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Comparing the Hydrological Response of Forested Headwaters (Unregulated and Regulated with Check Dams) under Mediterranean Semi-Arid Conditions

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Abstract: This study has evaluated the runoff and erosion rates in torrents of Southern Italy, two forested headwaters with very similar climatic, hydrological and geomorphological characteristics; in one headwater, 15 check dams were installed in the mid-1950s, while the other is not regulated with engineering works. To this aim, the hydrological variables have been modeled over 15 years after check dam installation using the HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System) model coupled to the MUSLE (Modified Universal Soil Loss Equation) equation. The model simulations have shown that check dams have not played a significant role in reducing the surface runoff compared to the unregulated torrent; in both catchments, the well-developed forest cover determined very low runoff coefficients (lower than 0.3%) with a scarce runoff generation capacity. Additionally, the reduction in peak flow due to the check dams was not significant, on average −7.4% compared to the unregulated headwater. Check dams have retained sediments for about 8–10 years after their installation, reducing erosion by about 35%, although soil loss was much lower than the tolerance limit in both catchments. After the sediment retention capacity of the dam sediment wedge was depleted, the sediment yield in the regulated torrent was even higher (by about 20%) compared to the unregulated catchment. Overall, the study has shown that the use of check dams as a catchment management strategy of forested headwaters under semi-arid Mediterranean conditions should be considered with caution, since the structures could be ineffective to reduce water and sediment flows during floods or, in some cases, check dams may increase erosion rates.

Keywords: check-dams; Mediterranean torrent; HEC-HMS; MUSLE; runoff; erosion; peak flow

1. Introduction

Control of the hydrological response in ephemeral torrents of the Mediterranean Basin is an essential task of land managers and authorities for catchment protection [1,2]. In these environmental contexts, the interaction of frequent and intense rainfall events and steep slopes are the main reasons of noticeable losses and quality degradation of soils [3,4], making erosion a global environmental hazard [5]. Soil erosion in catchments is driven by climate, topography, soil characteristics, and vegetation factors, which can be assessed using different methods (such as the hydrological modeling). Moreover, the natural dynamic and magnitude of erosion process can be heavily modified by human activities (such as deforestation, intensive agriculture, and overgrazing) [6]. Additionally, the forecasted climate changes, which have documented clear increases in rainfall erosivity [7], may be a triggering reason of heavier flood and hydrogeological risks at the catchment scale. Several actions can be adopted to control water and sediment flows in catchments, from soil conservation techniques on hillslopes to control works, such as check dams, in channels [8,9]. Check dams consist of transverse structures that are built in channels to reduce bed erosion [10], whose actions produce hydrological, morphological and ecological effects [11,12]. Check dams stabilize the channel bed and protect banks, reduce its longitudinal gradient, and modulate stream flows [13–15]. In headwaters, where water and sediment flows can be activated, the direct effects of check dams can be better identified among the factors influencing the catchment evolution (e.g., agriculture activities, urbanization, mining), since these environments are little affected by anthropogenic activities [16]. Moreover, the influence of check dams goes beyond the local scale of the headwaters, allowing mitigation of the hydrological effects in valley areas, resulting in floods and debris flows [17–19]. These beneficial actions have made check dams one of the most common strategy to protect catchments in semi-arid environments in combination with reforestation works [12,20–22]. For instance, construction of several check dams in the middle of the last century has avoided disrupting floods with heavy damage to infrastructures and loss of human lives in torrents of Southern Italy [23,24]. In this environment, the peculiar morphological characteristics of catchments (small drainage areas with short length and steep profile of channels), coupled with intrinsic climatic forcing (frequent and intense rainstorms), usually produce heavy flash floods with high erosive power, often causing hydro-geological instability and disruption [25–27].

Abundant scientific and technical literature exists about the design criteria of check dams, and their hydrological, morphological, and ecological effects on channels and catchments have been largely studied also in the Mediterranean torrents [1,21,22,28–33]. However, more research is needed to evaluate the ex post effectiveness of the existing check dams in controlling the catchment's hydrological response [34]. The geomorphological and hydrological effects of these structures are not completely clear, and undesired and secondary effects on channel morphology are possible [1,30]. The short-term effects of check dams (that is, a few years or one to two decade(s)) immediately after construction, when the hydrographic network of regulated catchments is still unstable, have been less explored compared to the long-term, when steady conditions of water and sediment flows have been established. This lower amount of information and even lack of data requires more studies evaluating how and to what extent the check dams are able to exert the desired functions in the hydrographic network.

Moreover, the majority of the available studies has evaluated the hydrological and morphological effects of check dams by comparing the hydrological functioning of the catchment system before and after check dam installation [21,24,35]. The catchment conditions are dynamically variable, and therefore, such a comparison can be not representative of torrent hydrology and morphology at a given time [36]. An approach based on comparisons of catchments with or without check dams under the same hydrological input and environmental conditions could be more suitable to provide useful indications on the effects of torrent control works and to inform attempts of catchment managers to optimize their design and functioning [37,38]. However, this approach has been rarely adopted, also because of the difficulty to collect historical observations of peak flows and erosion in unregulated and regulated catchments with the same climatic and geomorphological characteristics in the semi-arid environment.

To fill this gap, this study compares the short-term hydrological response of two neighboring forested headwaters (one regulated using check dams, and the other without control works) of Calabria (Southern Italy), having the same climatic, land use and soil characteristics. Hydrological models, which are successfully used since some decades for water resource management at the catchment scale, are effective tools for this analysis and give indications about the effectiveness of actions for catchment restoration [39,40]. The well-known HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System [41]) model, calibrated in a third and very similar catchment, was used to simulated surface runoff and peak flow, while sediment yield was simulated using the MUSLE (Modified

Universal Soil Loss Equation [42]) equation. These hydrological variables were compared between the two sub-catchments over 15 years after check dam installation. This modeling approach aims at evaluating whether the check dams have been effective in this observation period and the catchment protection strategy adopted has been suitable for torrents in Southern Italy.

2. Materials and Methods

2.1. Study Area

The torrents of Calabria (Southern Italy, Figure 1)—locally known as *fiumara(s)*—are water courses with small drainage areas, steep profile, and short lengths. Their hydrological regime is characterized by seasonal flowing (dry channels in summer and flash floods and highly erosive events in the wet seasons after heavy and low-frequent rainstorms).

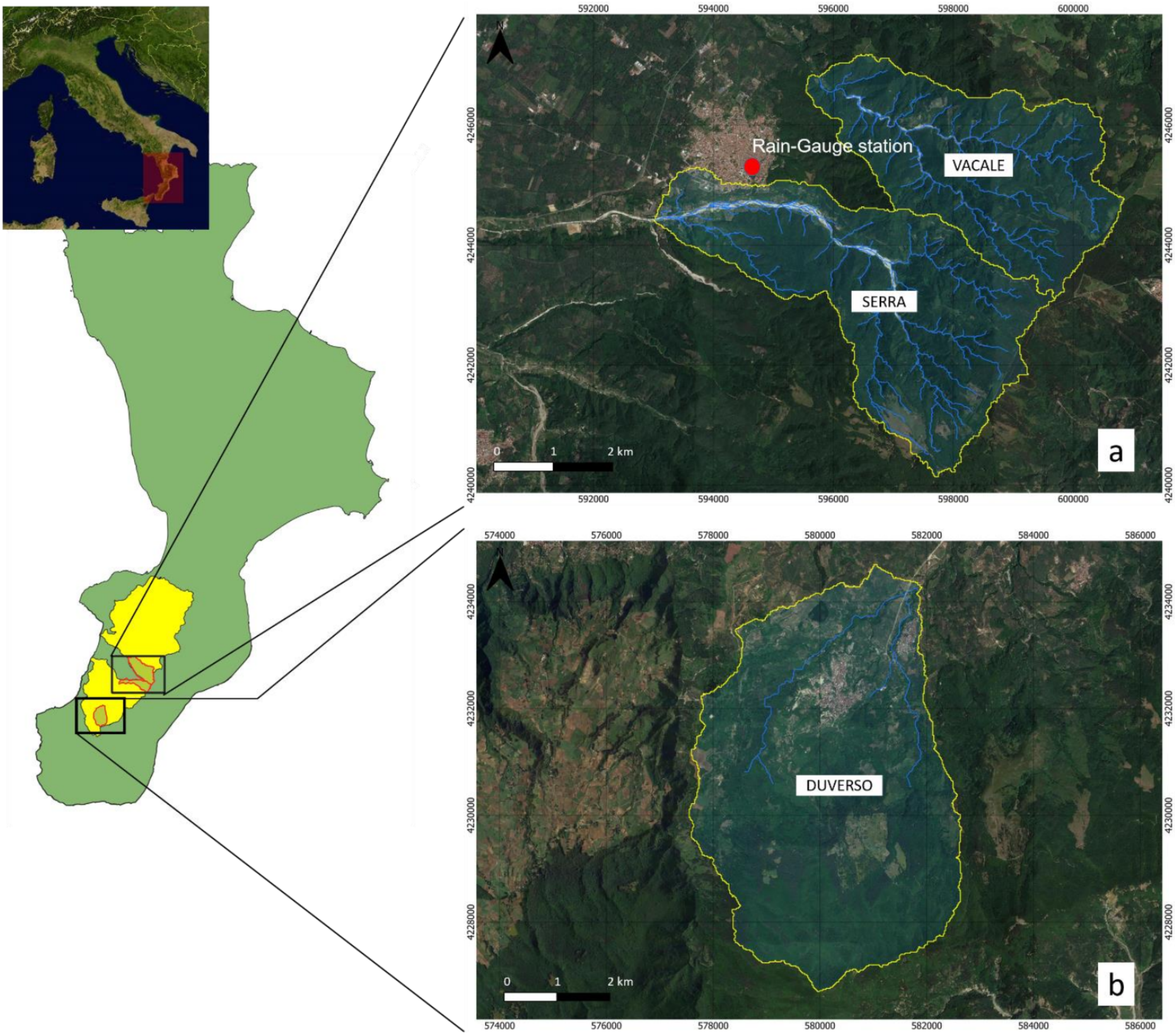


Figure 1. Location of the study area with Vacale and Serra (**a**) as well as Duverso (**b**) torrents (Calabria, Southern Italy).

