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Modeling the Soil Response to Rainstorms after Wildfire and Prescribed Fire in Mediterranean Forests

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Abstract: The use of the Soil Conservation Service-curve number (SCS-CN) model for runoff predictions after rainstorms in fire-affected forests in the Mediterranean climate is quite scarce and limited to the watershed scale. To validate the applicability of this model in this environment, this study has evaluated the runoff prediction capacity of the SCS-CN model after storms at the plot scale in two pine forests of Central-Eastern Spain, affected by wildfire (with or without straw mulching) or prescribed fire and in unburned soils. The model performance has been compared to the predictions of linear regression equations between rainfall depth and runoff volume. The runoff volume was simulated with reliability by the linear regression only for the unburned soil (coefficient of Nash and Sutcliffe E = 0.73–0.89). Conversely, the SCS-CN model was more accurate for burned soils (E = 0.81–0.97), also when mulching was applied (E = 0.96). The performance of this model was very satisfactory in predicting the maximum runoff. Very low values of CNs and initial abstraction were required to predict the particular hydrology of the experimental areas. Moreover, the post-fire hydrological "window-of-disturbance" could be reproduced only by increasing the CN for the storms immediately after the wildfire. This study indicates that, in Mediterranean forests subject to the fire risk, the simple linear equations are feasible to predict runoff after low-intensity storms, while the SCS-CN model is advisable when runoff predictions are needed to control the flooding risk.

Keywords: hydrological models; rainfall; surface runoff; linear regression models; curve number; SCS.CN model; mulching; wildfire; prescribed fire

1. Introduction

The importance of forests in the climatic context at the planetary scale is well known, since forests produce oxygen and store carbon, regulate water and energy fluxes, support biodiversity and provide other fundamental ecosystem services [1–3]. However, the fundamental role of forests is threatened by some natural and anthropogenic agents, such as the extreme weather events and fire, with a long history of influence on forest ecosystems [4]. Extreme weather events (e.g., heavy storms and severe drought) are more and more intensified by climate change trends and occur in all regions of the world [5,6]. The fire effects extend to several components of forests, such as soil, vegetation, air and surface water [7]. With regard to the effects on surface water and soil, fire strongly alters the hydrological response of recently burnt areas, increasing by many folds the soil's aptitude to generate runoff and erosion compared the unburned forest areas [8,9]. High runoff and erosion rates in forests increase the flooding risk, debris flow occurrence and water quality alteration in downstream areas, with possible loss of human lives and heavy damage to infrastructures and environment [10,11]. For instance, with regard to the Mediterranean climate, exceptionally high erosion rates (up to 100 tons per ha) have been reported immediately after wildfire by Menendez-Duarte et al. [12] in the Iberian peninsula, while Lopez-Batalla et al. [13] measured increases in flood runoff by 30% and in peak discharges by 120% in the same environments. These studies together with a large body of literature (see several examples in the milestone review of Shakesby [14]) clearly demonstrate the need to control and mitigate the hydrological response of forest soils after the wildfire adopting prediction tools and post-fire management actions.

The hydrological processes in forests are influenced by several factors, among which fire severity is important [15]. In other words, the more severe the fire, the more susceptible the soil to increases in runoff and erosion and worsening in water quality changes in the downstream ecosystems [7]. For instance, Lucas-Borja et al. [7] found increases in runoff and erosion in soil burned by wildfire by about 20% and even 200%, respectively, compared to unburned soils in Central-Eastern Spain.

The hydrology of burned forests is very complex, since it is the product of several factors, such as climate and edapho-climatic conditions, fire severity, soil, vegetation, morphology and land management after fire [15–19]. The needs to predict the impacts of fire on runoff and erosion and to implement the most effective actions for rehabilitation of fire-affected areas have increased the demand for hydrological models [16,20]. This demand is particularly important for forest managers working in the Mediterranean Basin, which is characterized by dry and hot summers followed by frequent and high-intensity rains immediately after the wildfire season [15,21]. In Mediterranean areas, increases in wildfire frequency and burned areas are expected under the forecasted climate scenarios [22,23].

In Mediterranean forests, the literature reports applications and verifications of hydrological models with different nature and complexity: from the simplest empirical models (such as the Soil Conservation Service (SCS)-curve number model to predict runoff, the universal soil loss equation, USLE, to simulate soil erosion) through the semiempirical models (e.g., the Morgan–Morgan–Finney model, MMF) until the most complex physically-based models (for instance, the Water Erosion Prediction Project, WEPP) or even the artificial neural networks [24,25]. Nonetheless, the empirical models are sometime more commonly used compared to the more complex models, mainly in data-poor environments (that is, in those situations with limited availability of parameter inputs) and for quick identification of sources of water, sediments and pollutants in forests [24–26].

Accurate predictions of surface runoff are fundamental to achieve reliable estimations of erosion rates and water quality parameters using hydrological models [27], particularly in forests subject to climate change and fire, since the latter factors play a large influence of the soil's hydrological response [28,29]. The Soil Conservation Service (SCS)-curve number (CN) model (hereinafter "SCS-CN model") is one of the most common methods for estimating the runoff volume generated by a rainstorm [30,31]. The popularity of this method is due to its simplicity, ease of use, widespread acceptance and large availability of input data [32]. Moreover, the SCS-CN model takes into account most of the factors that influence runoff generation, such as soil type, land use, hydrologic condition and antecedent moisture of the soil [33]. The model has also been incorporated as a hydrological submodel in several distributed rainfall–runoff models at the watershed scale (e.g., AnnAGNPS—annual agricultural non-point source pollution model, SWAT—soil and water assessment tool model and HEC-HMS—hydrologic engineering center-hydrologic modeling system model), supporting its robustness and popularity [33,34]). To date, there is no any alternative model that offers as many advantages as the SCS-CN model, which therefore is still commonly used in the large majority of environments and climatic conditions [35].

However, various studies conducted throughout the world on the applicability of the SCS-CN method have suggested a need for further improvement or overhauling of the model [32,36], since in some environments the method provides unsatisfactory predictions, particularly when the soil's hydrological response does not follow the runoff generation mechanism by saturation-excess. Moreover, in spite of the large number of requisites, the model has been surprisingly little used for hydrological predictions in fire-affected areas, and the CN values are not completely known in burned areas [37]. The hydrological research has been mainly carried out at the watershed scale, where post-fire runoff has been predicted using the SCS-CN method incorporated in watershed-scale models (e.g., WILDCAT4 Flow Model [38] and FIRE HYDRO [39]). For instance, the SCS-CN model was used by Candela et al. [40], who analyzed the flood frequency curves for pre- and post-fire conditions, showing an increase in the average curve numbers and a decrease in the catchment time lag. Increases by 25 units in post-fire CNs were estimated by Soulis [37] in a small Greek watershed using pre-fire and post-fire rainfall–runoff datasets. A daily-constant CN in the SWAT model was used by Nunes et al. [41] to simulate the effects of soil water repellency on runoff from burnt hillslopes in a Mediterranean forest throughout three years after fire. It is therefore evident that the modeling experiences are scarce at the plot scale. At this scale, modeling of soil hydrology is less complex compared to the watershed scale, where the hydrological response to Mediterranean storms is further complicated by a combination and overlaying of several hydrological processes (e.g., water routing in the channel network, ponding and uneven soil properties) other than surface runoff generation. Furthermore, the studies about the hydrological effects of post-fire management on runoff in forests using the SCS-CN model are scarce.

