

IDENTIFICATION OF THE SCS-CN PARAMETER SPATIAL DISTRIBUTION USING RAINFALL- RUNOFF DATA IN HETEROGENEOUS WATERSHEDS

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ABSTRACT

Knowledge of the mechanisms controlling runoff generation is important in hydrology, civil engineering and other environmental sciences. Simple methods for predicting runoff from watersheds are particularly important in hydrologic applications, such as flood design and water balance calculation models. The Soil Conservation Service Curve Number (SCS-CN) method is widely used for predicting direct runoff volume for a given rainfall event. However, previous results indicated that when the CN value is determined from measured rainfall-runoff data in a natural watershed it is not possible to attribute a single CN value to the watershed, but actually the calculated CN values vary systematically with the rainfall depth. In a previous study, the authors investigated the hypothesis that the observed correlation between the calculated CN value and the rainfall depth in a watershed reflects the effect of the inevitable presence of soil-cover complex spatial variability along watersheds. It was shown that the presence of spatial variability in the watersheds produces a progressive decrease in the calculated CNs as the storm size decreases and for excessively large storm sizes the CN tends to stabilize in an asymptotic “composite” CN value.

In this study, a method to determine SCS-CN parameter values from rainfall-runoff data in heterogeneous watersheds is proposed. This method exploits the observed correlation between the calculated CN values and the rainfall depths in order to identify the spatial distribution of CN values along the watershed taking in to account the specific characteristics of the watershed. The proposed method utilizes the available rainfall-runoff data, remote sensing data and GIS techniques in order to provide information on spatial watershed characteristics that drive hydrological behavior, which is valuable in environmental hydrologic analysis and modeling. Furthermore, it allows the estimation of CN values for specific soil-land cover complexes in more complex watersheds.

The proposed method was tested in a small experimental watershed in Greece. The watershed is equipped with a dense hydro-meteorological network, which together with a detailed land cover and soil survey using remote sensing and GIS techniques provided the detailed data required for this analysis.

1 INTRODUCTION

Runoff estimation in ungauged watersheds is one of the most common problems in applied hydrology. Thus, simple methods for predicting runoff in watersheds are particularly important in hydrologic applications, such as flood design or water balance calculation models (Ponce and Hawkins 1996, Steenhuis et al. 1995). The Soil Conservation Service Curve Number (SCS-CN) method was originally developed by the U.S. Department of Agriculture, Soil Conservation Service to predict direct runoff volumes for given rainfall events and mainly for the evaluation of storm runoff in small agricultural watersheds. It is documented in detail in the National Engineering Handbook, Section 4: Hydrology (NEH-4) (SCS 1956, 1964, 1971, 1985, 1993, 2004). Due to its simplicity, it soon became one of the most popular techniques among the engineers and the practitioners, mainly for small catchment hydrology (Mishra and Singh 2006). Its main advantages, reported in the literature, are that it is a well-established method, it features readily grasped and reasonably well-documented environmental inputs, and it accounts for many of the factors affecting runoff generation, incorporating them in a single CN parameter. In contrast, the main weaknesses reported are that the SCS-CN method does not consider the impact of rainfall intensity and its temporal distribution, it does not address the effects of spatial scale, it is highly sensitive to changes in values of its single parameter, CN, and it is ambiguous considering the effect of antecedent moisture conditions (Hawkins 1993, Ponce and Hawkins 1996, McCuen 2002, Michel et al. 2005). The SCS-CN method soon was adopted for various regions and for various land uses and climate conditions (Elhakeem and Papanicolaou 2009, King and Balogh 2008, Mishra and Singh 1999, Romero et al. 2007). Furthermore, its scope expanded beyond the evaluation of storm runoff and it became an integral part of more complex, long-term, simulation models (e.g. Adornado and Yoshida 2010, Geetha et al. 2008, Singh et al. 2008, Soulis and Dercas 2007, Tyagi et al. 2008 etc).