The climate of the study area (southern part of the Italian Apennine) is typically Mediterranean, Csb (mild temperate, dry and warm summer, in internal areas), according to Köppen–Geiger classification [43]. The Walter and Lieth diagram (Figure 2), built using meteorological records at the Cittanova station (geographical coordinates: 38°21′14.3″ N; 16°04′48.9″ E, reference period 1924–2018), shows mean temperatures between 24.2 (August) and 8.3 °C (January) and monthly precipitation between 34.1 (July) and 154.5 mm (December) with an annual mean of 1484 mm.

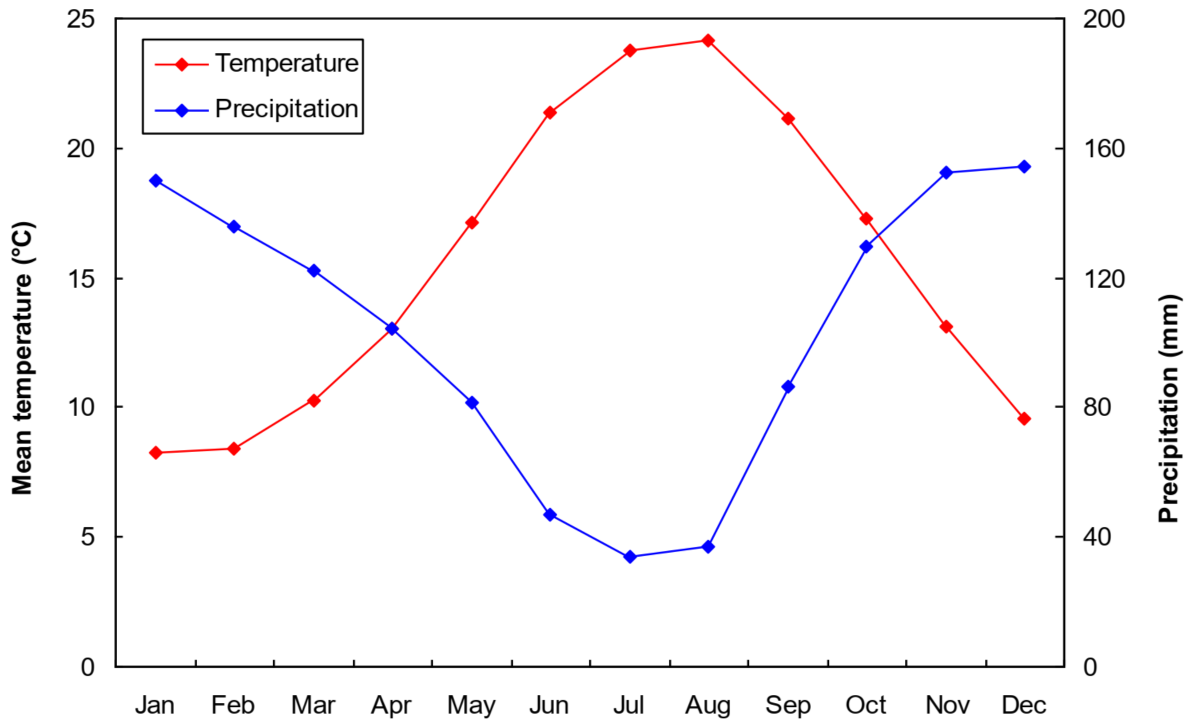


Figure 2. Walter and Lieth diagram for the meteorological station of Cittanova (Southern Italy, data of the period 1924–2018).

2.2. Main Characteristics of the Studied Sub-Catchments

Three sub-catchments (Duverso, Vacale and Serra) were selected in the studied area:

- Duverso (outlet coordinates 38°15′08.1″ N; 15°56′09.5″ E), contributor to the Petrace catchment;
- Serra (38°20′35.2″ N; 16°03′47.3″ E), contributor to the Petrace catchment;
- Vacale (38°28′23.1″ N; 16°01′51.5″ E), contributor to the Mesima catchment.

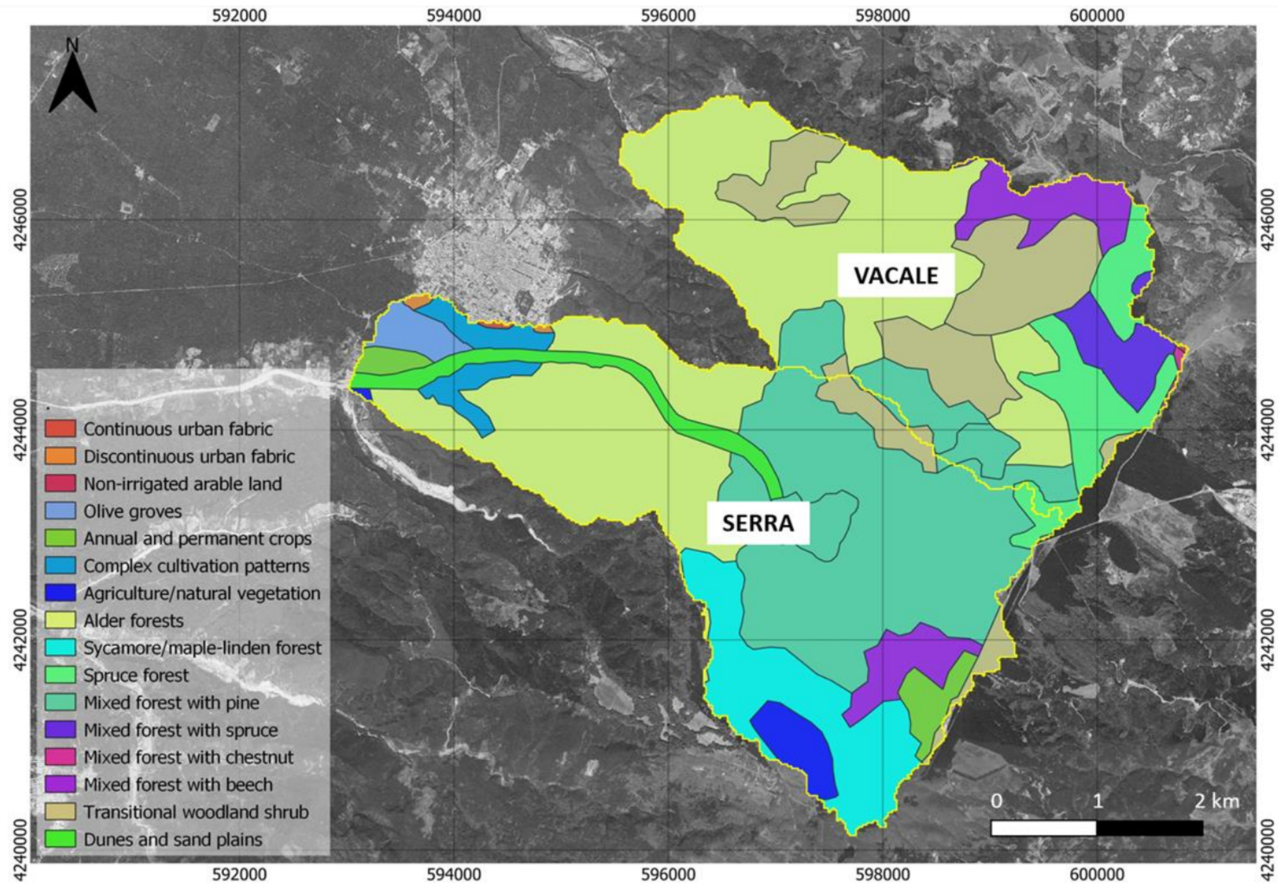
All reaches in the selected sub-catchments source from the Aspromonte mountain chain, which belongs to the Italian Apennine. The receiving torrents (Petrace and Mesima) flow to the Tyrrhenian coast of Calabria.

In more detail, the Duverso sub-catchment, chosen only for HEC-HMS model calibration, is about 18 km from the Vacale and Serra sub-catchments. This sub-catchment covers an area of 12.5 km^2 and the main channel is 5.2 km long with a mean profile slope of about 7%. Its minimum and maximum elevations are 450 and 630 m, respectively, above sea level (Table 1). Regarding land use, forests, which cover 77% of the sub-catchment area, are dominated by beech (*Fagus sylvatica L.*), elm (*Quercus ilex L.*), and artificial woods of pine (*Pinus nigra* ssp. *laricio* Poir.). Natural grasslands mixed with shrubland of brooms (8%) are located in south-faced hillslopes of the middle and lower part of the sub-catchment and in those parts of the main channel that have not flooded for many years. Agricultural areas (the residual 15%) are mainly olive groves and arable cropland for vegetable production (EEA ETC/TE 2002). Soils are Humic Dystrudept [44] with a loamy sandy texture for more than 90% of the area (Table 1 and Figure 3).

Table 1. Main characteristics of the selected sub-catchments (Calabria, Southern Italy).