Therefore, there is a need of further studies that must evaluate the runoff prediction capacity of the SCS-CN model in forest hillslopes or plots affected by fire of different severity—a fire parameter referring to the effects of wildfire on plant communities—in comparison with simpler models that estimate runoff directly from precipitation, such as the linear regression equations. In other words, is the SCS-CN model accurate to predict surface runoff in Mediterranean burned forests? Is it able to simulate post-fire hydrology with or without rehabilitation management actions (such as straw mulching) after a wildfire? When is its use convenient compared to a simpler linear regression between rainfall and runoff?

This study aims to reply to these questions, evaluating the hydrological performance of the SCS-CN model in two pine forests of Central-Eastern Spain affected by a wildfire and a prescribed fire, respectively, having different fire severity. More specifically, observations of rainfall–runoff patterns collected throughout one year in undisturbed soils (assumed as control) and in plots subject to prescribed fire/wildfire (the latter with or without a mulching treatment) are compared with the corresponding predictions of the SCS-CN model and linear rainfall–runoff regressions. The outcomes of this study help land managers to adopt strategies to control the hydrological effects of fire in Mediterranean forests.

2. Materials and Methods

2.1. Study Areas

Two experimental areas were selected in pine forests of the Province of Albacete, Castilla—La Mancha Region, Central Eastern Spain. The first area (Sierra de las Quebradas, municipality of Liétor) was affected by a wildfire in July 2016. The second forest (municipality of Lezuza) was subjected to a prescribed fire in March 2016, to reduce fuel loading and thus the potential risk and severity of subsequent fires (Figure 1). Prior to wildfire, the soil cover of the forest was mainly composed of plants, litter and stones with variable composition.

Both study areas have a semiarid Mediterranean climate, BSk according to the Köppen–Geiger classification [42]. The average annual rainfall and medium annual temperature are 282 (Liétor) and 450 (Lezuza) mm and 13.5 (Liétor) and 16 (Lezuza) °C, respectively (Spanish National Meteorological Agency, 1950–2016). According to historical data (1990–2014) provided by the Spanish Meteorological Agency, the maximum precipitation is concentrated in October (44.5 mm) and the minimum in May (39.6 mm); from June to September a hot and dry period (air relative humidity below 50%) occurs.

The mean minimum temperature of the coldest month is −0.9 °C and the mean maximum temperature of the hottest month is nearly 32 °C.

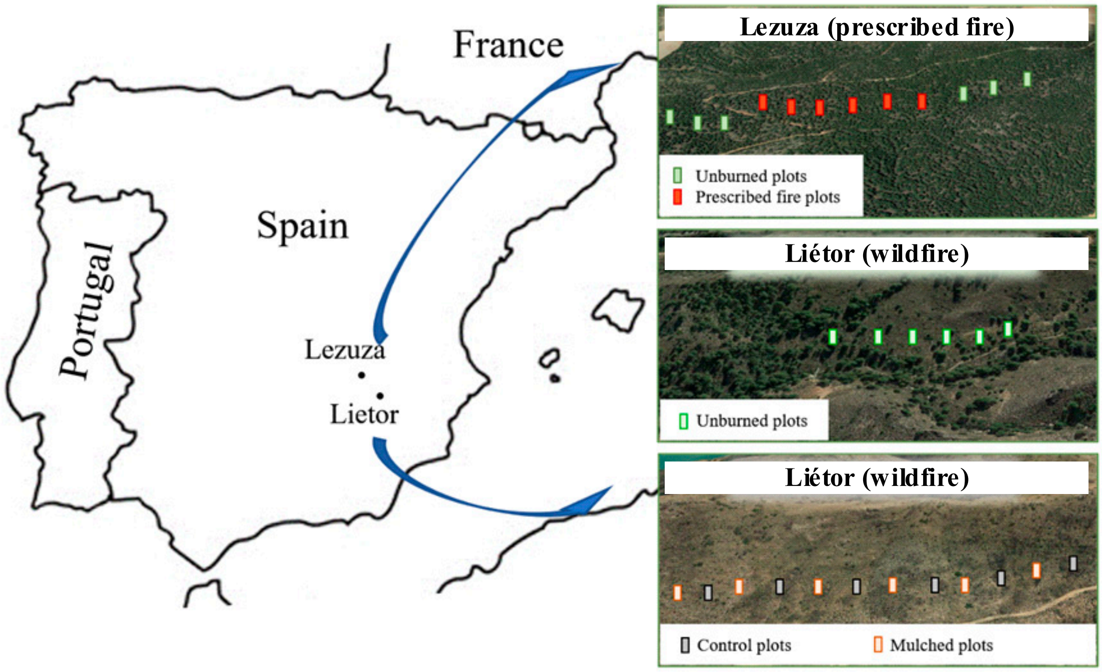


Figure 1. Location and layout of forest plots subject to prescribed fire and wildfire and monitored for hydrological observations (Lezuza and Liétor, Castilla La Mancha, Spain). Geographic coordinates and map source: Lezuza X: 557588E, Y: 4306475N; Liétor: X: 600081 E, Y: 4262798 N (unburned area); X: 598358 E, Y: 4264032 N (burned area); Google Earth, last access on 6/15/2019).

2.1.1. Wildfire-Affected Forest (Liétor)

The experimental area of Liétor is located at an elevation between 520 and 770 m a.s.l. with W-SW and N aspect and mean slope of 15–20% (Table 1). Soils are classified as Inceptisols and Aridisols with sandy-loam texture [43].

The wildfire burned about 830 ha of the forestland (mainly *Pinus halepensis* Mill). The mean tree density of this forest was between 500 and 650 trees per hectare with height between 7 and 14 m. *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* (L.) Moench, *Macrochloa tenacissima* (L.) Kunth, *Quercus coccifera* L. and *Plantago albicans* L. are the shrub or herbaceous species of the forest. The wildfire, classified as high-severity fire by the local forest managers according to the methodology proposed by Vega et al. [44], determined a tree mortality of 100% (Table 1). Forest floor was about 3–5 cm deep. This forest floor, as happened also in Lezuza, was blanketed with decaying *Pinus halepensis* M. needles and twigs and other wood debris such as cones or branches coming from trees. In both sites, the forest floor was blanketed with decaying *Pinus halepensis* M. needles and twigs and other wood debris such as cones or branches coming from trees in both sites, Lezuza and Liétor. More information related to this suggestion is provided in Table 1.

In September 2016 (two months after the wildfire), a mulching treatment was carried out in some areas of the burned site. Barley straw was spread manually on soil at a depth of 3 cm and a rate of 0.2 kg m^{-2} (dry weight), following the dose proposed by different authors for forests of Northern Spain, to achieve a burned soil cover over 80% [45].

