GeoHazards

Review

Evaluating Post-Fire Erosion and Flood Protection Techniques: A Narrative Review of Applications

George Papaioannou [1,*], Angelos Alamanos [2] and Fotios Maris [3]

[1] Department of Forestry and Management of the Environment and Natural Resources, Democritus University of Thrace, 68200 Orestiada, Greece
[2] Department of Civil Engineering, University of Thessaly, Pedion Areos, 38334 Volos, Greece
[3] Department of Civil Engineering, Democritus University of Thrace, Kimmeria Campus, 67100 Xanthi, Greece
* Correspondence: gpapaio@fmenr.duth.gr

Abstract: Wildfires affect and change the burned sites' condition, functionality, and ecosystem services. Altered hydrologic processes, such as runoff, increased streamflows, and sediment transport, are only a few examples resulting from burned soils, vegetation, and land cover. Such areas are flood-prone and face risks of extreme peak flows, reduced infiltration, water pollution affecting habitats, and hydromorphological changes. In this study, we present the different post-fire erosion and flood protection treatments that have been developed to avoid and mitigate the consequences and risks mentioned above. We categorize them into Land, Channel, Barrier, and Road treatments and analyze their types, such as cover-based methods, barriers, mulching, in-channel treatments, such as check dams, seeding, or even chemical treatments. Examples of how such treatments were used in real cases are provided, commenting on their results in flood and erosion protection. We found that cover changes were more effective than barriers, as they provided an immediate ground-cover increase in both Mediterranean and US sites. We explore the factors that play a role in their effectiveness, including storm duration and intensity, topography and slopes, land cover and uses, treatment implementation-installation, as well as fire-related factors such as burn severity. These factors have different effects on different treatments, so we further discuss the suitability of each one depending on the site's and treatment's characteristics. The outcomes of this work are expected to improve the understanding of the practical aspects of these treatments, providing for the first time a synthesis of the available knowledge on the multiple complex factors that can determine their efficiency.

Keywords: wildfires; post-fire; flood protection; soil erosion; sediment; reforestation; land treatments; in-channel treatments

check for updates

Citation: Papaioannou, G.; Alamanos, A.; Maris, F. Evaluating Post-Fire Erosion and Flood Protection Techniques: A Narrative Review of Applications. *GeoHazards* **2023**, *4*, 380–405. https://doi.org/10.3390/geohazards4040022

Academic Editors: Tiago Miguel Ferreira and Luuk Dorren

Received: 24 July 2023
Revised: 2 October 2023
Accepted: 5 October 2023
Published: 10 October 2023

1. Introduction

Watersheds receiving precipitation close to their usual-average levels and having generally good hydrologic conditions yield relatively small amounts of sediment, while their stream baseflow remains sustained for extended periods or even the entire year. For example, in watersheds with satisfactory hydrologic conditions (e.g., dominated by litter and vegetation exceeding 75% of their ground cover), only about 2% of rainfall becomes surface runoff, and erosion rates are low [1]. Even if such watersheds receive enough rainfall, sustainable annual streamflow conditions and little sediment production can be achieved with good hydrologic conditions [2].

However, this behavior can significantly change after wildfires. Wildfires affect all watershed characteristics, including soils, vegetation, and land cover, which are critical to fundamental hydrologic processes such as runoff, streamflows, and sediment transport [2,3]. In particular, depending on the burn severity and the wildfire's duration, post-fire areas have reduced organic litter and vegetation covering the ground surface (even less than 10% of the ground), so there is very limited water retention. Subsequently, increased runoff leads to sediment transport, soil erosion, and water quality deterioration, even after mild precipitation events [4]. Robichaud et al. [5] find that surface runoff can increase by over 70% in such cases, while erosion can increase by three orders of magnitude. In general, after a wildfire, precipitation events have noticeable effects, such as the formation of water-repellent soils that cause immediate runoff, floods, roughness reduction, high peak flows, hydrological connectivity alteration, disruption of the infiltration processes, topographical alterations, delivery of sediment, post-fire debris flows and ash to streams [5–8]. The above negatively affects habitats, bridges, roads, buildings, and other infrastructures [9–11]. Water quality and channel stability are also severely affected, along with soil erosion, due to the movement of soil particles. Studies in Australia also show the effects of such post-fire cascade effects and the impacts on erosion, flood risks, sediment transport, and water quality [12,13]. The hillside slopes can also be affected, leading to the immediate occurrence of dry ravels after a wildfire event [14]. The occurrence of dry ravels can further enhance surface material transport through channels [15,16]. Many studies provided evidence that the most severe sediment losses occurred within the first year after the wildfire [17–19]. However, the magnitude of the damages can vary depending on multiple factors, such as climate, fire frequency, soil type, geology, topography (especially slopes), and vegetation [20,21]. Regarding water quality, Rust et al. [22] studied several sites in the western USA and found that nutrient flux (different forms of nitrogen and phosphorus), major-ion flux, and metal concentrations are the most common pollutants in streams within the first five years after a wildfire.