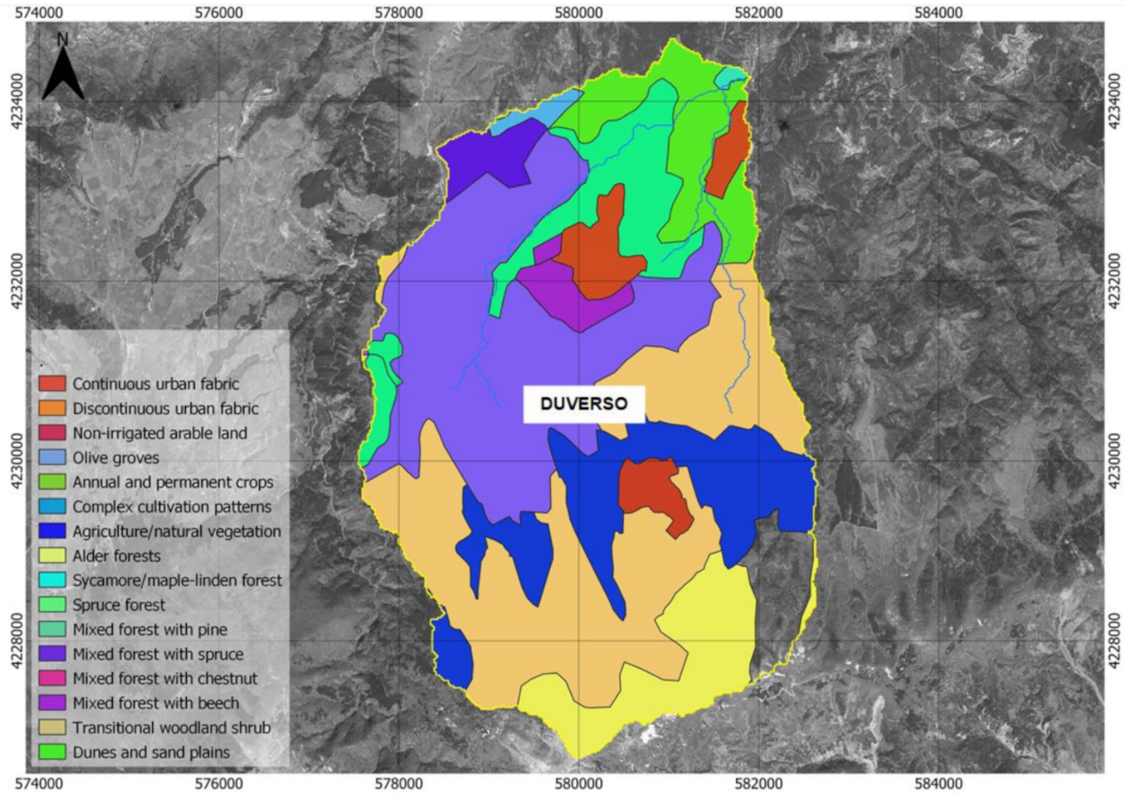
Characteristics	Sub-Catchments		
	Duverso	Serra (Unregulated)	Vacale (Regulated)
Average annual air temperature (°C)	16.7	16.3	16.3
Average annual rainfall depth (mm)	1503	1467	1467
Area (km^2)	12.5	14.6	11.3
Maximum altitude (m·a.s.l.)	630	650	600
Minimum altitude (m·a.s.l.)	450	400	400
Length of main stream (km)	5.2	6.6	4.7
Longitudinal slope (%)	7	6	7
Main aspect of vegetation		Broad lived forest	
Main land use		Woodland	
Main texture		Sandy loam	
Main type		Humic Dystrudept	
Main lithology		Granites and granodiorites	
Number of check dams	0	0	15
Average annual discharge (m^3 s^{-1})		0.80	

Note: data of the period 1924–2018.



(a)

Figure 3. *Cont.*



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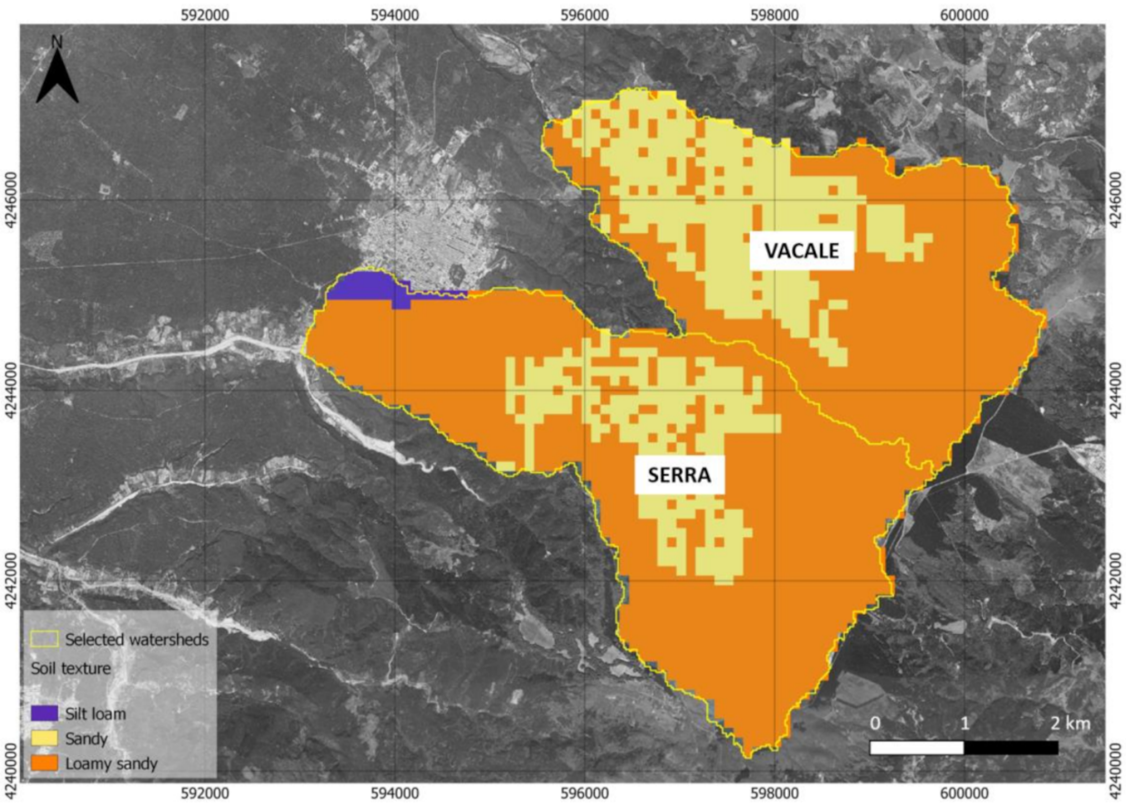

(c)

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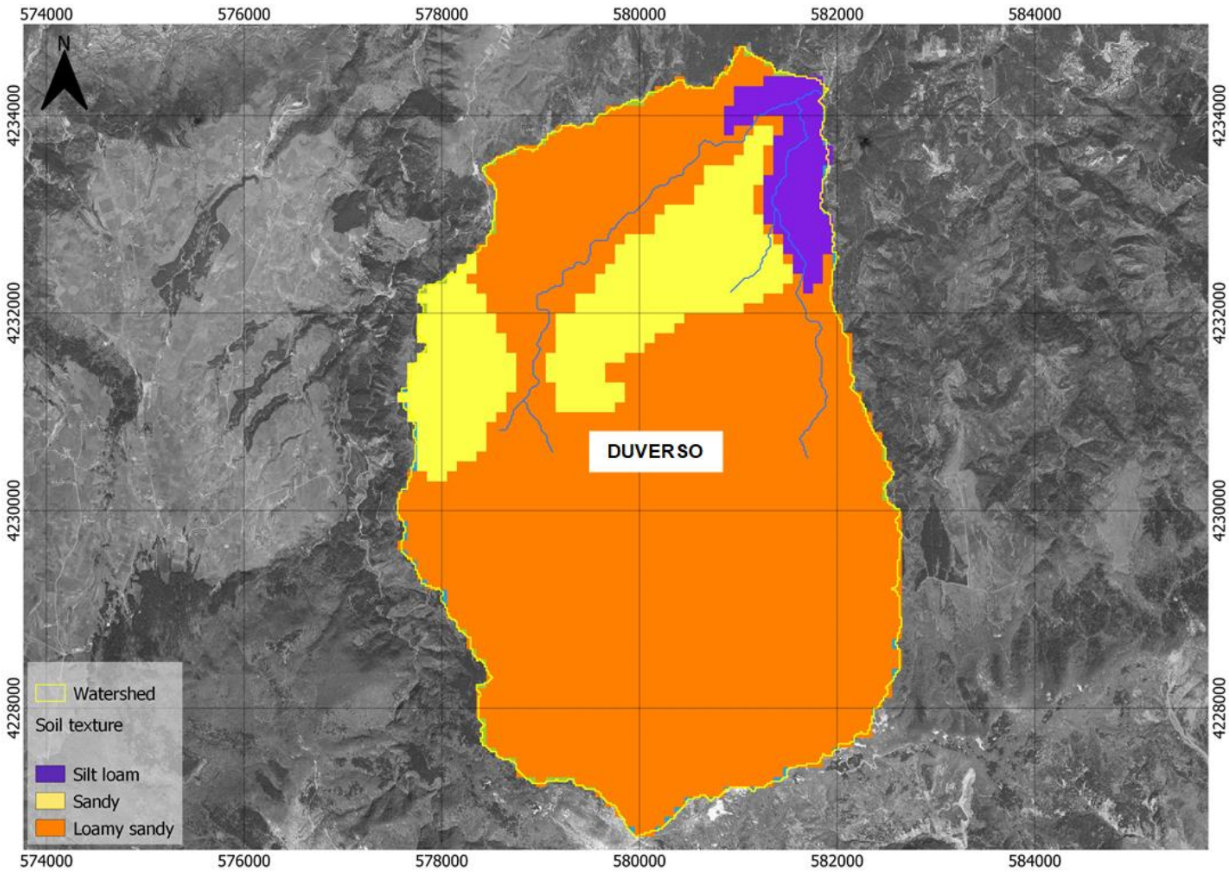

(d)

Figure 3. Land use (**a**) Serra and Vacale, (**b**) Duverso torrents, by photo-interpretation) and soil texture distribution, (**c**) Serra and Vacale, (**d**) Duverso torrents, from the map by ARSSA, 2003) of the investigated sub-catchments (Calabria, Southern Italy).