Table 1. Main characteristics of forests and plots subject to prescribed fire and wildfire (Lezuza and Liétor, Castilla La Mancha, Spain).

Characteristics		Prescribed Fire (Lezuza)		Wildfire (Liétor)		
		Soil Condition				
		Control	**Burned**	**Control**	**Burned**	**Burned and Mulched**
Number of plots		6	6	6	6	6
Plot area (m^2)		8		200		
Elevation (m)		1010–1040		520–770		
Slope (%)		15 (±4.4)	14.5 (±2.6)	15–20		
Aspect		N	N-NE	W-SW and N		
Tree density (n ha^{-1})		477 (±33)	529 (±60)	500–650		
Tree height (m)		8–13		7–14		
Tree diameter (cm)		27 (±7)	32 (±6)	25–35		
Tree canopy cover (%)		75–85		60–70		
Tree species composition		*P. pinaster* Ait., *P. halepensis* M.	*P. pinaster* Ait., *P. halepensis* M., *Q. ilex* L.	*Pinus halepensis* Mill		
Shrub/herb species		*Quercus coccifera* L., *Brachypodium retusum* P., *Thymus vulgaris* L., *Dactylis glomerata* L.	*Quercus coccifera* L., *Brachypodium retusum* P., *Thymus vulgaris* L., *Sanguisorba minor* S.	*Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* (L.) Moench, *Macrochloa tenacissima* (L.) Kunth, *Quercus coccifera* L. and *Plantago albicans* L.		
Canopy consumed by fire (%)		-	18 (±5)	-	90 (±15)	
Shrub/herb cover (%)	Pre-fire	56 (±9)	51 (±7)	65 (±9)		
	Post-fire	59 (±5)	10 (±3)	0 (±0)		
Litter (%)	Pre-fire	40 (±8)	44 (±7)	10 (±5)		
	Post-fire	38 (±9)	79 (±6)	5 (±2)		
Bare soil (%)	Pre-fire	4 (±1)	5 (±1)	25 (±8)		
	Post-fire	3 (±1)	11 (±3)	90 (±12)		

2.1.2. Forest Subjected to Prescribed Fire (Lezuza)

The forest area was selected in a relatively hilly area at an elevation from about 1010 to 1040 m a.s.l., with a 50-year old mixed plantation of *Pinus halepensis* and *Pinus pinaster*. The mean slope is around of 15% and the aspect is N-NE. Soils are classified as Alfisols with Xeralf Rhodoxeralf horizon with clay texture [43] (Table 1).

The tree density of this forest area was about 500 trees per hectare with a mean height of 6.40 m. The understory was dominated by *Quercus faginea* Lam. L., *Quercus ilex* subsp. ballota, *Quercus coccifera* L., *Juniperus oxycedrus*, *Brachypodium retusum* P. and *Thymus* sp. (Table 1). Forest floor depth was about 5–7 cm.

2.2. Description of Experimental Plots and Measurement of Runoff Volume

In the two selected forests, experimental plots were installed in unburned (control) and burned areas. Plots were randomly distributed in the experimental site in areas with the same morphological and ecological characteristics to ensure comparability.

More specifically, in the wildfire-affected forest of Liétor, eighteen rectangular plots (20-m long × 10-m wide) were installed at a distance between 200 and 500 m. Six plots were located in the forest outside of the burned site and assumed as a control. Twelve plots were instead located in the burned area, of which six were not treated, while six plots were mulched. In the forest subjected to the prescribed fire in Lezuza, twelve plots (4-m long and 2-m wide) were isolated, of which six were located in the unburned area and the other six in the burned site. The prescribed fire was carried out under controlled air conditions in the forests (wind speed of 14 km/h, air temperature of 14 °C and relative humidity of 63%), which are reference values for applying the prescribed fire as a forest protection measure. The upper and side borders of all plots in both areas were hydraulically isolated by geotextile fabric pounded into the ground, to prevent external water inputs. At the plot bottom, runoff was collected using a metal fence conveying the water into a pipe, which discharged to a plastic tank of 25 (Liétor) or 50 (Lezuza) liters. In these plots, immediately the runoff volumes were measured after each rainfall event throughout an observation period of about one year (Table 2).

Table 2. Main characteristics of precipitation events in plots subject to prescribed fire and wildfire (Lezuza and Liétor, Castilla La Mancha, Spain).

Event	Date	Days after Fire	Rainfall Height (mm)	Maximum Intensity (mm h^{-1})
Prescribed fire (Lezuza)				
1	4 Apr 2016	5	20.0	8.8
2	6 May 2016	37	20.1	8.4
3	18 May 2016	49	10.2	4.3
4	12 Oct 2016	196	21.1	8.8
5	19 Oct 2016	203	27.4	5.3
6	8 Nov 2016	223	17.0	5.6
7	2 Dec 2016	247	52.4	4.2
8	23 Dec 2016	268	59.6	11.6
9	11 Feb 2017	318	38.2	6.3
10	4 Apr 2017	377	20.2	5.7
11	28 Apr 2017	394	28.2	6.8
Wildfire (Liétor)				
1	21 Oct 2016	98	40.0	3.99
2	24 Nov 2016	129	41.0	1.48
3	8 Dec 2016	146	59.0	0.98
4	21 Dec 2016	159	93.8	2.1
5	30 Jan 2017	199	28.0	0.84
6	22 Feb 2017	222	16.8	1.14
7	8 Mar 2017	236	11.6	1.78
8	20 Mar 2017	248	102.6	16.2
9	12 May 2017	301	20.7	3.77

A weather station (WatchDog 2000 Series model) with a tipping bucket rain gauge was placed in each study area to measure total daily precipitation, storm duration, air temperature and rain intensity during the study period. In the hourly rainfall series of the experimental database, two consecutive events were considered separate, if no rainfall was recorded for 6 h or more [46,47]. The mean rainfall intensity was the total rainfall divided by the storm duration. The main variables characterizing the observed events are reported in Table 2.

2.3. Outlines on the SCS-CN Model

This model, proposed by the Soil Conservation Service of the United States Department of Agriculture in 1972, hypothesizes that:

$$\frac{V}{P_n} = \frac{W}{S} \quad (1)$$

being:

- V = runoff volume (mm);
- P_n = net precipitation (mm);
- W = water volume stored into the soil (mm);
- S = maximum water storage capacity of soil (mm).

P_n is the difference between the total precipitation (P) and the initial losses (I_a, as the water storage in the soil dips, interception, infiltration and evapotranspiration) prior to surface runoff. I_a is assumed to be proportional to S through a coefficient λ:

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

S is given by:

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10\right) \quad (3)$$

when the parameter CN is the so called "curve number". The CN can be considered as the soil's aptitude to produce runoff and is a function of the hydrological properties and conditions of soil, and land use. The CN varies between 0 and 100 (0 means that the soil does not produces runoff, 100 means that all the precipitation turns into surface runoff and then the hydrological losses are zero).