As years pass, watershed ecosystems can recover, the burned sites are stabilized, and all the above phenomena usually decline, along with the recovery of the vegetation and the land cover. There are also cases where wildfires can play an important positive role for ecosystems concerning vegetation renewal and the establishment of diverse habitats, among other functions. Thus, human fire suppression can result in unintended ecosystem changes [23–26]. In this study, we focus on the short-term flood and soil erosion risks caused by wildfires, and our goal is to describe the treatments for the recovery of burned sites and the protection from such risks. The importance of good hydrologic and land cover conditions in watersheds will be more valuable in the future as the changing climate increases the length of the fire weather seasons [27]. Considering all the consequences mentioned in the previous paragraph, one can understand how many co-benefits lie in the timely restoration of post-fire sites. As Girona-García et al. [7] noted, mitigating the prone areas to erosion and floods after wildfires is crucial to decreasing potential downstream risks and preserving the ecosystems' sustainability.

In order to speed up a burned watershed's land cover restoration and thus boost its hydrological and erosion response, several practices have been developed, known as post-fire erosion and flood protection techniques (or post-fire protection treatments—PPT). These can be cover-based and include barriers; mulch or hydromulch; erosion control mats; slit fences; seeding; or even in-channel treatments, such as check dams, grade stabilizers, in-channel tree felling, debris basins, channel deflectors, and stream channel armoring, while road and trail or even chemical treatments can be used.

While the literature review highlights the importance of immediate action by applying various PPTs, considerably less information is available about the operation and effectiveness of those PPTs. The lack of consistency in evaluating and assessing the PPTs' effectiveness is due to the highly variable influence of site-specific factors (climate, terrain slopes, land uses, burn severity, costs, etc.). The large dependence of a watershed's response to PPTs on multiple factors that interact makes any evaluation of PPTs challenging and the generalization of most findings almost impossible. Thus, the literature is restricted to specific case studies on a regional or local scale, evaluating PPTs under certain conditions. At the same time, the need and importance to timely restore the post-burned sites to avoid short-term flood and erosion damages are being increasingly recognized [28], calling for further research assessing the role of PPTs.

In this paper, we provide an overview of the different PPTs, describing each one of these treatments, analyzing their type and works required, the suggested suitable sites, and the specific factors affecting their effectiveness. To our knowledge, this is the first attempt to categorize, summarize, and analyze the effectiveness of PPTs in relation to most factors reported by the existing literature. Furthermore, we present several case study applications to improve the practical aspects of applying PPTs and the watersheds' behavior and indicate site-specific differences.

We believe this paper can be an insightful resource, allowing practitioners and researchers to assess and compare the different techniques. The contribution of this overview of the existing knowledge is expected to be also timely, given the increased risk that wildfires are posing worldwide, and considering the country-specific limited existing literature on the topic. Ultimately, the findings can set the basis for developing overarching research guidelines for properly applying PPTs, and guidance based on the factors that generally affect their performance.

