (Spain) watersheds. These watersheds were chosen as representative because they have the longest record and different soil characteristics. Figure 3 shows of these three variables for each event (red circles), rainfall and runoff (green circles) and initial soil saturation degree and runoff (blue circles). As can be seen, the range of variation of initial soil moisture content, evaluated as initial saturation degree, is greater in the Valescure watershed than in La Conchuela due to the soil characteristics of each watershed (Table 1). On the one hand, in Valescure watershed the soil shows a soil texture classified as sandy loam, which can store up larger volumes of rainfall before runoff occurs, due to its porosity and high permeability degree (Massari et al., 2014a). On the other hand, in La Conchuela, the first horizons from the soil profile (0-110 cm) presents an expansive clay with relevant shrink-swell potential, because of the high content of smectite clay, which leads to a low permeability degree (Gómez et al., 2014).

The relevance of the initial soil moisture content is evaluated in events with similar rainfall volume but different antecedent conditions. Contrary to the exclusively representation of the values of rainfall and runoff, Figure 3 helps to understand the fluctuations in runoff volumes for similar rainfall depths by plotting the spline surface that combines the response of each watershed for the combination of these three variables. The shape of both splines depends on the intrinsic characteristics of each watershed. In Valescure, the vast majority of rainfall events generate runoff for any initial soil moisture content, but in La Conchuela, 50 mm of rainfall together with a 70% of initial soil moisture content are necessarily required. Moreover, it should be highlighted that in La Conchuela relevant runoff events are observed when the initial soil moisture content is higher than 80% as consequence of the shrink-swell behaviour.

After recognizing the influence of the initial soil moisture content on the response of a watershed, we analyse the relationship between the parameter S from the NRCS-CN model, and the initial soil saturation degree by the correlation coefficient. Using Equation (13), obtained by solving equations (3) and (4) with $I_a = \lambda S$ and $\lambda=0.2$, the S value related to each PQ event is estimated. Subsequently, each S_{obs} is converted to a CN value using Eq. (5) and its correlation coefficient against the initial soil moisture content for each watershed is quantified.

$$S_{obs} = \frac{1}{2\lambda^2} \left(2\lambda P - \lambda Q + Q - \sqrt{\lambda^2 Q^2 - 2\lambda Q^2 + 4\lambda P Q + Q^2} \right) \quad (13)$$

According to the results shown in Table 2, this relationship is not constant and varies from one watershed to another, not remaining constant for all cases from each climatic condition. The group of variables with a correlation coefficient with a significance level higher than 99% is composed of the Italian watersheds, followed by the Valescure, Caatinga Nativa and La Conchuela watersheds. The remaining watersheds (Rafina and Walnut Gulch watersheds) do not show any correlation with the CN value. This lack of correlation is interesting from the point of view of justifying the change in the denomination of AMC to ARC. If the soil moisture has no significant influence over the CN parameter that relates rainfall and runoff, it is not appropriate to use the concept of AMC to define watershed initial conditions prior to the rainfall-runoff process. Thus, the assumption that the ARC factors include, but are not limited to, initial soil moisture content is justified (Grabau et al., 2009).

4.2. Stability and robustness of the new procedure RSS_a

Prior to the comparison of the models, the stability and robustness of the proposed methodology are evaluated for the representative watershed for each climatic scenario. For this purpose, the P-Q-ISMC dataset from each watershed is divided into two different groups to perform a calibration-validation procedure. Figure 4 provides the correlation of both observed and simulated runoff values for the set of values used for validation. As can be seen in that figure, the degree of correlation in Valescure watershed is high for runoff values below 100 mm. The criteria for determining the suitability of the new model are the Nash Sutcliffe Efficiency coefficient (NS), the Coefficient of Determination (R^2)

and the percentage of bias (PBIAS). In Moriasi et al. (2007) is established a performance rating as “very good” for $NS \in [0.75,1]$ and $PBIAS \in [-10,10]$; “good” for $NS \in [0.65,0.75]$ and $PBIAS \in [-15,15]$; and “satisfactory” for $NS \in [0.50,0.65]$ and $PBIAS \in [-25,25]$. The values for the different criteria analysed in calibration and validation are: NS coefficient NS equal to 0.96 and 0.84, R^2 equal to 0.97 and 0.96, and PBIAS equal to 1.23 and -9.65, respectively. In the La Conchuela watershed, the results of the fitting procedure are: NS equal to 0.80 and 0.68, R^2 equal to 0.81 and 0.733, PBIAS equal to 7.01 and 22.04, respectively. Therefore, the goodness-of-fit of the new procedure is ensured, especially for the NS and R^2 criteria.