The Serra and Vacale sub-catchments are the forested headwaters (one with check dams, the other without engineering works) that were selected for the aim of this study. The sub-catchments are neighboring, with the main streams flowing very close to each other. The Vacale sub-catchment covers an area of 11.3 km^2 and the main channel is 4.7 km long. The maximum and minimum elevations are 960 and 400 m above sea level. Serra sub-catchment covers an area of 14.6 km^2 and its main channel is 6.6 km long. The maximum and minimum elevations are 620 and 360 m above sea level. The mean profile slope is 6% (Serra) and 7% (Vacale) (Table 1 and Figure 3). The main land use of both sub-catchments is woodland (78%, Serra, and 84.5%, Vacale, of the total area), located in the upper areas. Natural forests over 1000 m are dominated by beech (*Fagus sylvatica L.*) and elm (*Quercus ilex L.*). Artificial woods (about 30% of the total forested area), dominated by pine (*Pinus nigra* ssp. *laricio* Poir.), have been planted in 1960s on degraded or previously deforested lands. Shrubland covers 22% of the Vacale and 3.5% of the Serra sub-catchment, while only Serra shows agricultural areas (12%, mainly citrus and olive groves as well as arable cropland for vegetable production) [45]. Shrub formations of brooms (*Cytisus scoparius L.* and *Cytisus villosus Pourret*) and weaver's broom (*Spartium junceum L.*) are located in the middle and lower part of the studied sub-catchments. Natural grasslands (various herbaceous species of the genus *Festuca*, *Lolium*, *Hypochaeris*, *Trifolium*, and *Vicia*) break the forests at the highest altitudes and are located in the abandoned areas. Some species, mainly *Poaceae*, have covered portions of the channel bed (also in this case not flooded for many years) and, in some reaches, the entire channel. Soil texture and type are the same as the Duverso sub-catchment (Table 1 and Figure 3).

The three sub-catchments were evidently characterized by the same geomorphological and ecological characteristics in the analyzed period. This large similarity allows disentangling the hydrological response to the same precipitation between the unregulated (Serra) and regulated (Vacale) sub-catchments.

In the main channel of the Vacale sub-catchment, 15 check dams (11 to 55 m wide and 0.5 to 3 m high) were built in the mid-1950s, in order to protect soil in the headwater and avoid disruptive floods in valley areas. After construction, the channel profile behind the structure has continued to evolve for several years, resulting from cycles of aggradation during normal runoff events and erosion during extreme floods in the sediment wedge. Several check dams were destroyed by the large floods of 1971, 1996, or 2003 [46]. In both sub-catchments, the land use underwent very slight changes, such as some wildfires in small areas (soon reforested), and abandonment of previously cultivated areas that have been converted to pastures; moreover, in the Vacale torrent, no new check dams have been built since 1970. This land use stability allows considering the torrent conditions in the period 1956–1971 still valid at present.

Hereinafter, Serra and Vacale will be indicated as UNREG ("unregulated") and REG ("regulated"), respectively.

2.3. Reach Selection

In the Vacale and Serra torrents, three reaches were selected for each sub-catchment, each one about 1.5 km long. Hereinafter, the reaches will be indicated as "R1," "R2," and "R3" for the Vacale sub-catchment and "U1," "U2," and "U3" for the Serra sub-catchment, with numbering upstream to downstream. The studied reaches are located in the main channel of the Serra sub-catchment, while, in Vacale, "U1" is located in the main channel, while the second and third reaches ("U2" and "U3") have been selected in two tributary reaches immediately upstream of "U1," Figure 4). Each reach shows a single thalweg, except in areas located immediately upstream of check dams, where the stream is branched.

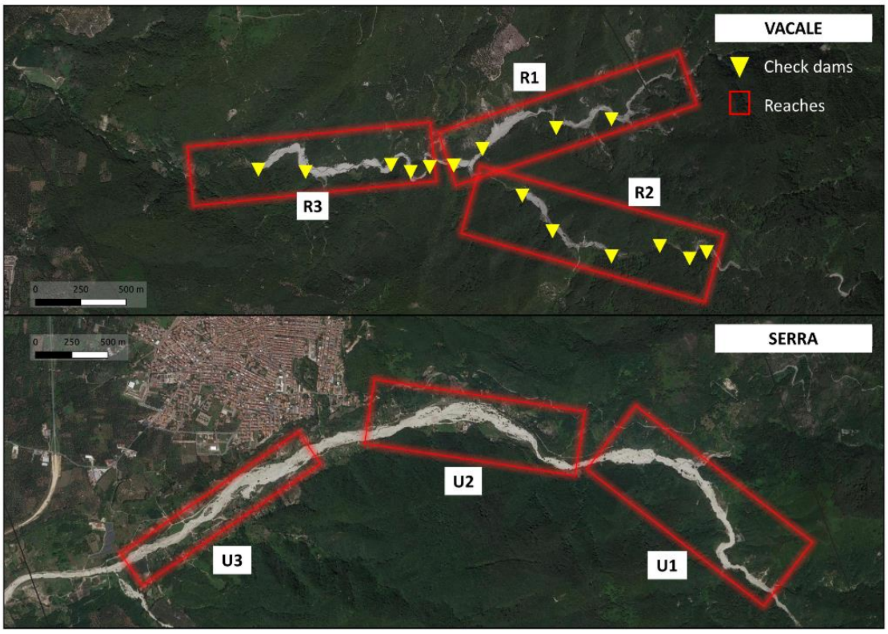

Figure 4. Location of the studied reaches ("RX" and "UX," red boxes) selected in the Vacale and Serra sub-catchments (Calabria, Southern Italy).

The hydrological response of the regulated vs. unregulated sub-catchments was modeled using the HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System [41]) and MUSLE (Modified Universal Soil Loss Equation [42]) models. Among models of different nature (e.g., empirical, physically based, conceptual) and complexity, HEC-HMS was adopted for two reasons. First, this model allows the simulation of the whole hydrograph under a given hyetograph (required due to the need to simulate not only surface runoff, but also peak flow after rainstorms with highly variable intensity). Second, HEC-HMS has been successfully used in similar climatic and geomorphological conditions as those of the experimental environment (e.g., applications in Spain, [47]; California, [48]; Iran, [49]; and Pakistan, [50,51]). Moreover, in a previous study, Zema et al. [52] used HEC-HMS to evaluate surface runoff and peak flow in the catchment of the Mesima torrent, demonstrating its good prediction capacity in the same environmental conditions.

Although HEC-HMS also predicts erosion at the catchment scale, we were forced to use the MUSLE equation, since HEC-HMS did not simulate sediment yield at a water flow under 1 m^3 s^{-1} (as in our case), due to the small sub-catchment size. However, the runoff and peak flow simulated by HEC-HMS were given to MUSLE as input to simulate erosion.

For the two modeled sub-catchments, observations of surface runoff, peak flow, and sediment yield are not available for the observation period (1956–1971). Erosion data availability is very rare for torrents of Southern Italy, and discharge observations are quite rare before the 1970s. To partly replace this lack of data, the HEC-HMS model was calibrated in the Duverso torrent, where observed daily discharges were available for the same period. The calibration does not ensure complete model reliability in predicting erosion, but accurate simulations of runoff are a prerequisite for the successful application of a process-based erosion model [53–55].

2.3.1. The HEC-HMS Model

HEC-HMS was developed in 1998 by the "US Army Corps of Engineers" [56], to simulate the rainfall-runoff processes at the catchment scale, both in small urban or rural catchments and large rivers [51,57]. The model subdivides the catchment in sub-areas with homogeneous land use and soil [58]. The model provides hydrographs from these sub-catchments and routes water and sediment flows through channels to the catchment outlet [58].

To simulate surface runoff, HEC-HMS uses several components, which (i) define the catchment area, sub-catchments, stream network, and diversions and junctions, (ii) calculate precipitation on each sub-catchment, (iii) estimate infiltration using 1 out of 11 methods, (iv) transform the rainfall excess into direct surface runoff through one out of seven rainfall-runoff transformation methods, and (v) apply the baseflow method to predict the delayed subsurface flow reaching the channel [51,57,59].

2.3.2. The MUSLE Equation

The MUSLE (Modified Universal Soil Loss Equation, [42]) equation is based on the original USLE model, in which five (K, L, S, C and P) of the six input parameters are linked to soil cover and properties, topography, and human activities, while the sixth climate factor (R) is replaced by a runoff factor. The MUSLE equation has the following general form:

$$A = a\left(Q' q_p\right)^b K \times LS \times C \times P \quad (1)$$

where A is the sediment production (t ha^{-1}) on a storm basis, Q is the runoff volume (m^3), q_p is the peak flow rate (m^3 s^{-1}), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), LS is the slope-length and steepness factor, C is the cover management factor, P is the conservation support practice factor, and a and b are site-specific empirical factors.