2. Categorization of Post-Fire Protection Treatments—PPT

There are many different kinds of PPTs. They all aim to speed up the recovery of burned watersheds, improving their response to hydrological processes and erosion. The way each PPT tries to achieve this differs. The most common PTTs' categorization is based on which watershed element they aim to improve. According to Napper [29], PPTs can be categorized per treatment type, such as land treatments, channel treatments, and road and trail treatments. These are described as follows:

Land treatments: Stabilizing burned areas can be accomplished using several land treatments by providing soil cover (reducing erosion), trapping sediment (reducing sedimentation), and/or reducing water repellency (improving infiltration). These treatments aim to speed up recovery while maintaining ecosystem functionality and integrity by limiting the expansion of unwanted species. Land treatments can be cover-based (working on the land cover improvements, including seeding) or barrier-based (installed barriers to trap sediments, reduce excess flow, or slow runoff).

Channel treatments: Channel treatments focus on mitigating the negative post-fire effects on water quality, loss of water control, lower water velocity, trapping sediment, and preserving channel characteristics. As a result, they are highly beneficial for downstream areas, minimizing the hazardous impact of potential high flows and flooding, erosion, deposition, and sediment transport.

Road and Trail Treatments: Combined with the previous two types (land and channel treatments), road and trail treatments can reduce the post-fire effect on the transportation infrastructure. They also protect life, safety, and property, supporting critical natural or cultural resources.

In the Annex, we have formed a Table to provide a detailed overview of the most typical works under each type of treatment, along with a description based on Napper [29], commenting on their suitability/effectiveness. In Table A1, the name of each PPT is shown along with the type of treatment according to the above three types. The type of work is related to their application, which can be cover-based, barriers to the flow and/or sediment transport, seeding, chemical treatment, or other.

In this section, Table 1 highlights the main factors that one must consider when assessing the effectiveness and suitability per type of treatment.

Table 1. Different treatment types with the most common works, and comments on site suitability and effectiveness.

Type of Treatment	Typical Works	Suitability and Effectiveness
Land—Cover-based	• Aerial Hydromulch • Ground Hydromulch • Straw Mulch • Slash Spreading • Erosion Control Mats, etc.	• Suitability: Areas with high-moderate burn severity; steep slopes; soils with high erodibility factor; low winds. • Effectiveness depends on: Proper installation, application rates, slope length and steepness, and wind conditions. Combinations of mulching and seeding are more effective in germination but not necessarily in surface cover. Wood-based mulches are equally or more effective than straw mulch in reducing post-fire erosion. Erosion Control Mats are costly solutions, with limited information about their effectiveness [29].
Land—Barriers	• Log Erosion Barriers • Fiber Rolls or Wattles • Silt Fences, etc.	• Suitability: Areas with high-moderate burn severity and highly erodible and water-repellent soils; slopes between 20–60%; accessible for maintenance and inspection. • Effectiveness depends on: Proper installation, slope, tree size and length. Barriers are more effective in low-intensity storms [30]. Their maintenance requires significant effort and attention. Barrier construction remains a typical hillslope treatment with better effectiveness when combined with other treatments [7].
Land—Seeding	• Soil Scarification • Ploughing • Seeding, etc.	• Suitability: Areas with high-moderate burn severity and highly erodible slopes; vulnerable to invasive and noxious plants spreading. • Effectiveness: While there is limited available information, seeding is inefficient in reducing sediment yield compared to no treatment [31,32]. Seeding (e.g., <60% surface cover) is not very effective in the first year after a fire and is neutral in the following seasons. Combining seeding with mulch treatments increases the germination potential.
Land—Chemical treatments	• Polyacrylamides (PAM) • other polymers	• Suitability: There is not adequate information to generalize their site suitability. Areas with very mild rainfall events are preferred, as they quickly boost vegetation development. • Effectiveness: Very few cases report their effectiveness, with no effects found on runoff and little erosion reduction achieved [33,34].
Channel—Barriers	• Check dams • In-Channel Tree Felling • Grade Stabilizers • Stream Channel Armoring • Channel Deflectors • Debris Basins, etc.	• Suitability: Areas with high burn severity; smooth slopes where sediment storage can be achieved; with <20% ground cover; small catchments and drainage areas; where construction, maintenance, and inspection are accessible; high risk value (road crossing, sensitive aquatic species) and need to protect the downstream areas. • Effectiveness: Channel barriers are more effective in smooth slopes when used in series and for mild storms and flows [7]. They can reduce most of the runoff and also significant amounts of erosion, but they have short-term effectiveness and require maintenance following runoff events [35]. Debris basins are expensive treatments [29].
Road and Trail	• Outsloping • Rolling Dips • Overflow Structures • Culvert Modification • Trail Stabilization, etc.	• Suitability: Areas prone to flow concentration (e.g., mild slopes, bad drainage with undersized culverts) that need immediate protection from floods (important access, infrastructure, vulnerability, etc.). • Effectiveness: Limited data suggest that if properly designed and installed correctly, they provide significant benefits in terms of discharge, reduced sediment delivery to stream channels, and less road maintenance [29].