4.3. Model comparison in the evaluated watersheds

Once the relationship between rainfall, initial soil moisture content and runoff has been revised and the robustness of the new procedure (RSS_a) analysed, the performance of the different models is compared. The estimation of the best parameterization for each model and watershed is developed by using the Least Squares method, selecting the Root Mean Square Error (RMSE) as the objective function to be minimized. Table 3 summarizes the RMSE obtained with the different models: NRCS-CN model with $\lambda=0.2$, with $\lambda=0.05$ (Woodward et al., 2003; Yuan et al., 2014) and with λ independent as another parameter; $S_f(\theta)$ model with $\lambda=0.2$ and with λ independent as another parameter; SS_a model and our new model RSS_a . Taking into account the climatic conditions, it is possible to appreciate the goodness-of-fit of the RSS_a in all cases, the $S_f(\theta)$ model being the second best model for both hypotheses about λ . The next model is the SS_a , which has even better results than the NRCS-CN model with λ as an independent variable, with also two parameters like the rest of models. On the other hand, the RSS_a is only the best model in 2 of the 5 Semi-arid watersheds (Walnut Gulch #4 and La Conchuela), $S_f(\theta)$ being the best model with λ as independent variable in three of these scenarios. However, with a reduction in the number of parameters in the $S_f(\theta)$ model to only one ($\lambda=0.2$), the goodness-of-fit is worse than in the RSS_a model in all cases.

The suitability of each model is also examined by the Nash-Sutcliffe Efficiency (NSE) criterion. The results obtained for Mediterranean climate watersheds corroborate the conclusion achieved with the RMSE value: the RSS_a is the best model (Table 4). The $S_f(\theta)$ model with λ as an independent variable and $\lambda=0.2$ appears as the next better option. Subsequently, the SS_a model and NRCS-CN model have the lower performances. The latter approach has poor results when applying the hypothesis of λ as an independent variable. By contrast with the previous cases, the optimal option for Rafina watershed is the NRCS-CN model with λ as a variable and $\lambda=0.05$. In semi-arid watersheds, the RSS_a only emerges as the best procedure in half of the watersheds for the NS criterion (Walnut Gulch 4, Caatinga Nativa and La Conchuela watersheds), obtaining results similar to the $S_f(\theta)$ model in the Brazilian case. In Walnut Gulch 102, the NRCS-CN model with λ as independent variable is the best option, and in Walnut Gulch 103 the $S_f(\theta)$ model is the most suitable option.

The last criterion evaluated is the percent bias (PBIAS), of which the optimal value is 0. It measures the average tendency of the estimated runoff volumes to be larger or smaller than observed data (Gupta et al., 1999). Positive values reveal a model underestimation bias, and negative values an overestimation bias. In the Mediterranean watershed, the RSS_a model is the best model in all cases, except in Rafina watershed. In Caatinga Nativa and La Conchuela watersheds, the RSS_a model is the optimal model again, followed by the $S_f(\theta)$ model. The most striking result emerges from the Walnut Gulch and Rafina watersheds, where the worst models are the RSS_a , SS_a and the $S_f(\theta)$, which are the methods that incorporate the initial soil moisture content as a variable in their formulations. The validity of the initial soil moisture content as an efficient variable to characterize ARC in these watershed was previously questioned in Table 2 by the low degree of correlation with CN values. Moreover, in Zhang et al. (2011) was analysed in several Walnut Gulch watersheds the relationships between measured runoff ratios and antecedent soil moisture and it was concluded that there was no significant correlation between those variables.

Due to the inconsistent results obtained in some watersheds when using soil moisture-based models, it is suggested that a fixed value of initial soil moisture content fixed at its average value should be used.