2.4. Brief Description of the Hydrological Models HEC-HMS and MUSLE

2.4.1. The HEC-HMS Model

To implement the HEC-HMS model in the Duverso torrent (selected only for runoff and peak flow calibration) and in the Serra and Vacale sub-catchments (for simulating runoff and peak flow), a 10 m resolution Digital Terrain Model (DTM) obtained by the 1955 Regional Technical Map [60] was used to simulate the stream network by GIS software (QGIS version 2.6 "Brighton"). Soil texture/type was given as input using the Soil Map of the Calabria Region [61]. Land use was obtained by remapping ortho-photographs of 1955 (Figure 4).

Using GIS software, the map of the homogenous response units (HRUs) was built, by overlaying the maps of land use and soil type and identifying the HRUs with a given land use and soil type. Therefore, each HRU is characterized by a specific land use and soil type on which its hydrological response depends.

For the regulated sub-catchment, the check dams were parameterized as a "reservoir" element with a broad-crested spillway outflow structure for the first seven events (until 1966). This date was set up considering that the solid material mobilized from the construction time was trapped in the sediment wedge behind the structure that was, therefore, progressively filled until depletion of the retention capacity. To evaluate this capacity, the sediment wedge volume was estimated according to the methods proposed and validated by Zema et al. [18] in the same environment. Considering this volume, the DTM was accordingly adjusted at each event date, in order to take into account the current bed profile. Subsequently, the profile slope of the event of November 1966 was set for the subsequent rainfall-runoff events.

Climatic data were collected from the database of the Regional Agency of Environmental Protection of the Calabria region (ARPACAL) for the period of 1955–1971. Precipitation height at time intervals of 60 min and daily temperatures were recorded at the gauging station of Cittanova, which is very close to the studied sub-catchments (Figure 1).

For model evaluation, all the events with a peak flow higher than 1 $m^3 s^{-1}$ were selected, resulting in a sample of 10 rainfall/runoff events between 1956 and 1971. For these events, the rainfall amount was in the range 21.5 mm (7–14 March 1971) to 217 mm (14–21 January 1961), while the minimum and maximum rainfall intensity was 0.18 and 1.81 mm h^{-1}, respectively (Table 2).

Table 2. Rainfall depth, duration, and intensity for the 10 selected events occurred at the Cittanova rain gauging station (Calabria, Southern Italy).

Rainfall Event	20–31 January 1956	3–9 November 1956	14–21 January 1961	1–8 March 1961	4–13 March 1966	17–25 September 1966	11–21 November 1966	15–20 January 1971	7–14 March 1971	20–24 November 1971
Depth (mm)	60.8	74.4	217.2	54.4	79.2	139.6	40.6	36.4	21.5	32
Duration (h)	216	96	120	120	168	144	192	72	120	120
Mean intensity (mm h^{-1})	0.28	0.78	1.81	0.45	0.47	0.97	0.21	0.51	0.18	0.27
Peak flow ($m^3 s^{-1}$)	1.4	13.6	1.05	5.0	n.a.	1.51	n.a.	3.2	1.16	n.a.

Note: n.a. = not available.

For model calibration, in addition to the hourly rainfalls recorded at the same gauging station, the peak water discharge ($m^3 s^{-1}$) was available for 7 out of the 10 events in the same database. These data were measured by an ultrasonic flow meter at the catchment outlet, close to the municipality of Cittanova. The baseflow was identified in the observed hydrograph by the 'straight-line' method.

Among the 11 infiltration methods of the HEC-HMS model, the "SCS-CN" method [62,63] was chosen. The SCS-CN method has been developed in the USA, but the literature reports several successful applications under Mediterranean conditions and in variable environments [64,65]. This infiltration method was selected because the required input parameters were available or could be easily estimated by the experimental database of the studied sub-catchments [52]. Moreover, a previous study by Zema et al. [52] demonstrated the accuracy of this infiltration method in the same environmental conditions.

The average value of the initial Curve Number (CN) was calculated for each identified sub-catchment. The CN, identified for each HRU of the sub-catchments according to [62], was weighted by its area. Furthermore, the initial CN was updated to the Antecedent Moisture Condition of the soils prior to each rainfall event. AMC was determined by the total rainfall in the 5-day period preceding a storm [62]. Thus, the "Initial Abstraction" and the "Lag time" (for the SCS-UH transform method), which depend on CN, were calculated for each sub-catchment. The "SCS unit hydrograph" method was selected among the seven rainfall-runoff transformation methods, because it requires only the input of lag time.

A default CN (equal to 59, according to the USDA-SCS guidelines) was initially adopted. The peak flow simulations provided by HEC-HMS were compared to the corresponding observations at the outlet of the Duverso sub-catchment, using as a goodness-of-fit measure the index of efficiency (E, Nash and Sutcliffe, 1970). Since the prediction capacity of the model with default CN was unsatisfactory (E < 0), the model was manually calibrated by adjusting the initial CN (trial-and-error procedure) until the maximum value of E was obtained. The optimal CN resulting from the calibration of the Duverso torrent was used for HEC-HMS and MUSLE applications in Vacale and Serra sub-catchments. The total volume of the surface runoff and the peak flow were simulated at the outlets of both torrents for each of the 10 rainfall events. The other parameters required by the HEC-HMS model are shown in Table 3.

2.4.2. The MUSLE Equation

The runoff volume (Q) and peak flow rate (q_p) of each rainfall-runoff event modeled using HEC-HMS were given the MUSLE equation as input. The MUSLE equation was used to simulate the sediment yield at an event scale for the Vacale and Serra sub-catchments. The other parameters required by the MUSLE model are shown in Table 3.

2.5. Statistical Analysis

The statistical significance of differences in surface runoff, peak flow, and sediment yields between the Vacale and Serra sub-catchments was evaluated using a one-way analysis of variance (ANOVA) with repeated measures along with a Tukey test (designed for the pairwise comparisons). Simulations of the hydrological variables at the reaches of the two sub-catchments were considered as replicates; the presence or absence of check dams was the ANOVA factor. The significance level was set at $p < 0.05$. The ANOVA analysis of variance assumes that the residuals are normally distributed. Thus, data were tested for the assumption of normality by using the Aderson–Darling methodology, which is based on the function of empirical distribution. Moreover, the Mann–Kendall test [66] was also applied to the modeled hydrological variables, in order to assess the presence and significance of trends over the observation period.

Table 3. Values of the input parameters adopted to simulate runoff and sediment yield using the HEC-HMS (SCS-CN method) and MUSLE models applied in the three sub-catchments (Calabria, Southern Italy).

Model	Input Parameter (Units)	Sources	Sub-Catchments			
			Duverso		Serra (Unregulated)	Vacale (Regulated)
			Default Model	Calibrated Model		
SCS-CN	CN (-)	USDA-SCS' manual [62]	59	71	segu71	71
	λ (-)		0.20			
	Lag time (min)	-	10			
MUSLE	a (-)	[67]	-		0.87	
	b (-)				0.57	
	K-factor (tons h MJ^{-1} mm^{-1})	[68]			0.038 (before reforestation) 0.030 (after reforestation)	
	C-factor (-)	[69]			0.33 (before reforestation) 0.15 (after reforestation)	
	P-factor (-)	-			1	

The statistical analysis was performed using XLSTAT release 2019.1 (Addinsoft, Paris, France).

3. Results and Discussion

3.1. HEC-HMS Calibration (Duverso Torrent)

Calibration of the HEC-HMS model in the Duverso torrent using the default value of initial CN (equal to 59) gave a low accuracy in predicting the peak flow. High mean differences among the observed and simulated values up to −96% were found, showing a noticeable model's tendency to underestimation. A calibrated CN, set to 71, increased the soil's capacity to produce surface runoff, which reduced the model underestimation (Figure 5). After CN setup, the mean peak flows simulated by HEC-HMS were closer to the corresponding observations, with average differences lower than 7%. Additionally, the evaluation criteria used for model evaluation confirmed the good capacity of peak flow prediction by the model. The coefficients of determination and efficiency were equal to 0.92 and 0.87, respectively. According to Moriasi et al. [70], these differences are considered as acceptable in runoff modeling experiences. Further trials to improve a model's prediction capacity using different CNs between winter and summer did not improve the peak flow prediction capability of HEC-HMS.

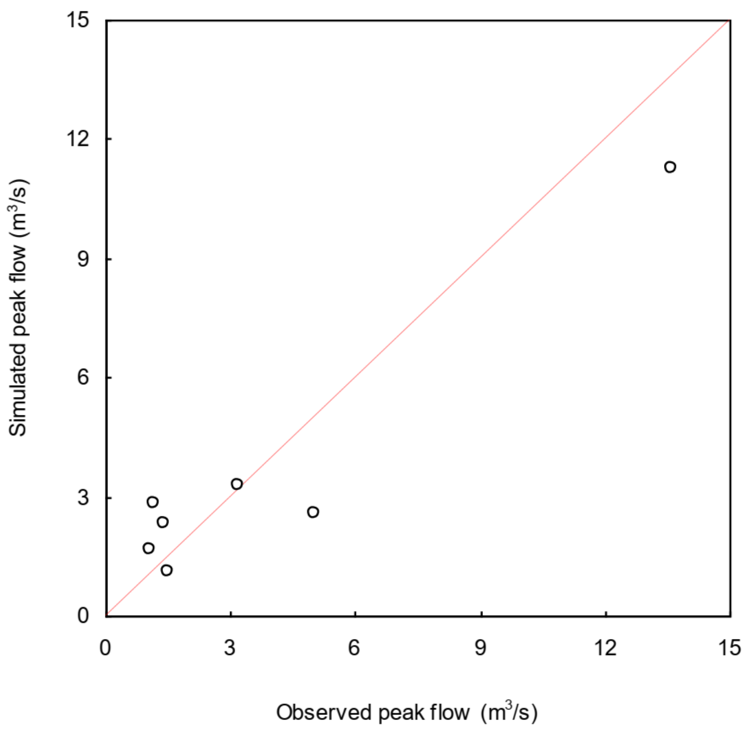

Figure 5. Scatterplot of the observed vs. simulated peak flow events in the Duverso torrent (Calabria, Southern Italy).