The SCS-CN method is based on the following basic form calculating runoff from rainfall depth,

$$\begin{aligned} Q &= \frac{(P - I_a)^2}{P - I_a + S} & \text{for } P > I_a \\ Q &= 0 & \text{for } P \leq I_a \end{aligned} \quad (1)$$

where P is the total rainfall, I_a is the initial abstraction, Q is the direct runoff and S is the potential maximum retention. Based on a second assumption, that the amount of initial abstraction is a fraction of the potential maximum retention

$$I_a = \lambda S \quad (2)$$

Eq. (1) becomes

$$Q = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S} \quad (3)$$

The potential retention S is expressed in terms of the dimensionless curve number (CN) through the relationship

$$S = \frac{25400}{CN} - 254 \quad (4)$$

with S , in mm, taking values from 0, when $S \rightarrow \infty$, to 100, when $S=0$. The determination of all the NEH-4 SCS-CN values commonly used in hydrologic practice, assume the initial abstraction rate to be set to the constant value, $\lambda=0.2$, in order S (or its transformation CN) to remain the only free unknown parameter of the method.

CN values can be obtained from tables for various soil types, land cover and land management conditions, however CN estimation based on real data from local or nearby similar watersheds is preferable. In order to estimate S from real data, Eq. (3) can be solved by the quadratic formula to (Hawkins 1979)

$$S = 5 \left(P + 2Q - \sqrt{4Q^2 + 5PQ} \right) \quad (5)$$

Combining Eq. (7) with Eq. (6), CN value can be directly estimated from rainfall and runoff data

$$CN = \frac{25400}{5 \left(P + 2Q - \sqrt{4Q^2 + 5PQ} \right) + 254} \quad (6)$$

Though, even when the CN value is determined from measured P - Q data, the calculated CN values via Eq. (6) actually vary significantly from storm to storm on any watershed. For this reason, various methods to estimate a single CN value characterizing the watershed from measured runoff data were proposed (Bonda 1997, Hawkins et al. 1985, Hawkins 1993, Hjelmfelt 1980). However, the proposed methods lead to different CN values and in spite of the great number of studies on the SCS-CN method and its widespread use, there is not an agreed procedure to estimate CN from measured runoff data. Antecedent Moisture Condition (AMC) was initially assumed to be the primary cause of storm to storm variation, but this effect is of questionable origin, not recommended for use, and it was revised at the latest version of NEH-4 (Hjelmfelt et al. 2001, McCuen 2002, Ponce and Hawkins 1996, SCS 2004, Soulis et al. 2009, Steenhuis et al. 1995).

Hawkins (1993) in his study on the asymptotic determination of runoff curve numbers from measured runoff analysing a significantly large number of watersheds, where CNs are calculated from real P - Q storm data, concluded that a secondary systematic correlation almost always emerges in watersheds between the calculated CN value and the storm rainfall depth itself. In most of the watersheds, these calculated CNs approach a constant value with increasing rainfall depth that it is assumed to characterize the watershed. Depending on the type of correlation between rainfall and CN values calculated from measured runoff, distinguished watersheds in three categories namely watersheds with “standard” behaviour, “violent” behaviour, and “complacent” behaviour. In the “standard” behaviour, which appears most frequently, the larger calculated CN values correspond to the smaller rainfall depths, and decline

progressively with increasing storm size, approaching a stable near constant asymptotic CN value with increasingly larger storms (Fig. 1). Hawkins (1993) suggests the use of a single asymptotic CN value, observed for very large storm sizes, to be used to characterize such watersheds. In less common cases of watersheds the observed CN declines steadily with increasing rainfall with no appreciable tendency to approach a constant value (“complacent” behaviour, Fig. 1). According to Hawkins (1993), an asymptotic curve number cannot be safely determined from data for this behaviour. In the last behaviour concerning also a small number of watersheds the calculated CNs have an apparently constant value for all rainfall depths except very low rainfall depths where CN increases suddenly (“Violent” behaviour). Additional examples of watersheds presenting similar behavior were presented by Hjelmfelt et al. (2001). Bonda (1997) proposed a method for the determination of runoff curve numbers incorporating derived distributions. This method provided improved results in “violent” and “standard” watersheds, but still failed in “complacent” watersheds.