According to this model, the runoff volume V is:

$$V = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S} \quad (4)$$

To estimate CN in agroforest areas, the soil hydrological class, vegetation cover, hydrological condition (good, medium and poor) and cultivation practice and the antecedent moisture condition (AMC) of the soil must be determined.

The soil hydrological class (A to D) is related to the soil's capability to produce runoff, on its turn due to the soil infiltration capacity. A low runoff production capability corresponds to the A soil hydrological class, while the highest runoff capability is typical of less permeable soils D.

The actual AMC of the soil subject to a rainfall/runoff event was estimated as a function of the total height of precipitation in the five days before the event in the two different conditions of crop dormancy or the growing season. On this regard, three AMCs are identified:

- AMC_I: dry condition and minimum surface runoff;
- AMC_{II}: average condition and surface runoff;
- AMC_{III}: wet condition and maximum surface runoff.

The SCS guidelines make the CN values available in tables for a soil of given hydrological class and condition, vegetal cover, cultivation practice and average AMC (AMC_{II}). The values of CNs related to AMC_{I} (CN_I) or AMC_{III} (CN_{III}) can be calculated through the following equations:

$$CN_I = \frac{4.2CN_{II}}{10 - 0.058CN_{II}} \quad (5)$$

$$CN_{III} = \frac{23CN_{II}}{10 + 0.13CN_{II}} \quad (6)$$

The parameter AMC takes into account the influence of the soil water content on the hydrological response of the soil to the rainstorm and distinguishes "dry" (AMC_{I}), "average" (AMC_{II}) and "wet" (AMC_{III}) conditions depending on the total rainfall height of the five days before the event.

2.4. Model Implementation

2.4.1. Linear Regression between Rainfall and Runoff

A linear regression model was established between the surface runoff volume (dependent variable) and the rainfall height (independent variable) for each event, as follows:

$$V = aP \quad (7)$$

where:

- V = runoff volume (mm);
- P = total precipitation (mm);
- a = slope (-).

The intercept of this linear equation was forced to zero, in order to avoid runoff without any precipitation.

2.4.2. SCS-CN Model

The SCS-CN model was first applied considering the "default" input parameters, that is, the values of λ and CN derived from the SCS guidelines for woods (control plots) or pasture (burned plots) for the soil hydrologic group A of the experimental soils and AMC "I" for all the modeled events (since no or vey low precipitation was recorded in the antecedent five days). However, the runoff prediction capacity was totally unsatisfactory using default CNs, since very large errors between predictions and observations were achieved. Therefore, the SCS-CN model was adjusted by manual trials tuning both λ and CN parameters until the maximum coefficient of efficiency E (see below) was achieved using optimal λ and CN (Table 3).

Table 3. Optimal values of the Soil Conservation Service-curve number (SCS-CN) model parameters used for runoff predictions in plots subject to prescribed fire and wildfire (Lezuza and Liétor, Castilla La Mancha, Spain).

Input Parameter	Soil Condition				
	Prescribed Fire (Lezuza)		Wildfire (Liétor)		
	Unburned	Burned	Unburned	Burned	Burned and Mulched
Soil hydrologic class			A		
λ			0.0001		
CN	15	16	0.25	3 (27) *	3 (22) *
AMC			I		

Note: * indicates the CN value of the first modeled event.

2.5. Evaluation of Model Prediction Accuracy

The runoff simulations of the linear regression equation and SCS-CN model were analyzed for "goodness-of-fit" with the corresponding observations. More specifically, the observed and simulated runoff volumes were visually compared in scatterplots. Then, the main statistics and the indexes of goodness-of-fit commonly used in literature (e.g., [27,48–50]) were adopted (Table 4): (i) the maximum, minimum, mean and standard deviation of both the observed and simulated values; (ii) the coefficient of determination (r^2); (iii) the coefficient of efficiency of Nash and Sutcliffe [51] (E); (iv) the root mean square error (RMSE) and (v) the coefficient of residual mass (CRM, also known as "percent bias", PBIAS). Table 4 reports the equations and the range of variability of these indexes [52–55]. Generally speaking, these indexes are based on the analysis of the errors between simulations and predictions of the modeled hydrological variables.

Table 4. Indexes and related equations and range of variability to evaluate the runoff prediction capacity of the linear regression and curve number models in forest plots subject to prescribed fire and wildfire (Lezuza and Liétor, Castilla La Mancha, Spain).

Index	Equation	Range of Variability	Acceptance Limit and Notes
Coefficient of determination (r^2)	$r^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\overline{O})(P_i-\overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\overline{P})^2}}\right]^2$	0 to 1	>0.5 [56–58]
Coefficient of efficiency (E, Nash and Sutcliffe [51])	$E = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\overline{O})^2}$	$-\infty$ to 1	"Good" model accuracy if E ≥ 0.75, "satisfactory" if 0.36 ≤ E ≤ 0.75 and "unsatisfactory" if E ≤ 0.36 [55]
Root mean square error (RMSE)	$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{n}}$	0 to ∞	<0.5 of observed standard deviation [59]
Coefficient of residual mass (CRM or PBIAS, Loague and Green [50])	$\mathrm{CRM} = \frac{\sum_{i=1}^{n}O_i-\sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i}$	$-\infty$ to ∞	<0.25 [54] CRM < 0 indicates model underestimation CRM > 0 indicates model overestimation [60]

Notes: n = number of observations; O_i, P_i = observed and predicted values at the time step i; $\overline{O}$ = mean of observed values.

3. Results and Discussion

3.1. Hydrological Characterization

3.1.1. Wildfire-Affected Forest (Liétor)

During the observation period, only nine events (total rainfall of 413 mm) produced surface runoff. For these events, precipitation height and mean intensity were in the range 11.6–93.8 mm and 0.98–28.0 mm/h, respectively. Expectedly, in the burned plots the runoff (on average 0.60 mm with a maximum value of 2.20 mm) was higher compared to the unburned soils (average of 0.03 mm and maximum of 0.08 mm). This may be due to the reduced infiltration and some combination of sealing, soil water repellency, loss of surface cover and decrease in soil aggregate stability, for the loss of organic matter [61].

In the mulched soil the mean and maximum runoff was 0.53 and 1.65 mm, respectively (Figure 2). These volumes were lower compared to the runoff generated in the burned plots. This shows the effectiveness of mulching as post-fire management technique to reduce the runoff generation capacity of the burned soils. These results confirm several other studies about the efficacy of mulch application, in order to control the hydrological response of soil after wildfires (e.g., [8,62–66]).