It is worth noting that the costs of post-fire erosion and flood protection techniques can vary widely depending on factors such as the size and severity of the burn area, the steepness and slope of the terrain, the proximity to water bodies and infrastructure, the type of vegetation present, and the specific technique employed [31]. These factors affect not only the costs but also the effectiveness of most treatments. There is very limited information on the cost-effectiveness of PPTs. A recent assessment based on 63 sites in Spain, Portugal, USA, and Canada [36], finds that land treatments are the most cost-effective (e.g., straw mulch, wood-residue mulch, and hydromulch). The cost-effectiveness of barrier PPTs was found to be low because their effectiveness is low related to the reduced erosion rates, and they might have high implementation costs in some cases [36]. Concerning the barriers, it is noteworthy to mention that log erosion barriers had slightly better cost-effectiveness values than other barrier types [36]. Keeping in mind that the cost ranges can be highly variable, seeding PPTs generally have low costs (but require considerable time and labor to implement), while chemical treatment erosion control mats are considered costly PPTs. In certain cases, invasive plant management may also be necessary to prevent further ecosystem damage but can be expensive.

According to Girona-Garcia et al. [7], while all treatment types significantly reduce post-fire soil erosion, the cover and barrier treatments also significantly reduce the runoff. In particular, straw and wood mulches were much more effective in mitigating erosion than hydromulch. This finding is in line with Robichaud et al. [37]. Mulch is generally more effective in short-duration and high-intensity rainfall events than erosion barrier treatments that provide little ground cover.

However, the effectiveness of the different mulch types depends on several factors, e.g., application rates, while other measures (e.g., seeding) still have uncertain potential. Seeding can provide hardly any protection during the initial post-fire damaging runoff events since it must grow first.

Barrier treatments were effective when applied in the appropriate slopes for immediate protection from excess runoff and sediment transport.

Channel and road treatments are effective when properly applied to serve certain purposes, namely, to avoid expected failures in certain channels, culverts, and road passages at risk.

Based on limited information, chemical treatments were found inefficient for runoff and erosion reduction. According to Robichaud et al. [38], their effectiveness majorly depends on the occurrence of light rainfall events in order to allow vegetation to grow shortly after fire.

3. Application Examples

Before delving into the drivers of the suitability and effectiveness of the different PPTs of Table 1, it is worth reviewing the existing literature that provides real-life application examples that tested the effectiveness of various PPTs under certain conditions. These real-life application examples are particularly useful for identifying the parameters affecting the effectiveness of PPTs, which will be discussed next. The examples presented below illustrate that different PPTs have been applied in different sites worldwide, provide a picture of their practical application, and that their results have been approached from different angles (e.g., different study periods, effects on runoff or erosion were studied, etc.). Even in cases where the same treatment was applied in different sites, its effectiveness can vary (as we can see from the application examples using mulching treatments below). So, the following examples show the case- and conditions- specific nature of the effectiveness of the PPTs.

Example 1: Increasing ground cover to reduce soil erosion

Fernández et al. [19] investigated the effectiveness of three post-fire treatments (cut-shrub barrier, straw mulch, and wood-chip mulch) on soil erosion reduction after a wildfire occurred in Galicia, North-West Spain. Before the burn, the entire area was dominated by shrubland. The type of these works refers to cover changes and barriers to improve the soil and hydrological conditions. The authors found that straw mulch application during the first year reduced sediment production by 66% in comparison with the control plots (previous conditions), while stabilization treatments such as erosion barriers (branches cut from shrubs) and wood-chip mulch were ineffective concerning soil erosion compared to the untreated control. Straw mulch treatment's effectiveness for reducing post-fire soil erosion lies in achieving an immediate ground cover increase (by 80%).