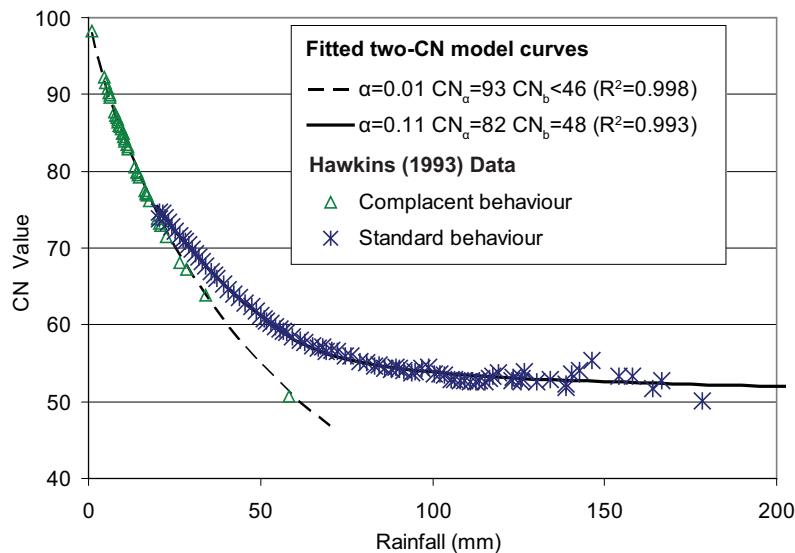


Figure 1. Two-CN model curves proposed by Soulis and Valiantzas, (2011) fitted to the data presented by Hawkins (1993) for the “Standard” (Coweeta watershed #2, North Carolina) and the “complacent” (West Donaldson Creek, Oregon) behaviour watersheds

All previously developed methodologies for estimating CNs from measured data focus mainly on the determination of a single asymptotic CN value characterizing the watershed hydrologic response for high rainfall depths. The observed deviations from the asymptotic behaviour for lower rainfall depths are not essentially taken into consideration and are rather attributed to various sources of temporal variability e.g. high rainfall intensities or wetness of the watershed that eventually posed in doubt the validity of the CN method. For this reason, the resulting CN values fail to describe the watershed response in small and medium rainfall events, limiting the applicability of the method to its original scope, namely the estimation of peak runoff values. Furthermore, the above methods fail to determine a final CN value in “complacent” watersheds or

when the available runoff dataset does not contain events large enough to determine the final CN value.

To overcome the above issues, Soulis and Valiantzas (2011) investigated the novel hypothesis that the observed correlation between the calculated CN value and the rainfall depth in a watershed reflects the effect of the inevitable presence of soil-cover complex spatial variability along watersheds. They showed that the presence of spatial variability in the watersheds produces a progressive decrease in the calculated CNs as the storm size decreases and for excessively large storm sizes the CN tends to stabilize in an asymptotic “composite” CN value. Based on this hypothesis, they introduced the simplified concept of a two-CN heterogeneous system to model the observed CN-rainfall variation by reducing the CN spatial variability into two classes. The behaviour of the CN-rainfall function produced by the proposed two-CN system concept was found to be similar to the variation observed in natural watersheds (Fig 1).

In this study, the above concept is extended in order to facilitate the determination of SCS-CN parameter values from rainfall-runoff data in heterogeneous watersheds. This method exploits the observed correlation between the calculated CN values and the rainfall depths in order to identify the spatial distribution of CN values along the watershed taking in to account the specific characteristics of the watershed. The proposed method utilizes the available rainfall-runoff data, remote sensing data and GIS techniques in order to provide information on spatial watershed characteristics that drive hydrological behavior, which is valuable in environmental hydrologic analysis and modeling. Furthermore, it could facilitate the estimation of the CN values corresponding to specific soil-land cover complexes by utilizing data coming from not entirely homogeneous watersheds. The proposed method is demonstrated in the small scale experimental watershed of Lykorrema stream in Greece.