This good performance shown by the model in Mediterranean catchments is in close accordance with Zema et al. [52], who found a coefficient of efficiency up to 0.90 in modeling peak flow at the outlet of Mesima torrent (receiving catchment of Vacale torrent). However, these authors used as water infiltration sub-component the "Initial and Constant" method, since the "SCS-CN" method was more accurate for runoff volume estimations. Regarding other HEC-HMS applications in semi-arid or arid conditions, the optimal CNs proposed in this study are lower than the values (between 80 and 85) used by Tassew et al. [71] in a sub-catchment of the Upper Blue Nile (Ethiopia), and Derdour et al. [72], Aqnouy et al. [73], and Skhakhfa et al. [74] in semi-arid catchments of Northern Africa. However, the conditions of these catchments are significantly different from the three headwaters of our study, and this justifies the differences. Many other studies about HEC HMS applications report a range of 60–70 for CNs in catchments with different conditions [75–77].

3.2. Comparison of the Surface Runoff and Peak Flow between the Regulated (Vacale) and Unregulated (Serra) Torrents

The average surface runoff simulated by HEC-HMS was 0.17 mm for the Serra (unregulated) sub-catchment and 0.16 mm for the Vacale torrent (regulated), while the average peak flow (referred to the unit drainage area) was 0.066 (Serra) and 0.061 (Vacale) $m^3 s^{-1} km^{-2}$. The maximum runoff was 0.56 and 0.58 mm for the Serra and Vacale torrents, respectively, both recorded on 14–21 January 1961 after a rainfall of 217 mm (Figures 6 and 7). The runoff coefficient was between 0.02% and 0.28%, with a mean of 0.17% (Figure 8). The reason of these very low values in both sub-catchments may be the large forest cover that is evidently effective in limiting the runoff generation capacity [8,78–80]. Moreover, a significant (r^2 = 0.63, $p < 0.05$, Mann–Kendall test) evolutionary trend with decreasing runoff coefficients over time can be noticed in both sub-catchments (Figure 8), which can also be explained by the hydrological effectiveness of tree cover growing after reforestation works in the mid-1950s [24]. As a matter of fact, the vegetation cover in both sub-catchments progressively increased over time, reaching the maximum coverage more or less 15 to 20 years after check dam construction.

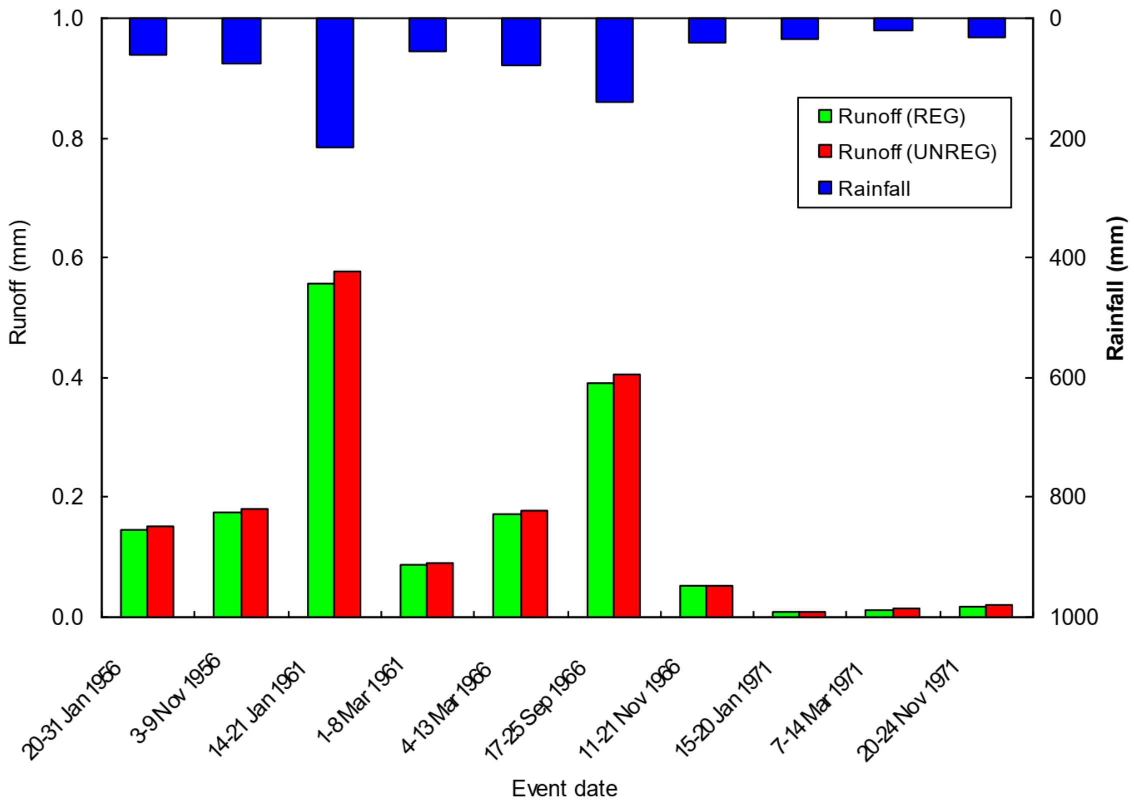

Figure 6. Rainfall height and surface runoff simulated by the HEC-HMS model in unregulated (UNREG) and regulated (REG) sub-catchments (Calabria, Southern Italy)—events are not reported on the time scale.

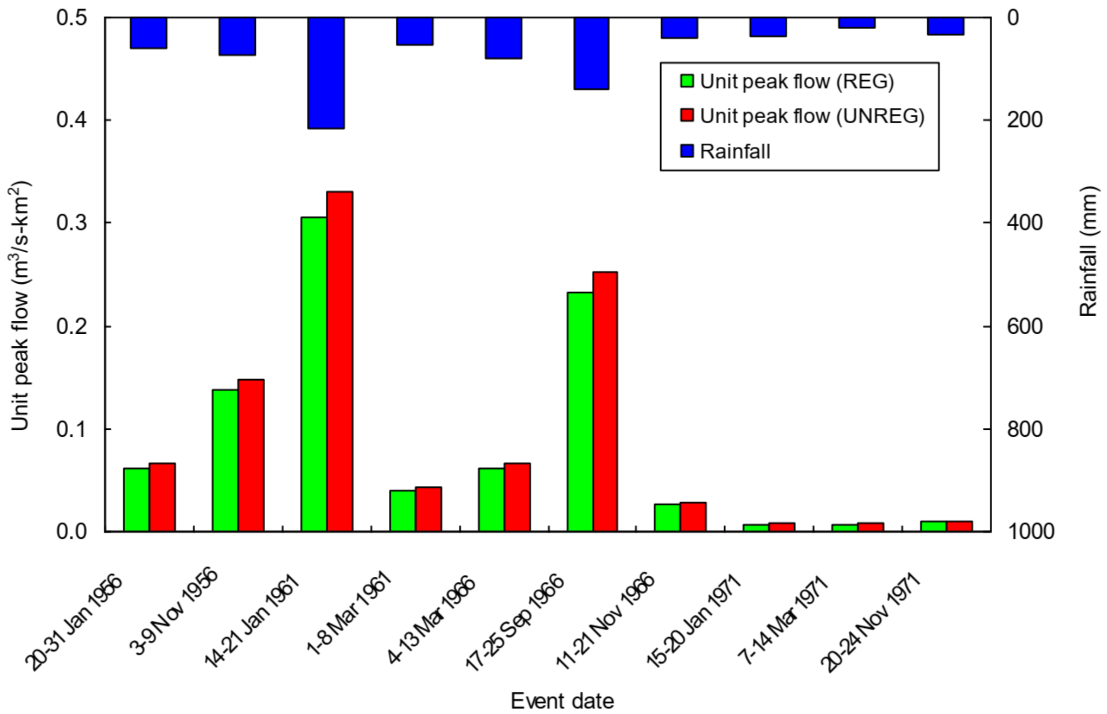

Figure 7. Rainfall height and peak flow simulated by the HEC-HMS model in unregulated (UNREG) and regulated (REG) sub-catchments (Calabria, Southern Italy)—events are not reported on the time scale.