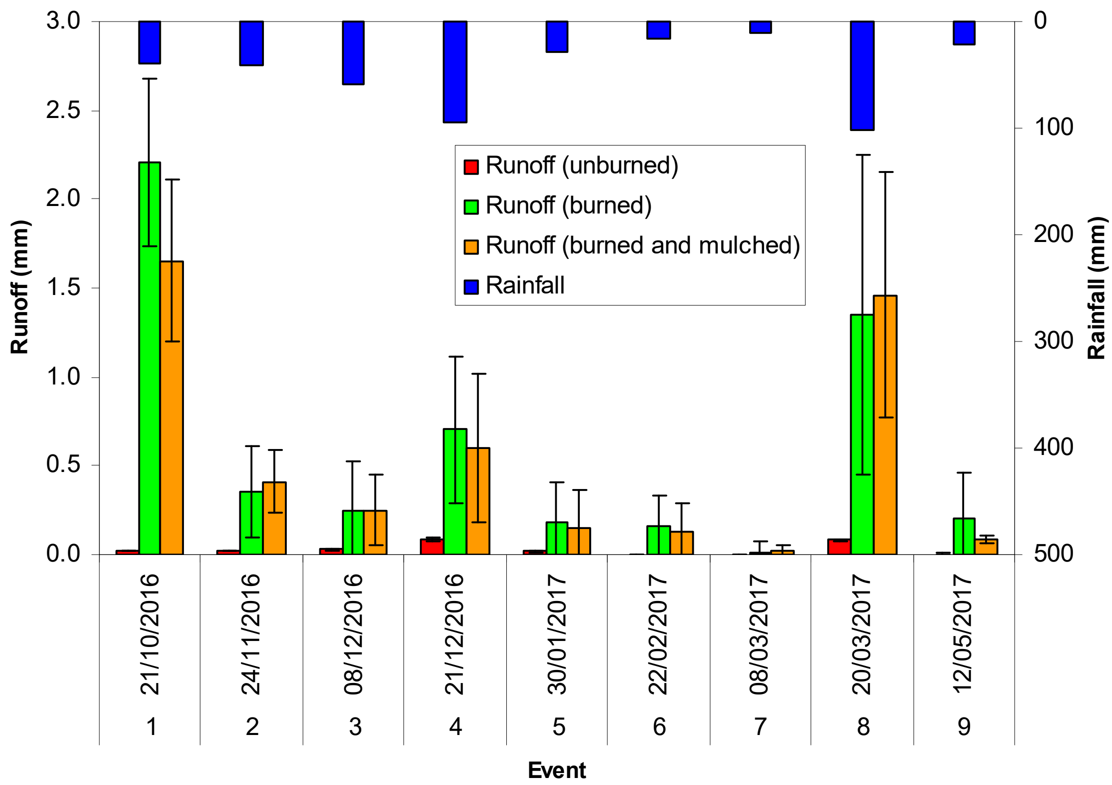


Figure 2. Rainfall and runoff volumes observed in forest plots subject to prescribed fire (Lezuza, Castilla La Mancha, Spain). Vertical bars are the standard deviations.

A sudden increase in the runoff generation capacity was evident in the first event after the fire (21 October 2016), presumably due to the ash release (that sealed the soil) and changes in the physicochemical properties (as the depletion in the organic matter content, which reduces the aggregate stability of the soil) [28,67]. A temporal reduction in runoff generation was found in burned soils (treated or not). This indicates a decrease in the hydrological response over time since the fire, also noticed by several authors in the early storms immediately after wildfire (e.g., [68–70]). The higher runoff is due to both the changes in soil hydrological properties and to the reduction of the vegetal cover after fire. As a matter of fact, the development of a water-repellent layer (also due to the ash released by fire) over the soil surface and the destruction of soil aggregates reduce water infiltration and thus increase runoff [71,72]. Over time, the shrub and herb vegetation quickly recovery, which decreases the runoff generation on the soil left bare by wildfire [73].

3.1.2. Forest Subjected to Prescribed Fire (Lezuza)

Sixteen storms (totaling 368 mm) produced runoff. The mean runoff from these rainfall events was 0.39 mm and the maximum was 0.69 mm. In the burned plots, the mean and maximum runoff volumes recorded were 0.40 and 0.75 mm, respectively (Figure 3). For few events, runoff from burned soils was lower compared to the control plots, while, for the majority of the monitored storms, the soil subjected to prescribed fire produced noticeably more runoff compared to the unburned plots. This waiving soil response to storms confirms the low impacts of low-intensity fires on the hydrological response of soils, already observed by several authors (e.g., [28,74]). This means that the prescribed fire has a limited potential to change the soil properties that drives the hydrological behavior, such as the repellency and infiltrability. However, as observed for the wildfire, attention should be paid to the first rainfall events occurring immediately after fire, when the removal of almost all the vegetal cover (including the litter) may leave the soil bare and thus exposed to rainfall erosivity.

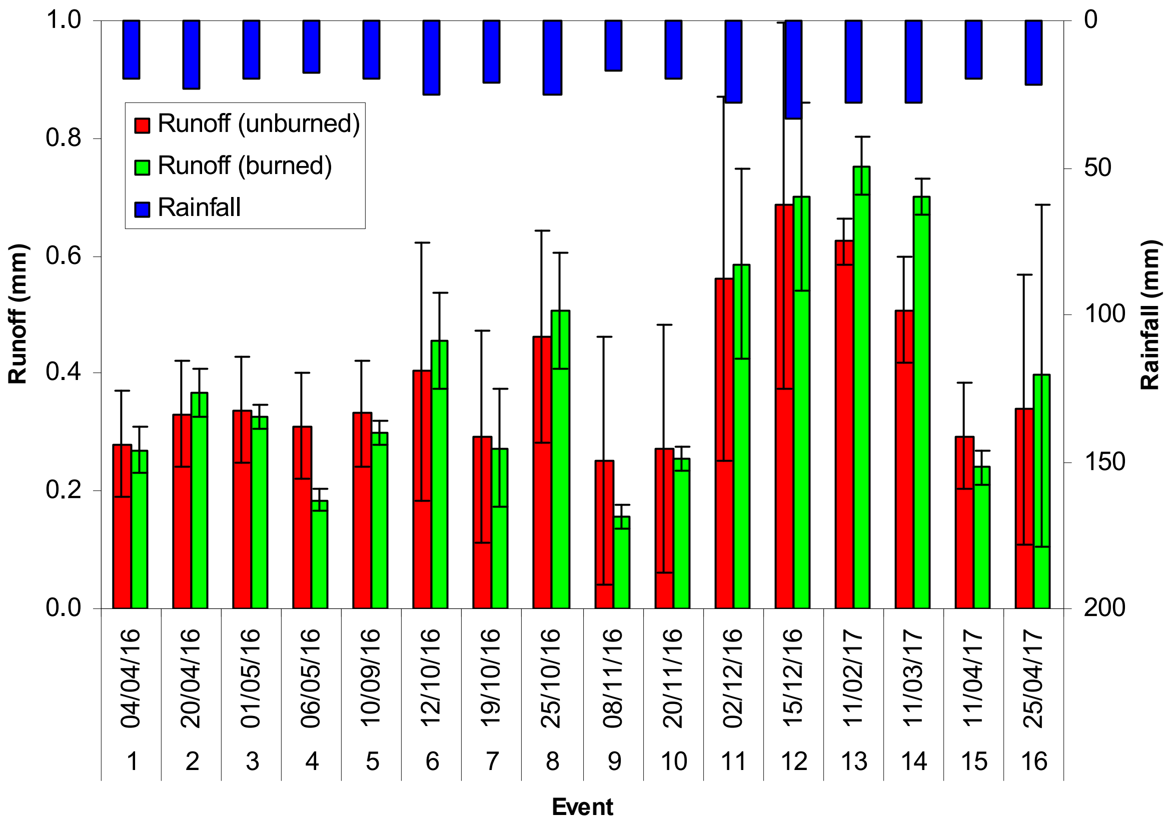


Figure 3. Rainfall and runoff volumes observed in forest plots subject to wildfire (Liétor, Castilla La Mancha, Spain). Vertical bars are the standard deviations.