2 MATERIALS AND METHODS

2.1 Spatial Identification Methodology

All previously developed methodologies for estimating CNs from measured data focus mainly on the determination of a single asymptotic CN value characterizing the entire watershed's hydrologic response. Soulis and Valiantzas (2011) hypothesized that the effort to determine a single CN value in watersheds characterized by significant spatial heterogeneity may produce the observed correlation between the calculated CN value and the rainfall depth. Based on this hypothesis, they introduced the simplified concept of a two-CN heterogeneous system to model the observed CN-rainfall variation by reducing the CN spatial variability into two classes.

Generally, more than two CN value categories may appear in natural watersheds. Thus in order to more closely describe the real conditions of natural watersheds it would be preferable if the number of the CN value categories identified was equal to the number of Soil-land cover complexes existing in each watershed. However, every added CN category requires the determination of two extra parameters (the corresponding CN value and the area it covers), giving rise to the overparameterization problem. Though, the involved parameters have a clear physical meaning allowing the position of constraints taking in to account the specific characteristics of the examined watershed and facilitating the determination of the remaining parameters based on the available

rainfall-runoff measurements.

In this manner, the proposed methodology extends the number of CN value categories identified to the actual number of soil-land cover complexes existing in the watershed. The proposed method exploits the available rainfall-runoff data, remote sensing data, and GIS techniques in order to identify the spatial distribution of CN values along the watershed taking into account the specific characteristics of the watershed.

Assuming that the total Q at the watershed's outlet is the sum of the partial Q_i ($i=1$ to n) coming from each of the n different Soil-land cover complexes existing in the watershed, which is characterized by a $CN = CN_i$ and covers an a_i percentage of the total area, Equation (6) yields:

$$CN = \frac{25400}{5 \left(P + 2 \sum_{i=1}^n Q_i - \sqrt{4 \left(\sum_{i=1}^n Q_i \right)^2 + 5P \sum_{i=1}^n Q_i} \right) + 254} \quad (7)$$

where:

$$Q_i = 0 \quad \text{if } 0.2P < \frac{25400}{CN_i} - 254$$

$$Q_i = \frac{a_i}{100} \frac{\left(P - 0.2 \left(\frac{25400}{CN_i} - 254 \right) \right)^2}{P + 0.8 \left(\frac{25400}{CN_i} - 254 \right)} \quad \text{if } 0.2P \geq \frac{25400}{CN_i} - 254 \quad (8)$$

and

$$\sum_{i=1}^n \alpha_i = 100 \quad (9)$$

The corresponding CN_i values can be estimated based on Equation (7) accomplishing the following steps:

1. The measured P and Q values are sorted separately and then realigned on a rank order basis to form P - Q pairs of equal return period (Hawkins 1993, Hjelmfelt et al. 1980, 2001). Then the measured P - Q data are transformed in the equivalent P - CN data using equation (6).
2. The watershed is divided in a set of n relatively uniform subareas corresponding to the main Soil-land cover complexes existing in the watershed by overlaying the available land cover and soil data. The resulting subareas are clearly spatially identified along the watershed and the corresponding area percentages (a_i , $i=1$ to n) are calculated using a GIS.
3. Additional constraints are posed, if needed, based on specific characteristics of the watershed (i.e. the CN of water bodies or impermeable areas like paved

- roads can be set equal to 100)
4. Eq. 7 is fitted to the transformed *CN-P* measured data curve yielding a set of best estimates for the *CN_i* values corresponding to each Soil-land cover complex.
 5. The estimated CN values are assigned to the corresponding subareas in the GIS, yielding the spatial distribution of CN values along the watershed.

2.2 Case study site

The proposed method is demonstrated in the small scale experimental watershed of Lykorrema stream (15.2 km²), which is situated in the east side of Penteli Mountain, Attica, Greece, and is centered at approximately N38.02° and E23.55° (Fig. 2). This watershed was selected because it has been presented in the international literature as an example of the “complacent” behaviour, and detailed geographical data were available (Soulis et al. 2009).