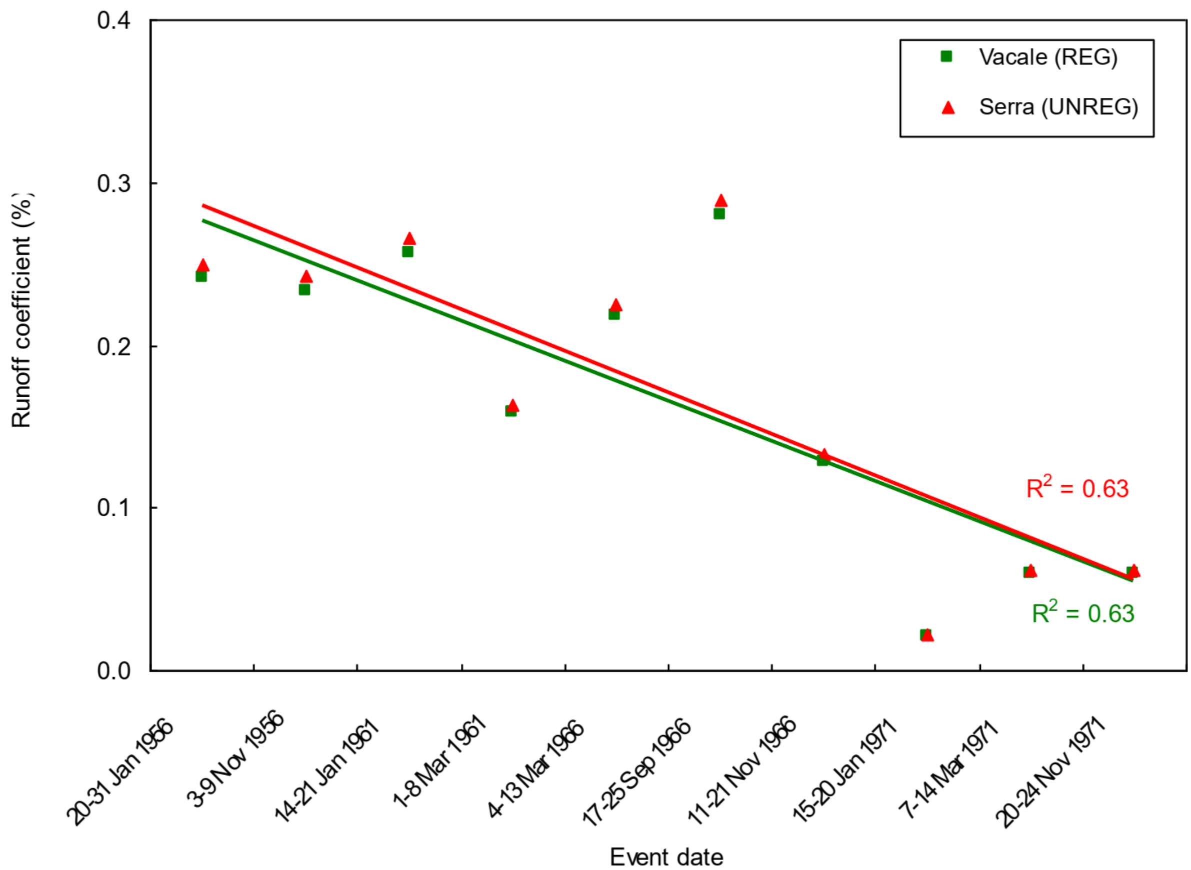

Figure 8. Temporal evolution of runoff coefficients in unregulated (UNREG) and regulated (REG) sub-catchments (Calabria, Southern Italy)—events are not reported on the time scale.

Surface runoff volume was always higher in the Serra torrent compared to Vacale, but not significantly ($p < 0.05$). The same rainfall events produced differences in runoff between −2.93% (event of 15–20 January 1971) and −3.87% (20–24 November 1971) (Figure 6). The comparison of the runoff coefficients recorded for the same storm event between the regulated and unregulated torrents shows that the presence of check dams determined reductions between 2.93% (event of 15–20 January 1971) and 3.87% (20–24 November 1971), and the differences were never significant ($p < 0.05$) (Table 4). This low check dam influence on the surface runoff compared to the torrent without structures is expected, since the hydraulic control works do not noticeably impact a soil's infiltration capacity, of which the change would reduce the water volume. In contrast, check dams may enhance sedimentation of finer particles that can form a channel bed with lower soil hydraulic conductivity compared to the gravel or sand material of unregulated channels. Therefore, the lack of significance for the difference in runoff between the two catchments—which have the same climate and similar land uses—could mainly be due to the natural variability of soil and its hydrological response. The presence of check dams may have also promoted some effects on the runoff generation and changes in the sub-catchments (e.g., subsurface flow, establishment and growth of riparian vegetation, etc.), although these effects are not noticeable. The different runoff volume modeled in the two sub-catchments is again in accordance with the literature, which has demonstrated that catchments with check dams show a different runoff response to precipitation compared with those without structures [81,82]. Surface runoff is thought to be more influenced by the increase of vegetation cover on hillslopes (due to natural afforestation and reforestation works) and channels (due to riparian vegetation growth) [12,20,21,23,28,83] compared to check dams.

Table 4. Percent difference in hydrological simulations using the HEC-HMS and MUSLE models between the Vacale and Serra torrents (Calabria, Southern Italy).

Event Date	Surface Runoff *	Peak Flow *	Sediment Yield *
20–31 January 1956	−3.34	−6.73	−47.07
3–9 November 1956	−3.64	−6.87	−47.21
14–21 January 1961	−3.22	−7.55	−38.60
1–8 March 1961	−3.10	−7.34	−38.48
4–13 March 1966	−3.22	−6.73	−26.10
17–25 September 1966	−3.17	−7.42	−26.38
11–21 November 1966	−3.63	−6.41	−26.12
15–20 January 1971	−2.93	−12.79	17.85
7–14 March 1971	−3.64	−4.86	23.28
20–24 November 1971	−3.87	−6.97	21.54
Mean	−3.37	−7.37	−18.73

* Negative differences indicate reduction in the modeled variable for Vacale torrent (regulated) compared to Serra (unregulated).

The maximum peak flow simulated by HEC-HMS was 0.331 $m^3\ s^{-1}\ km^{-2}$ in Serra and 0.336 $m^3\ s^{-1}\ km^{-2}$ in Vacale, also in this case on 14–21 January 1961 (Figure 7). The reductions in the hydrological response recorded in the regulated sub-catchment compared to the unregulated torrent were more noticeable for peak flows compared to runoff. The mean and maximum differences were −7.37% and −12.79%, respectively (the latter recorded for the event of 15–20 January 1971) (Table 4). Additionally, for the peak flow, the differences between the two torrents were never significant ($p < 0.05$).

The limited effects of check dams on peak flow are somewhat expected in the investigated sub-catchments, although they contrast some findings in the literature. Several studies have shown that, in relation to runoff control, check dams reduce peak discharge and increase the time to peak [14,81,84,85], since, as a result of channel morphologic adjustments after check dam construction, the longitudinal channel bed profile aggrades upstream of structures and the cross section widens, and therefore, the stream velocity decreases with the flood lag effect [15]. In the regulated headwaters under investigation, presumably the runoff volumes and discharges are too low to be affected by the check dam presence. In more detail, when the peak flow is lower than the maximum discharge that the check dam weir can convey, the water stream is not influenced by the presence of the structure. Therefore, the hydraulic parameters (velocity, depth, and width) do not vary and the water stream flows in the regulated channel under undisturbed hydraulic conditions, as in the unregulated torrent. In other words, the lamination effect played by the control works on the water stream is not so effective or even very limited, as compared to large channels, such as in valley reaches, where water flows are considerable. In these reaches, check dams are more effective in protecting areas downstream during torrents and strong floods. The effectiveness of check dams were particularly evident in the middle reaches of the torrents of Southern Italy after the disrupting floods of the mid-1950s [24] as well as in high-gradient stream channels of the North Italian Alps [86]. However, the runoff control function of check dams was not effective everywhere: in southern Arizona (USA), rock check dams were not effective in reducing runoff and the response to peak flow was not persistent [81,87]. In southeastern Spain and in the tributary basins of the Yellow River (China) [88,89], check dams were found to have a minimal effect against the impact of extreme floods, especially if structures were ill-designed and not properly maintained.

3.3. Comparison of the Sediment Yield between the Regulated (Vacale) and Unregulated (Serra) Torrents

Erosion simulations using HEC-HMS coupled to MUSLE gave average sediment yields of 0.186 (Serra) and 0.118 (Vacale) tons ha^{-1}. The maximum values were 0.706 (Serra) and 0.433 (Vacale) tons ha^{-1}, both recorded for the event of 14–21 January 1961 (Figure 9). As for the runoff and peak flow, erosion was higher in the Serra torrent compared to Vacale. However, this happened only for the first seven events (until November 1966). In the following period (January to November 1971), the sediment yield in the regulated torrent was higher compared to the unregulated sub-catchment. In more detail, in the first period after the same rainfall events, the differences in sediment yields were between 26.1% (event of 4–13 March 1966) and 47.2% (3–9 November 1956), while, in the events of 1971, erosion in the Vacale torrent was 17.8% to 23.3% higher compared to the Serra sub-catchment (Figure 9 and Table 4). Averaging all the events, the regulated catchment gave a sediment yield that was lower by 18.7% than the unregulated torrent. All differences were not significant ($p < 0.05$). The low efficiency of check dams in limiting the erosion at the catchment scale in comparison to the erosion rates detected in the other torrent without control works may be somewhat surprising at a first sight. It is well known how check dams impact catchment hydrology and morphology (for instance, by reducing channel profile slope, e.g., Zema et al. [90], and favoring the growth of riparian vegetation, e.g., Bombino et al. [11] and Zaimes et al. [91]). These effects influence the flow regime by reducing the water velocity, which in turn modifies the travel time of water particles, and thus, affects the peak flow [19,92]. However, a deeper analysis highlights that the check dam action depends on structure functioning after construction [81]. In more detail, immediately after installation, check dams retain a large amount of the solid material transported by floods in the empty wedge upstream of the structure. After their retention capacity is depleted, check dams are still able to limit erosion, since the structures stabilize the channel bed by decreasing the longitudinal slope in the sediment wedge [18,83]. However, the most intense floods can mobilize the surface sediments (visible as bars or sediment accumulation above the spillway level), deposited by ordinary streamflow, thus increasing the sediment yields at the catchment scale. This happens mainly because check dams slow down the water stream and determine sedimentation of the finer material; as a consequence, the under-saturated water flow increases its erosive capacity downstream of the check dams and this allows bed scouring and re-mobilization of fine material [15,16,30,93–95]. Presumably, the equilibrium profile slope (which has been estimated between 4% and 5% in the studied headwaters using traditional methods based on sediment grain size and hydraulic characteristics of water flow) had not been established in the 15–20 years of the monitoring period, that is, in the short term after check dam construction. Check dams achieved their purpose, but many years after their installation. Therefore, the erosion rates are close between the sub-catchments and sometime higher in the regulated torrent (due to the bed material mobilization between two consecutive check dams) compared to the channel without check dams. Additionally, Luo et al. [96], although in a different climatic and geomorphological context (a restored small catchment in Loess Plateau, China), reported that check dams were less effective in reducing water and sediment flows than revegetation and terraces, which instead determined significantly lower unit soil loss compared to an unregulated catchment. Galia et al. [97], in regulated catchments in the Czech Republic, demonstrated that torrent control works increased the longitudinal connectivity of sediments compared to unregulated channels with the same catchment-scale characteristics. This contrasted the general perception of check dams as decelerators of erosion, showing that sequences of consolidation check dams (as in our study) in small regulated channels can increase sediment flows downstream. In contrast, Alfonso-Torreno et al. [98] found that check dams were effective in favoring sediment deposition and reducing lateral bank erosion in a small catchment affected by gully erosion in SW Spain.