This assumption is based on the hypothesis that the variability of soil moisture has no influence on the runoff volumes, and so does not contribute to improving the watershed response. As shown in Table 6, the NS efficiency is increased in all models, and the PBIAS criterion is improved for the RSSa and SSa models, getting values below 4 (in absolute terms), while with the hypothesis of considering soil moisture content these values are over 18 (in absolute terms). This result reinforces the suitability of the RSSa model when compared to other models based also on two parameters and only depending on rainfall and runoff as variables. In conclusion, the most interesting finding is the efficiency of different soil moisture-based models to generate runoff when prior moisture content has relevance to the runoff values. Among them, the new procedure RSSa shows the highest degree of fitting, corroborating this new procedure as the best model. On the other hand, if soil moisture has no influence on the runoff, the use of a fixed soil moisture value as the antecedent condition instead of soil moisture as a variable is preferred. Under this hypothesis, the results are clearly better with the RSSa and SSa models.

To complete the previous analysis, Table 7 shows the parameterization obtained with each model and under both hypotheses about initial soil moisture content: all Mediterranean watersheds plus Caatinga Nativa and La Conchuela with initial soil moisture content as a variable; and Rafina and Walnut Gulch watersheds with initial soil moisture content fixed at its average value. It is advised that in all cases the parameter S is greater than S_a , but the ratio S_a/S is not constant. Neither do the parameters obtained with the SS_a model have a constant relationship between S and S_a . These results challenge the fixed ratio $S_a/S = 0.33$ proposed in Michel et al. (2005). With the NRCS-CN model it is possible to appreciate and corroborate the ideas exposed in Woodward et al. (2003) and Yuan et al. (2014) about the validity of the initial ratio λ , because the best λ value is closer to 0.05 than to 0.2.

4.4. Scale effects in the estimation of parameters

Finally, the influence of scale effects in runoff estimation and their relevance to the parameters adopted in each case are evaluated. The analysis is developed for each group of watersheds belonging to a similar river basin: Niccone river basin, Italy and Rillito river basin, US. For each group of watersheds, a common parametrization is estimated for all models, as described in Table 8. Comparing

these results against the values estimated for each watershed in Table 7, it can be appreciated that the scale effects on parametrization are greater in Semi-arid zones and for all models. Therefore, there is a question about the maximum watershed area where any of these models could be applied, and its relationship with climate conditions, but this analysis is out of the scope of the present work. These Semi-arid watersheds were analysed in Simanton et al. (1996), exposing a reduction of the CN parameter in the NRCS-CN model, which was explained by the spatial rainfall distribution and flow abstractions in ephemeral channels and verified in Yuan et al. (2014). In this paper, the parameter S included in the RSS_a model increases when the drainage area increases. This conclusion was also achieved in the work exposed above, using NRCS CN model (S is inversely proportional to CN, Eq. 5). Although parameter S would be only dependent on soil properties (mainly soil texture, soil formation, particle size or homogeneity), in practice, it is also affected by scale effects, as it has been highlighted previously.

Analysing the NS criterion of efficiency obtained for each watershed for a common parameterization (Table 9), in comparison with individual results presented in Table 4, it is noticed that the reduction of the goodness-of-fit is higher for large watersheds. No relevant variation has been found in the NRCS-CN and $S_f(\theta)$ models for both criteria when applying the hypothesis of λ equal to 0.2, 0.05 and evaluating this as another parameter to be calibrated. The results obtained with the SS_a model are close to the values shown by the RSS_a model for the Mediterranean watersheds. However, the differences generated by scale effects in the case of the semi-arid watersheds are relevant, especially for the largest watershed of this river basin (Walnut Gulch 4) which also has different soil texture with a mixture of coarse and finer soils.

Summarizing, the RSS_a procedure can be used for both climatic conditions, taking into account that scale effects play a key role in semi-arid watersheds, where their influence over the watershed response cannot be neglected.

5. CONCLUSIONS

This paper presents a new model, RSS_a , to quantify the runoff generation using the combination of rainfall and initial soil moisture content. RSS_a model solves the lack of integration of soil moisture in the NRCS by adding a Soil Moisture Accounting procedure. Previously proposed methodologies do not clarify how to take into account the watershed initial conditions prior to the rainfall-runoff process. In contrast, RSS_a model defines a procedure for the evaluation of this variable and it improves the runoff estimation when compared to NRCS CN-based models in the twelve watersheds utilized as comparison frameworks. The goodness of the RSS_a procedure is unquestionable for most of the Mediterranean watersheds analysed, and it appears as a good alternative for not very large semi-arid watersheds.