The region is characterized by a Mediterranean semi-arid climate with mild, wet winters and hot, dry summers. Precipitation occurs mostly in the autumn–spring period. The yearly average precipitation value for the last six years studied is 690mm. The watershed is divided in two sub-watersheds. The Upper Lykorrema watershed (7.84 km²) presents a relatively sharp relief, with elevations ranging between 280 m and 950 m. Its average elevation is 560 m and its average slope is as high as 36%. The Lower Lykorrema watershed (7.36 km²) also presents a relatively sharp relief with elevations ranging between 146 m and 643 m. Its average elevation is 310 m and its average slope is 21%. The watershed is dominated by coarse soils with high hydraulic conductivities and a smaller part is covered by medium textured soils presenting relatively high hydraulic conductivities. The dominant vegetation type in the watershed is pasture with a few scattered tufts of trees. There is also a dense road network, mainly in the lower part of the watershed, where a settlement exists. A small part of the watershed is covered by bare rock. The Upper and Lower Lykorrema experimental watersheds are operated from the Agricultural University of Athens, Greece and the National Technical University of Athens, Greece, respectively. Detailed description of the hydrology, climate and physiography of Lykorrema experimental watershed and of the available geographical and hydro-meteorological databases are provided by Soulis (2009) and Soulis et al. (2009).

2.3 Storm events

The study area is equipped with a dense hydro-meteorological network, which is fully operational since September 2004. For the current analysis, all the storm events producing significant direct runoff that took place from September 2004 to August 2008 were used (30 events). A storm event was considered significant when the value of peak flow rate in the hydrograph was greater than 0.15m³/s for the Upper Lykorrema watershed and 0.25m³/s for the entire watershed. The end of an event was defined when a six-hour period without rainfall occurred. The watershed areal rainfall estimation was made using Thiessen polygons method, while base-flow was separated using the constant slope graphical method (Dingman 2002). The potential maximum retention *S* and the *CN* value were directly estimated from the measured rainfall and runoff data using Eqs. (5) and (6). Details on the characteristics of these events are provided by Soulis et al. (2009).