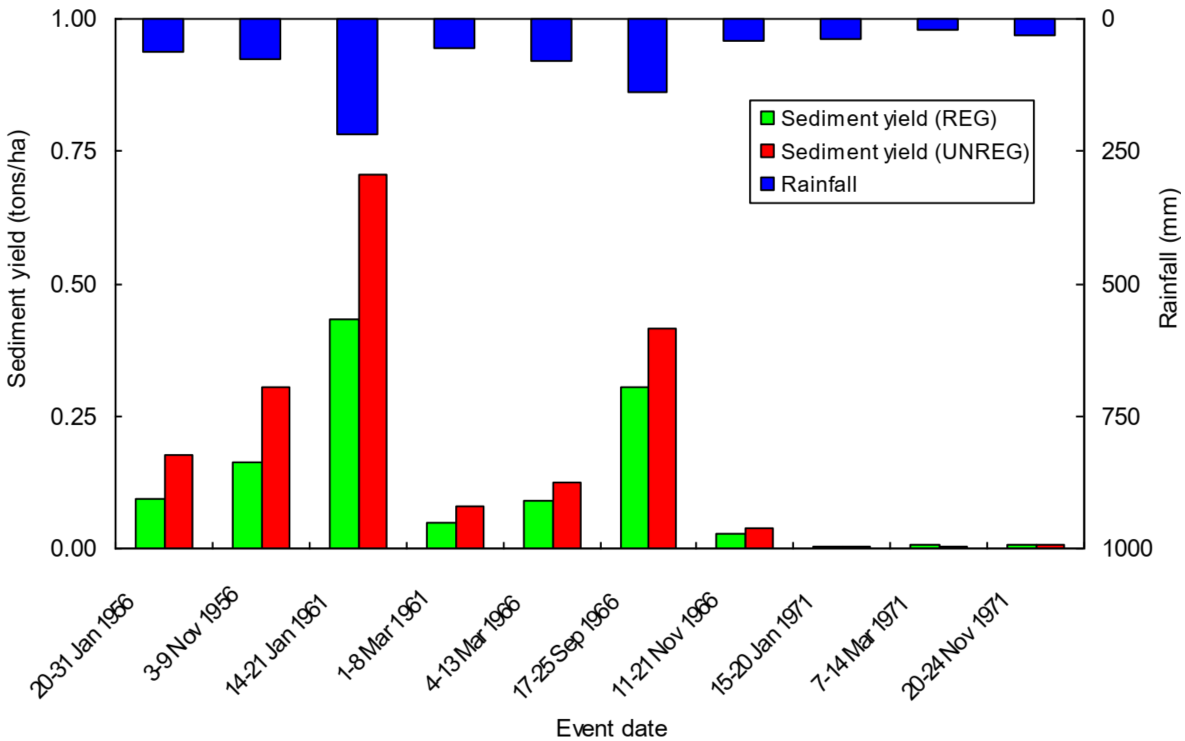

Figure 9. Rainfall height and sediment yield simulated by the MUSLE equation in unregulated (UNREG) and regulated (REG) sub-catchments (Calabria, Southern Italy)—events are not reported on time scale.

The predictions provided by the modeling approach of this study, although affected by uncertainty (due to the lack of model verification against observed data of erosion) show that the soil loss in both sub-catchments is much lower compared to the tolerance limit of 10 to 20 tons ha^{-1} yr^{-1} [68,99]. These low values may be due to the fact that erosion rates are limited by the fast-growing vegetation cover in the sub-catchments. Moreover, for erosion, significant (r^2 = 0.59, Vacale torrent, and r^2 = 0.63, Serra torrent, $p < 0.05$, Mann–Kendall test) evolutionary trends of unit sediment yields (that is, the erosion produced by the unit precipitation) were detected over time in both sub-catchments (Figure 10). This means that the fast-growing tree cover due to reforestation works in the mid-1950s was effective in reducing the soil erodibility at the catchment scale [24]. Moreover, it can be presumed that the large forest cover of the studied headwaters, which has not been affected by noticeable changes over the last 60 years, has played an important role in keeping low runoff and erosion rates. In addition, land-use changes, such as cultivation of steep slopes, land abandonment, and overgrazing, which may increase sediment flows or declines in soil fertility [100], have not been observed. Thus, the check dam actions are less important than in highly dynamic and unstable catchments.

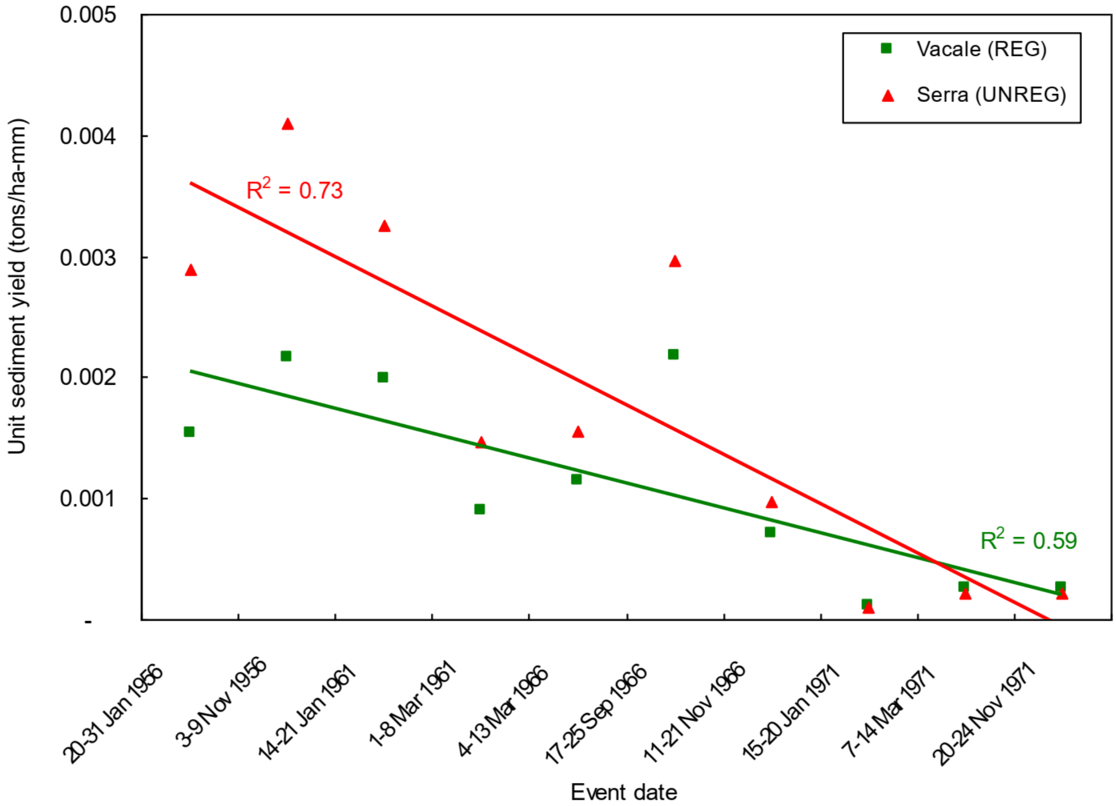

Figure 10. Temporal evolution of unit sediment yield (per unit precipitation) in unregulated (UNREG) and regulated (REG) sub-catchments (Calabria, Southern Italy).

4. Conclusions

The HEC-HMS model coupled to the MUSLE equation has shown that check dams play a limited role in reducing the surface runoff and peak flow in a Mediterranean forested headwater compared to a similar but unregulated torrent. The well-developed forest cover determines a very low runoff generation in both sub-catchments, further limited by the progressive tree growth after reforestation works in the mid-1950s. Moreover, the control works were marginally effective in decreasing the peak flow.

Erosion was higher in the unregulated torrent only for the first seven events after check dam installation in the regulated sub-catchment, while, at a later time, the reverse effect was estimated between the two sub-catchments. Therefore, check dams have reduced erosion at the catchment scale for about 8–10 years after their installation, that is, when the structures were able to retain solid material (although soil loss in both studied catchments was much lower than the tolerance limits) in the empty or partially filled sediment wedge. After the sediment retention capacity was depleted, the sediment yield in the regulated torrent was higher compared to the unregulated sub-catchment, since extreme floods can mobilize sediments deposited by previous but less intense stream flows. Therefore, the erosion rates in the regulated torrent may be close and sometime higher compared to the sub-catchment without check dams.

Overall, the study has shown that the use of check dams as a catchment protection strategy should be considered with caution in some environments. In forested headwaters of the semi-arid Mediterranean conditions, the effectiveness of these structures in reducing water and sediment flows during floods could be low. Perhaps an increase in forest cover may be suggested as an alternative strategy in these headwaters, leaving the check dam installation as management action in valley reaches, where water and sediment flows are higher.

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