Finally, the study presented in this paper also shows that the soil moisture content variable should only be used to model runoff behaviour when prior conditions and the watershed response are correlated. In other cases, the variability of antecedent soil moisture may not be useful for runoff estimation. In such cases, it is suggested to set a fixed value as the initial condition. This research will serve as a base for future studies with the RSS_a model, where new factors to better characterize the antecedent conditions were identified. Furthermore, it is also recommended to include the scale effect in the factor analysis, because of its significant influence especially in Semi-arid zones.

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TABLES

Table 1 Description of the watersheds analysed: climatic type, location, area, soil texture, methodology to measure soil moisture content and reference

Climatic Type	Watershed	Area [km ²]	Soil Texture	Methodology to measure soil moisture content	Reference
Mediterranean zones	Colorso P. Marte (Italy)	13	Sandy Loam	FDR - 10 cm	Brocca et al. (2009b)
	Vallaccia P. Marte (Italy)	35	Sandy Loam	FDR - 10 cm	
	Vallaccia Molino (Italy)	57	Sandy Loam	FDR - 10 cm	
	Niccone Reschio (Italy)	104	Sandy Loam	FDR - 10 cm	
	Niccone Miglianella (Italy)	137	Sandy Loam	FDR - 10 cm	Tramblay et al. (2010); Massari et al. (2014b) Massari et al. (2014b)
	Valescure (France)	3.83	Sandy Loam	TDR - 25 cm	
	Rafina (Greece)	109	Clay	FDR - 25 cm	
Semi-arid zones	Walnut Gulch Flume 102 (US)	0.015	Sandy Loam	TDR - 15 cm	Keefer et al. (2008); Langhans et al. (2014); USDA-Southwest http://www.tucson.ars.ag.gov/dap
	Walnut Gulch Flume 103 (US)	0.0368	Sandy Loam	TDR - 15 cm	
	Walnut Gulch Flume 4 (US)	2.26	Sandy Loam	TDR - 15 cm	
	Caatinga Nativa (Brazil)	0.02	Silty Clay Loam	Gravimetric	Araújo Neto et al. (2013); Rodrigues et al. (2013)
	La Conchuela (Spain)	0.08	Clay	Water Balance Method	
					Gomez et al. (2014)

Table 2 Correlation coefficient between CN parameter and initial soil moisture content (initial saturation degree). *: correlation is significant at a level of 99%

Watershed	Correlation Coefficient
Colorso P. Marte (Italy)	0.86*
Vallaccia P. Marte (Italy)	0.85*
Vallaccia Molino (Italy)	0.81*
Niccone Reschio (Italy)	0.84*
Niccone Miglianella (Italy)	0.75*
Valescure (France)	0.65*
Rafina (Greece)	-0.42
Walnut Gulch Flume 102 (US)	0.03
Walnut Gulch Flume 103 (US)	0.04
Walnut Gulch Flume 4 (US)	0.01
Caatinga Nativa (Brazil)	0.63*
La Conchuela (Spain)	0.41*

Table 3 Goodness-of-fit in model application to watersheds

Watershed	RSS _a	SS _a	RMSE				
			NRCS-CN			S _f (θ)	
			$\lambda=0.2$	$\lambda=0.05$	$\lambda=\text{Var Ind}$	$\lambda=\text{Var Ind}$	$\lambda=0.2$
Colorso P Marte	1.39	2.39	2.61	2.40	2.29	1.53	1.53
Vallaccia P Marte	1.34	2.06	2.97	2.78	2.69	1.50	1.54
Vallaccia Molino	0.83	2.10	2.27	2.02	1.90	0.95	1.79
Niccone Reschio	1.25	2.40	3.27	3.02	2.90	1.70	1.70
Niccone Miglianella	1.45	2.49	3.33	3.09	2.98	1.84	1.84
Valescure (France)	15.61	15.5	23.68	21.92	21.62	20.4	22.74
Rafina (Greece)	2.82	3.14	1.74	1.26	0.73	1.47	2.79
WG Flume 102	3.19	4.19	2.69	2.32	2.17	2.35	3.66
WG Flume 103	2.87	3.30	3.11	2.73	2.57	2.59	2.98
Walnut Gulch 4	1.69	2.05	2.21	1.93	1.77	2.63	2.84
Caatinga Nativa	1.04	1.07	3.47	3.77	2.50	0.75	1.12
La Conchuela	4.89	5.61	7.70	7.65	7.58	5.41	5.80