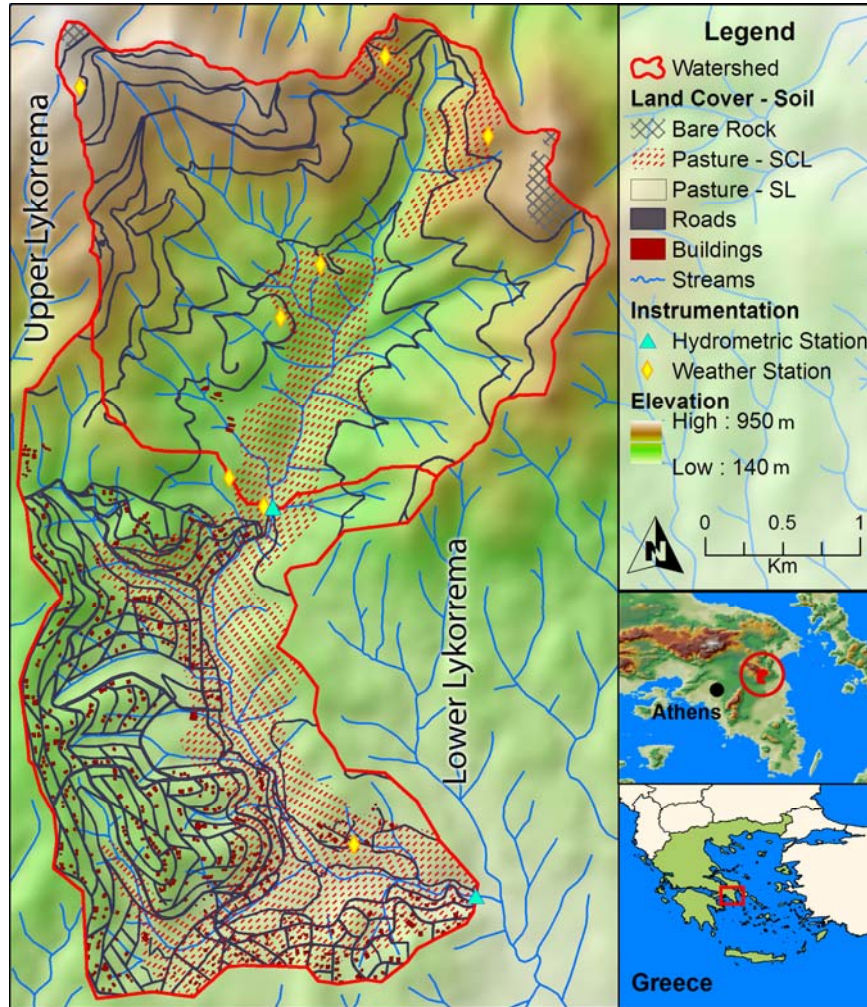


Figure 2. Map of the Lykorrema experimental watershed.

Table 1. Characteristics of the three main soil-land cover complexes present in the Lykorrema watershed

Soil-land cover complex		Area percentage, a_i (%)		Estimated CN value, CN_i ($R^2=0.99$)
Description	Number, i	Upper Lykorrema	Entire Watershed	
Pasture-SL	1	77.1	49.7	29.8
Pasture-SCL	2	17.8	40.2	47.9
Impermeable	3	5.1	10.1	99.5

3 RESULTS AND DISCUSSION

In order to demonstrate the use of the proposed methodology, the CN values characterizing the Lykorrema watershed were estimated based only on the data coming from the Upper Lykorrema watershed. Then, the resulted CN values were validated using all the available data.

Exploiting the available spatial data coming from a detailed soil survey in the area and a detailed land cover classification based on remote sensing techniques, the three main soil-land cover complexes existing in the Lykorrema watershed were spatially identified and the corresponding area percentages were calculated (Fig. 2 and Table 1). The first complex includes areas characterized by sandy loam (SL) soils with very high hydraulic conductivity that are covered by a mixture of pasture and shrublands with a few scattered tufts of trees. The second complex includes areas with similar land cover as the first one but characterized by sandy clay loam (SCL) soils with relatively high hydraulic conductivity. The last complex includes almost impermeable areas i.e. roads, buildings, areas covered with bare rock and streams.

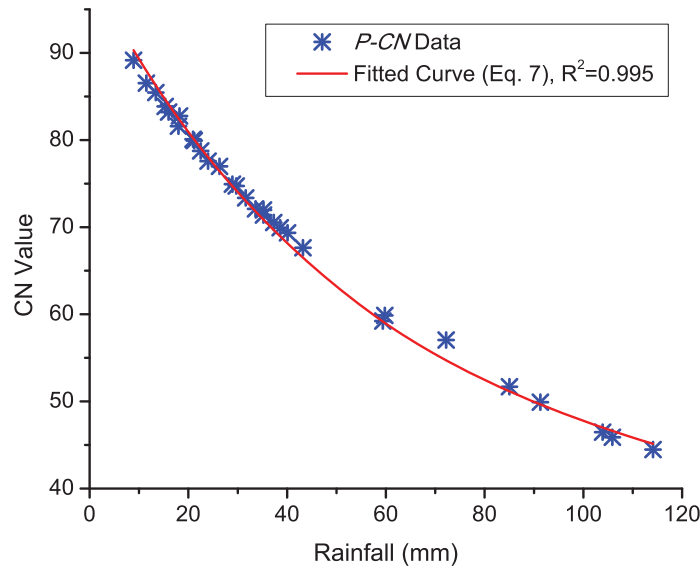


Figure 3. Eq. 7 fitted to the P -CN data curve of the Upper Lykorrema watershed

The measured P and Q data of the Upper Lykorrema watershed were ordered to form P - Q pairs of equal return periods and transformed in the equivalent P -CN data, as it was previously described. Following, Eq. 7 was fitted to the resulted P -CN data curve for the Upper Lykorrema watershed yielding the best estimates of the CN values corresponding to the three Soil-land cover complexes existing in the watershed (Fig. 3 and Table 1). The resulted CN values were validated in comparison to the original rainfall runoff data, i.e. before being ordered and realigned.