Example 2: Mulching cover treatments

Robichaud et al. [39] investigated the post-fire mulching treatments effect (wood strand mulch, wheat straw mulch, and hydromulch) on runoff and erosion, in four different burned sites in the western USA. The most effective treatment for sediment yield reduction was the wood strand mulch, followed by wheat straw mulch and hydromulch, which did not reduce sediment yields on either site tested. The authors underline, however, that the results may vary a lot as the longevity of the different treatments differs, affecting thus their performance in reducing sediments' yield over a period of 4–7 years or less.

Example 3: Soil stabilization treatments to reduce runoff and soil erosion

After a wildfire in Lietor in South-East Spain, Lucas-Borja et al. [40] examined the impact of different combinations of salvage logging and (straw) mulching on post-fire soil erosion and runoff. The authors found that mulching in recent fire-affected mountainous terrains is an efficient treatment immediately after the wildfire, even though runoff was not affected by mulching either in not logged or logged plots.

Example 4: Seeding and mulching treatments

Following a wildfire in North-West Spain, Fernández et al. [41] compared the effectiveness of different combinations of needle cast and mulching to reduce soil erosion. In particular, they applied combusted canopy and helimulching (Figure 1), combusted canopy, and scorched canopy treatments. Their sediment yield results showed that combusted canopy treatment areas had significantly higher soil erosion, following the combusted canopy and helimulching and scorched canopy treatments where the soil erosion rates were similar. The findings are in line with the author's previous work (Example 1), where they note the importance of immediately covering the burned ground. In this case, helimulching covered approximately 90% of the soil, whereas the fallen needles from the scorched trees totally covered the burned soil.

Figure 1. Helimulching operations in this study area. Retrieved from Fernandez et al. [41].

Example 5: Assessing ground cover and contour-felling treatments

In this example, the case study is the post-fire area North-West of Loveland, Colorado, in Central USA. Wagenbrenner et al. [42] investigated the effectiveness of three post-fire rehabilitation treatments by comparing the sediment yields of untreated plots, straw mulching, seeding, and contour felling over the period 2000–2003. The authors report that important variations of sediment yields were observed depending on the treatment used and were correlated mostly with the ground cover amount. Natural regrowth is a considerable positive factor, while seeding, in this case, did not affect either sediment yields or the amount of ground cover. With mulching, sediment yields are significantly reduced (around 95% or more). Moreover, the authors report that trenches behind the contour-felled logs had higher infiltration rates than the disturbed areas till they were filled with sediments. Figure 2 below shows an example of a contour-felled log in this site.

Figure 2. A contour-felled log. The trench upslope of the log is created by excavating the soil and piling it against the log to prevent underflow. Retrieved from Wagenbrenner et al. [42].

Finally, the contour-felling treatments largely depend on the installation quality, resulting in variable sediment storage capacities (e.g., they cannot reduce sediment yields from more intense and longer storms but could retain much of the generated sediment in an average year). Thus, it might not be the best treatment for areas with frequent storms of high intensity.

Example 6: Contour-felled log erosion barriers in different sites

Robichaud et al. [30] evaluated the effectiveness of contour-felled log erosion barriers in reducing post-fire runoff and erosion in six small burned watersheds in the Western USA. The authors noted the relationship between sediment yields and runoff and rainfall characteristics. As expected, they proved that higher intensity and longer duration rainfalls generally result in higher runoff and sediment yield. They underline the importance of properly installing the contour-felled log erosion barriers to improve their effectiveness.

Example 7: Mixed check dams and bio-engineering interventions

A large wildfire took place in 2007 in the Canary Islands, Spain. Lovreglio et al. [43] investigated the effect of different treatments on reducing soil erosion and the reestablishment of vegetation. These treatments included traditional channel works, bio-engineering interventions, and a series of mixed check dams (stones with a core filled with forest residues and wooden elements) constructed in gullies created by surface runoff (Figure 3).