3.2. Hydrological Modeling

3.2.1. Linear Regression

The simulation of runoff volumes gave satisfactory results for the unburned soil both in Lezuza and Liétor, as shown by the values of E (close or over 0.75) and r^2 (>0.62) indexes and the closeness between predictions and observations (mean error of 10-15%). RMSE values (0.01, Lezuza, and 0.07, Liétor) were under the limit of acceptance of Table 4 (half std. dev.) only for the runoff measured in Lezuza (0.165), but not in Liétor (0.005). In general, the linear models tended to overestimate the runoff volumes in unburned and burned and mulched plots (CRM < 0), while underestimating the runoff in burned plots (CRM > 0; Figure 4). In the latter condition, the maximum runoff values were noticeably underestimated (difference between 25 and 40%; Table 5).

The performance of the linear regression Equation (7) was only acceptable but not satisfactory in burned soils (with or without treatment), because E (between 0.52, soil burned by wildfire, and 0.62, soil burned by wildfire and then mulched) was lower than the suggested limit of Table 4 and the differences between the maximum values of observations and predictions were over 20%; only the mean values were close each others (error <12%; Table 5 and Figure 5a,b); the values of RMSE, which was acceptable in Lezuza (0.12 vs. a limit of 0.15), were 0.62 (burned and untreated plots) and 0.46 (burned and mulched soils) and therefore were over the acceptance limit (Table 4). This limited performance is mainly due to inaccurate prediction of the most intense rainfall–runoff event (21 October 2016), immediately following the fire. Moreover, for the burned soils, the RMSE values were higher than 50% of the standard deviation of observed runoff and thus not satisfactory; for soils burned by wildfire, also the coefficient of determination was poor ($r^2 < 0.39$). This unsatisfactory model performance is also visually shown by the large scattering of the simulations around the regression line (Figure 5a,b), which highlights a particular prediction inaccuracy for the first rainfall event (21 October 2016 recorded in Liétor). This inaccuracy is due to the soil changes induced by the wild fire (e.g., water repellency, decreases in infiltration and interception), which alters its hydrological response to rainstorms, but disappear some weeks or a few months after the fire [7–9,26]. Moreover, the linear equation was not able to simulate the variability of the hydrological processes with the precipitation, since the same runoff was observed for the same precipitation. This means that linear regressions are not able to simulate with reliability the surface runoff produced in burned plots, although these models may give an indication at least of the magnitude of the hydrological response of soils under different precipitation input and conditions.

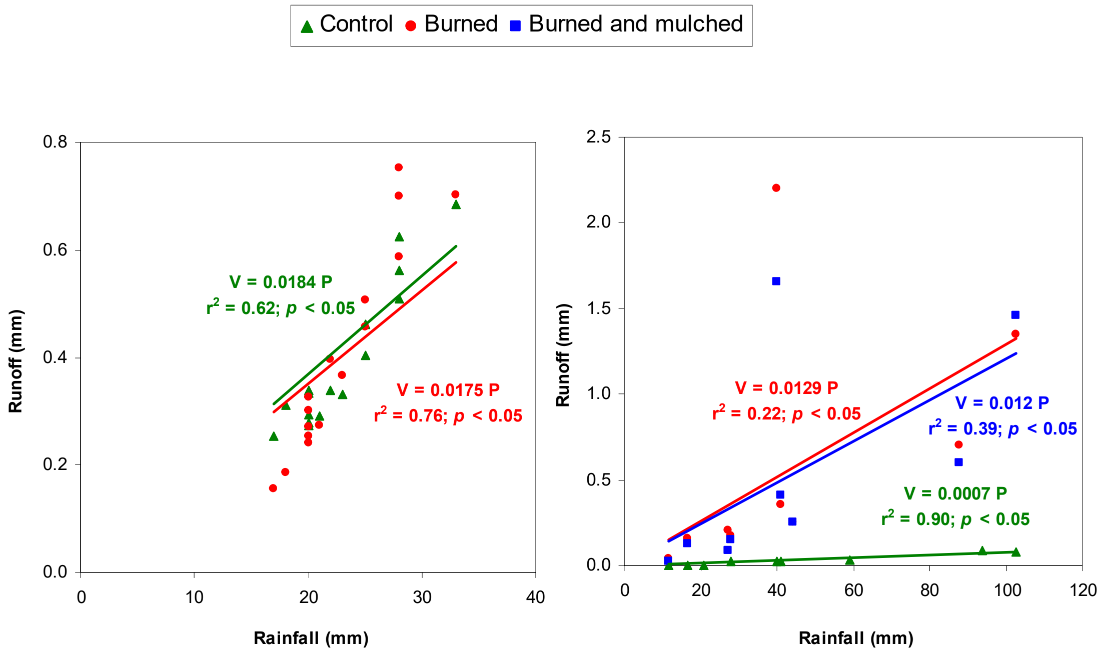
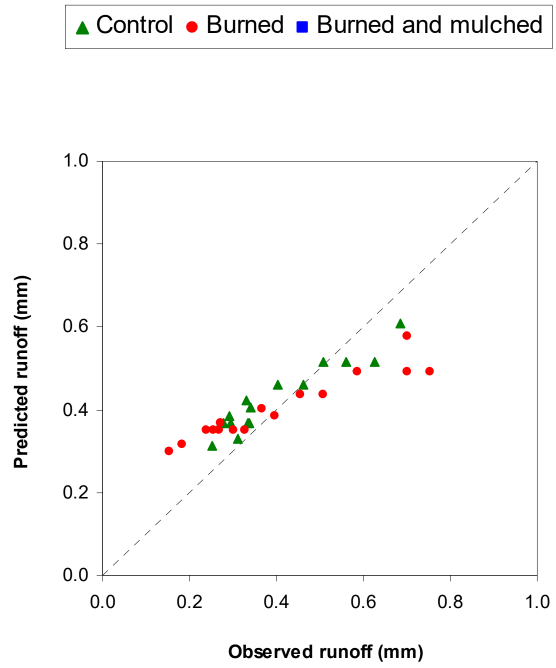


Figure 4. Linear regressions between observed rainfall and runoff in plots subject to prescribed fire and wildfire (Lezuza, **Left**, and Liétor, **Right**; Castilla La Mancha, Spain). V is the runoff volume and P is the rainfall height, while r2 and p are the coefficient of determination and the significance level, respectively.