Table 4 Performance evaluation of NS efficiency criterion in model application to watersheds

Watershed	RSS _a	SS _a	NS efficiency criterion				
			NRCS-CN			S _f (θ)	
			λ=0.2	λ=0.05	λ=Var Ind	λ=Var Ind	λ=0.2
Colorso P Marte	0.62	-0.11	-0.32	-0.11	-1.33	0.55	0.54
Vallaccia P Marte	0.75	0.41	-0.23	-0.08	-0.01	0.69	0.67
Vallaccia Molino	0.80	-0.27	-0.48	-0.17	-0.03	0.74	0.72
Niccone Reschio	0.78	0.20	-0.50	-0.28	-0.18	0.59	0.59
Niccone Miglianella	0.73	0.20	-0.42	-0.22	-0.13	0.57	0.57
Valescure (France)	0.93	0.93	0.84	0.86	0.87	0.88	0.85
Rafina (Greece)	0.52	0.40	0.82	0.90	0.97	0.87	0.53
WG Flume 102	0.37	-0.08	0.55	0.67	0.71	0.66	0.17
WG Flume 103	0.58	0.45	0.51	0.62	0.66	0.66	0.55
Walnut Gulch 4	0.46	0.21	0.08	0.30	0.41	-0.30	-0.52
Caatinga Nativa	0.97	0.96	0.62	0.55	0.80	0.98	0.96
La Conchuela	0.79	0.73	0.49	0.49	0.50	0.75	0.56

Table 5 Performance evaluation of Percent Bias (PBIAS) in model application to watersheds

Watershed	Percent Bias PBIAS (%)						
	RSS _a	SS _a	NRCS-CN			S _f (θ)	
			$\lambda=0.2$	$\lambda=0.05$	$\lambda=\text{Var Ind}$	$\lambda=\text{Var Ind}$	$\lambda=0.2$
Colorso P Marte	-0.36	-19.25	-15.35	-10.54	-8.60	-3.84	-4.74
Vallaccia P Marte	2.07	-16.44	-13.67	-9.66	-7.60	-5.13	-3.05
Vallaccia Molino	-1.02	-25.19	-15.13	-10.45	-8.09	-4.26	-6.07
Niccone Reschio	0.40	-7.87	-12.64	-10.34	-9.24	-5.55	-5.29
Niccone Miglianella	0.52	-6.77	-11.79	-9.66	-88.94	-5.21	-5.01
Valescure (France)	4.86	4.86	-12.44	-10.4	-9	-9.2	-12.23
Rafina (Greece)	-47.46	-64.29	-37.62	-28.23	-7.79	-21.06	-50.74
WG Flume 102	-35.56	-74.75	-32.06	-18.08	-8.47	-8.51	-30.35
WG Flume 103	49.50	-18.99	-29.77	-18.12	-10.73	-15.32	-27.96
Walnut Gulch 4	-34.19	-46.43	-53.60	-33.94	-12.99	16.63	-5.81
Caatinga Nativa	0.17	-21.26	-3.53	9.91	-15.66	-11.12	-1.59
La Conchuela	6.22	-14.47	-39.89	-28.83	-73.75	23.39	-28.73

Table 6 Performance evaluation of NS efficiency criterion and Percent Bias (PBIAS) in model application to watersheds with initial soil moisture content fixed at average value.

Watershed	NS Efficiency Criterion				Percent Bias PBIAS (%)			
	RSS _a	SS _a	S _f (θ)		RSS _a	SS _a	S _f (θ)	
			λ =Var Ind	λ =0.2			λ =Var Ind	λ =0.2
Rafina (Greece)	0.97	0.97	0.97	0.82	2.82	2.83	-7.8	-31.62
WG Flume 102	0.72	0.72	0.71	0.55	2.23	2.23	-8.47	-32.06
WG Flume 103	0.68	0.68	0.65	0.49	-3.02	-3.02	-10.65	-29.77
Walnut Gulch 4	0.43	0.43	0.41	0.08	3.48	3.46	-12.99	-53.6