In Fig. 4a the spatial distribution of the identified CN values along the watershed is illustrated, highlighting the ability of the proposed methodology to provide information on spatial watershed characteristics that drive hydrological behavior. In Fig. 4b the

predicted runoff values using the CN values resulted by the proposed methodology (Table 1) are plotted in comparison to the original measured runoff values, against the total rainfall depth, for the Upper and the Entire Lykorrema watersheds. It can be seen that there is good agreement between the predicted and the measured runoff values for both watersheds ($R^2=0.863$ and $R^2=0.916$ for the Upper and the Entire Lykorrema watersheds respectively).

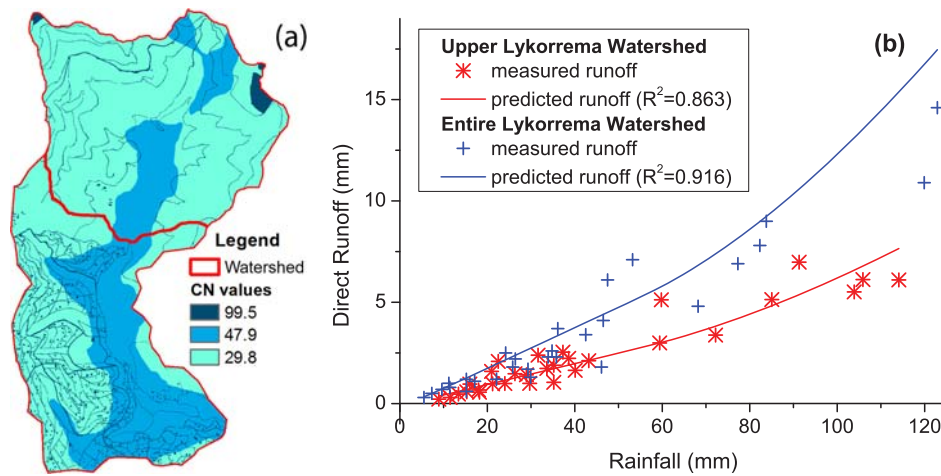


Figure 4. (a) Identified CN values spatial distribution, (b) Predicted runoff values in comparison to the original measured runoff values, against the total rainfall depth, for the Upper and the Entire Lykorrema watersheds

4 CONCLUSIONS

Soulis and Valiantzas (2011) stated the hypothesis that the correlation between the calculated CN value and the rainfall depth, which was observed in previous studies (e.g. Hawkins 1979, 1993, Hjelmfelt et al. 2001), reflects the effect of the inevitable presence of soil-cover complex spatial variability along watersheds. Based on this hypothesis, they introduced the concept of a simplified idealized heterogeneous system composed by two different CN values. The behaviour of the $CN-P$ function produced by this system was analysed systematically and it was found similar to the $CN-P$ variation observed in natural watersheds. They also demonstrated that the two-CN system approach provides reasonable accuracy in predicting runoff volumes and it over performs the previous original method.

In this study, a methodology to determine the spatial distribution of the SCS-CN parameter values from rainfall-runoff data in heterogeneous watersheds is proposed based on the same hypothesis. This methodology exploits the observed correlation between the calculated CN values and the rainfall depths in combination with specific characteristics of the watershed, such as soil and land cover types, in order to extend the number of the identified CN value categories to the actual number of soil-land cover complexes, which are present in the watershed.

The proposed methodology was calibrated and validated using the detailed hydro-

meteorological and spatial data available for the Lykorrema experimental watershed in Greece. It was demonstrated that the proposed methodology is able to provide reasonable accuracy in predicting runoff volumes and at the same time to effectively describe the CN values spatial heterogeneity that drives the watershed's hydrological behavior. This last capability, i.e. to provide information on CN values spatial distribution and thus spatially distributed runoff estimations, can be proven valuable in spatial distributed hydrological modeling and environmental hydrologic analysis. Furthermore, it allows the estimation of CN values for specific soil-land cover complexes in heterogeneous watersheds, which may facilitate future studies aiming at the adaptation and the documentation of the SCS-CN method in various regions and for various land uses.

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