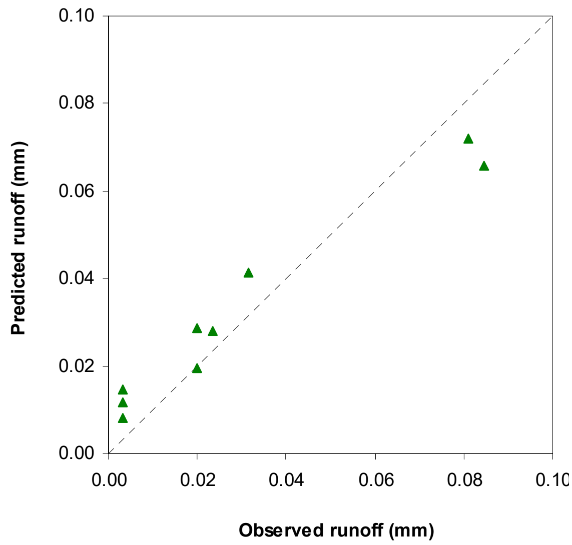
Table 5. Statistics and indexes to evaluate the runoff prediction capacity of linear regression models in forest plots subject to prescribed fire and wildfire (Lezuza and Liétor, Castilla La Mancha, Spain).

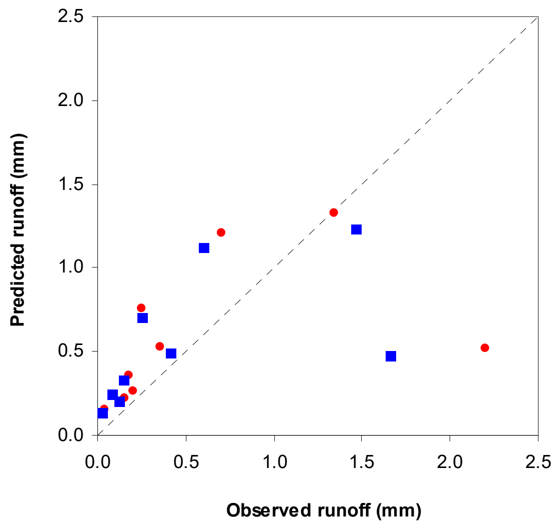
Runoff Volume	Mean	Standard	Minimum	Maximum	r^2	E	CRM	RMSE
			Prescribed fire (Lezuza)					
			Control					
Observed	0.39	0.25	0.14	0.69	-	-	-	-
Simulated	0.42	0.31	0.08	0.61	0.62	0.73	−0.08	0.07
			Burned					
Observed	0.40	0.16	0.19	0.75	-	-	-	-
Simulated	0.40	0.30	0.08	0.58	0.75	0.60	0.01	0.12
			Wildfire (Liétor)					
			Control					
Observed	0.03	0.00	0.03	0.08	-	-	-	-
Simulated	0.03	0.01	0.02	0.07	0.90	0.89	−0.07	0.01
			Burned					
Observed	0.60	0.04	0.72	2.20	-	-	-	-
Simulated	0.59	0.15	0.43	1.32	0.22	0.52	0.02	0.62
			Burned and mulched					
Observed	0.49	0.01	0.62	1.66	-	-	-	-
Simulated	0.55	0.14	0.40	1.23	0.39	0.62	−0.11	0.46

Notes: r^2 = coefficient of determination; E = coefficient of efficiency; CRM = coefficient of residual mass; RMSE = root mean square error.



(a)





(b) (c)

Figure 5. Scatterplots of runoff observations vs. predictions using linear regressions in plots subject to prescribed fire (Lezuza, **a**) and wildfire (Liétor, control soils, **b**, and burned soils **c**) (Castilla La Mancha, Spain).

3.2.2. SCS-CN Model

The predictions of runoff volume became more accurate for the majority of fire (in terms of severity) and soil conditions (Figure 6a,b). Compared to the linear regressions, the runoff predictions improved in the unburned plots of Lezuza (E = 0.87 and r^2 = 0.92), but slightly worsened in all the plots of Liétor (E = 0.88 and r^2 = 0.95; Table 6).