Table 7 Parametrization of the models analysed

Watershed	RSS _a		SSa		NRCS-CN				S _f (θ)		
					$\lambda=0.2$	$\lambda=0.05$	$\lambda=\text{Var}$	Ind	$\lambda=0.2$	$\lambda=\text{Var}$	Ind
	S	Sa	S	Sa	S	S	S	λ	a	a	λ
Colorso P Marte	115.9	92.3	7.7	115.7	48.7	92.6	144.1	0.001	217.9	254.6	0.151
Vallaccia P Marte	154.2	116.7	4.1	102.5	45.6	84.3	126.6	0.001	202.7	135.6	0.386
Vallaccia Molino	102.3	82.4	5.6	111.3	47.6	89.5	137.1	0.001	282.5	282.5	0.118
Niccone Reschio	196.7	139.4	9.3	100.0	38.3	66.2	92.1	0.001	171.4	161.1	0.225
Niccone Miglianella	181.7	128.6	8.5	96.2	37.1	63.5	87.3	0.001	166.6	158.6	0.220
Valescure (France)	819.1	88.2	831.3	138.8	109.8	153.2	177.6	0.001	171.9	278.5	0.001
Rafina (Greece)	770.0	287.9	770.	467.6	203.4	390.2	634.6	0.001	330.3	1030.8	0.001
WG Flume 102	174.7	77.3	174.7	148.4	53.9	89.4	122.0	0.001	103.5	234.2	0.001
WG Flume 103	183.3	49.2	183.3	73.3	47.8	77.7	103.4	0.001	71.3	154.1	0.001
Walnut Gulch 4	629.7	310.7	629.7	639.1	104.7	206.8	368.3	0.001	215.4	757.4	0.001
Caatinga Nativa	111.9	86.1	6.9	141.5	89.3	166.0	29.2	1.000	252.0	153.9	0.453
La Conchuela	219.4	178.5	84.66	1498.39	89.6	138.0	138.0	0.017	500.3	956.7	0.011

Table 8 Parametrization of the models evaluated to analyse scale effects

Watershed group	RSS _a		SS _a		NRCS-CN				S _f (θ)		
					λ=0.2	λ=0.05	λ=Var. Indep.		λ=0.2	λ=Var. Indep.	
	S	S _a	S	S _a	S	S	S	λ	a	a	λ
Niccone River	132.7	100.9	6.03	104.7	43.6	79.2	106.4	0.001	195.3	213.7	0.169
Rillito River	248.2	95.1	248.1	166.4	60	101.6	132.2	0.001	105.2	250.2	0.001

Table 9 Performance evaluation of NS criterion of efficiency in model application to watersheds to analyse scale effects over parametrization. ***: no runoff generated

Watershed	NS criterion of efficiency						
	RSS _a	SSa	NRCS-CN			S _f (θ)	
			$\lambda=0.2$	$\lambda=0.05$	$\lambda=\text{Var Ind}$	$\lambda=\text{Var Ind}$	$\lambda=0.2$
Colorso Pmarte	0.52	-0.18	-0.41	-0.20	-0.12	0.46	0.45
Vallaccia Pmarte	0.74	0.40	-0.24	-0.09	-0.03	0.65	0.66
Vallaccia Molino	0.69	-0.41	-0.56	-0.25	-0.14	0.64	0.63
Niccone Reschio	0.66	0.03	-0.60	-0.37	-0.29	0.49	0.49
Niccone Miglianella	0.58	0.00	-0.56	-0.36	-0.28	0.42	0.43
WG Flume 102	0.62	0.38	0.53	0.65	0.69	0.71	0.55
WG Flume 103	0.56	-0.57	0.44	0.56	0.60	0.52	0.30
Walnut Gulch 4	-5.4	-10.1	-1.36	-1.07	-0.92	-1.57	-2.55

FIGURE CAPTIONS

Figure 1 Schematic diagram of the SSa_a model with the two possible positions of the initial soil moisture content (V_0^1 and V_0^2) with regard to the runoff threshold S_a .

Figure 2 Locations of the 12 watersheds studied. Green text: Watersheds belonging to Mediterranean climatic type. Red text: Watersheds belonging to semiarid climatic type

Figure 3 Plot of rainfall, runoff and initial soil saturation degree for Valescure and La Conchuela watersheds. Red balls: points depending on the three variables, Green balls: projection of points over the plane composed of rainfall-runoff axis; Blue balls: projection of points over the plane composed of the initial saturation degree-runoff axis.

Figure 4 Comparison of observed and simulated runoff for the validation of P-Q-ISMC dataset for Valescure (left) and La Conchuela (right) watersheds.