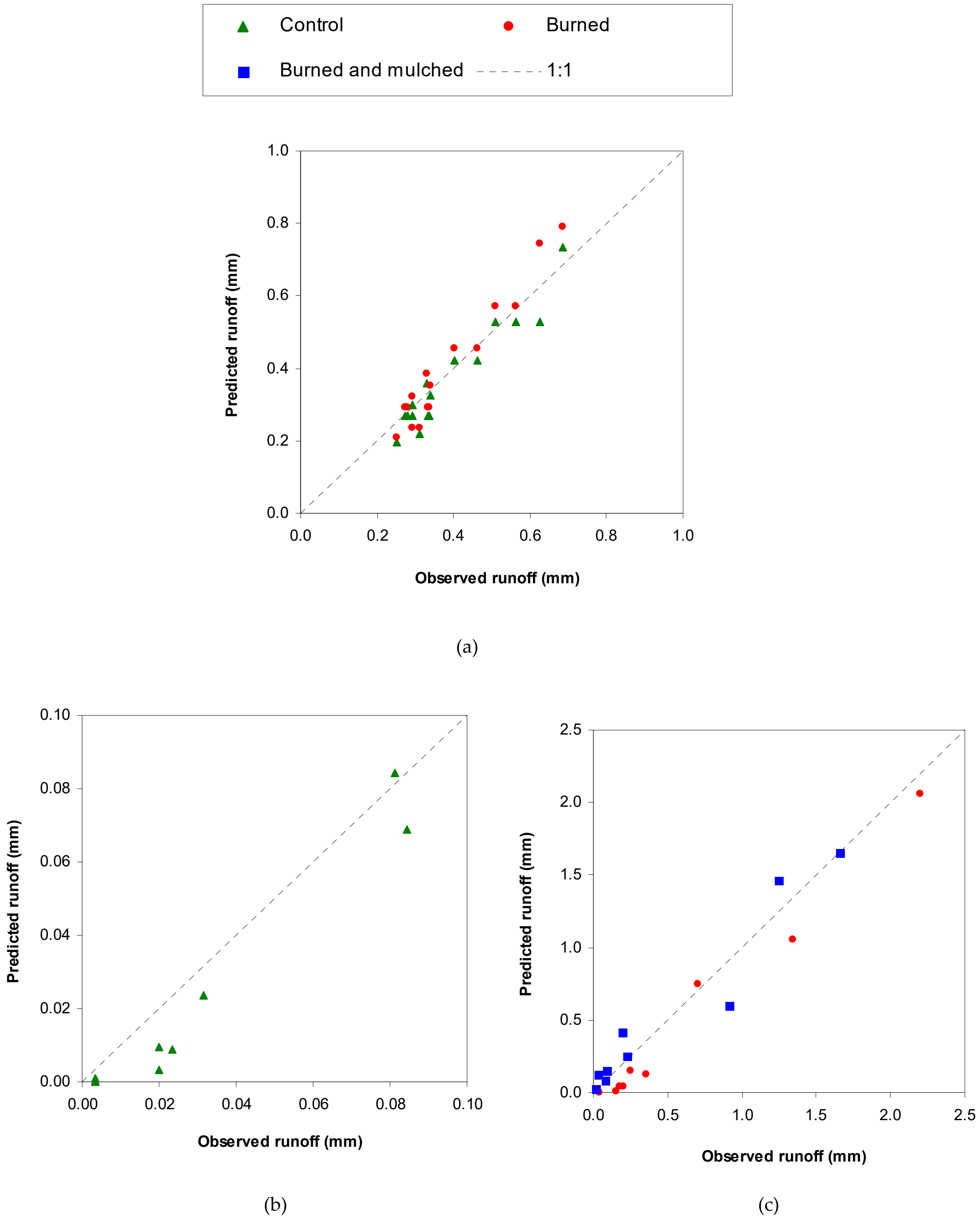


Figure 6. Scatterplots of runoff observations vs. predictions using the curve number model in plots subject to prescribed fire (Lezuza, **a**), and wildfire (Liétor, control soils, **b**, and burned soils, **c**) (Castilla La Mancha, Spain).

Conversely, the runoff was predicted with greater accuracy in burned soils (with or without treatment), as shown by E > 0.80—with peaks of 0.96-0.97 after wildfire—and $r^2 > 0.94$, these indicators being noticeably over the acceptance limit (Table 4). The RMSE values were always lower than 50% of the observed standard deviation (Table 6). In general, the SCS-CN model always showed a runoff overestimation (see CRM < 0). It should be noticed that the mean runoff values were predicted with less accuracy compared to the linear regression equations (differences between predictions and observations over 20% in some cases), but the SCS-CN model was much more reliable in predicting the maximum runoff volumes (differences lower than 7% for soils burned by wildfire and 15% for plots subjected to prescribed fire; Table 6). This indicates that, when accurate predictions of runoff are required to control the flooding risk (linked to the highest runoff volumes), the SCS-CN should be preferred to the simpler linear regressions.

Table 6. Statistics and indexes to evaluate the runoff prediction capacity of the curve number model in forest plots subject to prescribed fire and wildfire (Lezuza and Liétor, Castilla La Mancha, Spain).

Runoff Volume	Mean	Standard	Minimum	Maximum	r^2	E	CRM	RMSE
Prescribed fire (Lezuza)								
Control								
Observed	0.39	0.14	0.25	0.69	-	-	-	-
Simulated	0.37	0.15	0.20	0.73	0.92	0.87	0.06	0.05
Burned								
Observed	0.39	0.14	0.25	0.69	-	-	-	-
Simulated	0.41	0.18	0.21	0.79	0.95	0.81	-0.03	0.06
Wildfire (Liétor)								
Control								
Observed	0.03	0.03	0.003	0.08	-	-	-	-
Simulated	0.02	0.03	0.000	0.08	0.95	0.88	0.26	0.01
Burned								
Observed	0.60	0.72	0.04	2.20	-	-	-	-
Simulated	0.47	0.70	0.00	2.06	0.98	0.97	0.22	0.16
Burned and mulched								
Observed	0.49	0.62	0.01	1.66	-	-	-	-
Simulated	0.53	0.61	0.02	1.65	0.94	0.96	-0.07	0.15

Notes: r^2 = coefficient of determination; E = coefficient of efficiency; CRM = coefficient of residual mass; RMSE = root mean square error.

Some additional considerations about SCS-CN model application in the experimental conditions should be made.

First, very low values of CN and λ were provided in this study as input to the model, in order to predict with accuracy runoff after the two fire-severity conditions. This means that the water losses during and immediately after the rainfall (reflected by I_a and S, such as water storage in the soil dips, interception, infiltration and evapotranspiration) are very high and the storms produce very small runoff volumes. In more detail, the small CN simulates a large water storage capacity (S) of soil through the infiltration process and λ must be decreased even by three orders of magnitude to simulate the very low initial water losses, due to interception and evapo-transpiration.

Second, both for wildfire and prescribed fire, unrealistic input parameters are required to simulate such a minimal runoff generation capacity of these soils. As a matter of fact, values of 15–16 (after wildfire) or even 0.25–3 (after prescribed fire) for CN and 0.0001 for λ against common values over 30 for CN and 0.2 for λ are needed to fit the runoff predictions to the corresponding observations. This should be taken into account when the SCS-CN model must be implemented in soils having a small hydrological response.

Third, a unique CN value as input for the SCS-CN model is not able to reproduce the increase in runoff immediately after wildfire. The worsening of the hydrological response of the burned soil both after wildfire and prescribed fire has been shown by a number of studies (e.g., [9]) and particularly in Mediterranean forests (e.g., Keizer et al. [8], in a Portuguese eucalypt forest; Lucas-Borja et al. [7,62], in pine forests of Central Spain). This increase is mainly due to soil water repellency and vegetation cover removal due to fires, but these effects disappear some months after fire. In order to simulate the hydrological effects of a repellent and almost bare soil, it is necessary to increase the CNs in this so-called "window-of-disturbance" [15,75] up to values that may be noticeably high. Soil mulching "smoothes" the increase in the soil hydrological response and this requires a lower increase in CN values.

4. Conclusions

This study evaluated the runoff prediction capacity of the SCS-CN model in comparison with linear regression equations after storms in two pine forests of Central-Eastern Spain affected by wildfire (with or without a rehabilitation treatment using straw mulching) or prescribed fire.

The simulation of runoff volumes by the linear regression gave satisfactory results only for the unburned soils. Conversely, for the burned plots, the linear regressions failed in simulating the runoff with reliability. The SCS-CN model was instead accurate to predict the runoff volume particularly in burned soils, also when mulching was applied. Although the mean runoff was predicted with less accuracy compared to the linear equations, the model performance was very satisfactory in predicting the maximum volumes. Moreover, all the soil conditions (unburned, burned and burned and mulched) were simulated with reliability. To reproduce the peculiar hydrology of the experimental areas, very low values of CNs and initial abstraction were required, which may appear unrealistic; moreover, the post-fire hydrological window-of-disturbance could be reproduced only by increasing the CN for the storms occurring few months after wildfire.

The performances of the two tested models indicate that, in Mediterranean forests subject to the fire risk, the use of simple linear equations is suggested for predicting runoff generated by relatively low storms, while the SCS-CN model is more reliable and therefore advisable when runoff predictions are needed to control the flooding risk.

Overall, the study has confirmed the viability of the SCS-CN method to reproduce the complex hydrological response of unburned and burned (and treated or not) soils of Mediterranean forests. Although this assumption is limited to the experimental conditions, the results are encouraging towards larger applications of this method in other climatic and geomorphologic conditions. However, further modeling studies are needed, in order to explore the runoff prediction capacity of the model in fire-affected forests with different ecological and soil characteristics. These studies should also be enlarged from the plot to the watershed scale, using more complex hydrological models based on the SCS-CN method. Once validated in a wide range of environmental contexts, the use of these models may support the land managers to control runoff and erosion in mountain forests that are prone to both the wildfire and hydrogeological risks.

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