The results showed that selected bio-engineering techniques reduced soil erosion rates, facilitated the germination of seedlings, and allowed forest ecosystem restoration. Finally, the advantages attributed by the authors to the specific mixed check-dam are (a) noticeable sediment storage capacity composed of large material such as rocks or vegetal debris, (b) remarkable vegetation recovery and colonization, (c) high design adaptability, and the components used to the environment conditions.

Figure 3. During the application of channel works, re-sprouting of local small trees (pinus canariensis), and series of mixed check dams. Retrieved from Lovreglio et al. [43].

Example 8: Different dam treatments from various case studies

In this example, we provide a brief overview of post-fire case studies using different dam treatments to reduce runoff and soil erosion. Robichaud et al. [44] used straw bale check-dams after the 2010 Twitchell Canyon Fire in the Tushar Mountains of South-Central Utah, USA. They found that these dams trapped less than 50% of the total sedimentation, with the efficiency decreasing over time. Applying this treatment may be justifiable in areas where rainfall intensity is expected to be lower and soil is less erodible. Another example considering dam treatment to 'block' runoff and sediment yield is reported by Badía et al. [45], who applied a hillslope log debris dam in a post-fire site in the Castejón Mountains of Ebro Basin, Spain (Figure 4).

Figure 4. An example—detail of a hillslope log debris dam (bottom). Retrieved from Badía et al. [45].

The third year after the wildfire, which was the first year after the dam's construction, a significant decrease in runoff and sediment yields was reported due to the combined effect of immediate mulching using branches and the overlapping logs damming effect. Considering the performance of the log dams for all study sites according to soil erosion and runoff, it was approximately 90% and 52%, respectively. The finding regarding the check dams' effectiveness in reducing soil erosion and runoff, with decreasing performance over time, is a common element in the above studies and also in agreement with the one of Quiñonero-Rubio et al. [46], who used check dams at Upper Taibilla and Rogativa catchments in South Spain. They also find that check dams have a more significant impact on controlling sediment yield for a short time period. Other studies (in Spain and China) support that despite check dams having a short-lived effect, they can be efficient and valuable sediment control measures [35,47].

Example 9: Seeding treatments

The study mentioned above by Quiñonero-Rubio et al. [46], also highlights that reforestation has sustained and important long-term effects, sometimes with smaller economic cost than, e.g., check-dams for large areas. Achieving fast reforestation is crucial to avoid flood damage or other ecosystem degradation effects. Seeding has been used alone or in combination with other cover-based techniques, such as mulching, for soil erosion reduction, vegetation cover increase, and minimizing the establishment and spread of non-native plant species [32]. For example, Groen and Woods [48] used aerial straw mulch and seeding to reduce post-wildfire erosion in North-West Montana (Fox Creek), USA. Straw mulch was found to be more efficient than the seeds, mainly because of the seeding's limited and slow increase in ground cover. The same finding is supported by the study of Díaz-Raviña et al. [49], comparing the short-term efficiency of seeding and mulching treatments in a post-fire area in North-West Spain (Laza). Concerning the broader ecosystem effects of seeding treatments, and their long-term efficiency, there is little evidence: In a review of 94 relevant studies in the Western USA, Peppin et al. [32] conclude that post-wildfire seeding is an ineffective post-fire soil protection measure in the short term, concerning the invasion of non-native species the effect of seeding is ambiguous, and it is possible to affect the native vegetation recovery negatively. Finally, based on the analysis of Girona-García et al. [7], despite seeding being frequently used as post-fire treatment, it is categorized as an ineffective measure, especially in the first year, because seeding does not have an instant protective effect. However, as presented in the work of Peppin et al. [32] more long-term studies should be conducted to properly evaluate the effectiveness of seeding, especially after the first years after the wildfires.

Example 10: Chemical treatments

Chemical treatments can also be applied to modify burned soil attributes and improve their infiltration rate, runoff, and soil erosion. The most commonly used practice is an anionic polyacrylamide (PAM) add-on, which is a dry, granular material. Prats et al. [34] used PAM in north-central Portugal and compared its performance versus forest residue mulching. They found that chopped eucalyptus bark mulch reduced runoff and soil erosion, whereas PAM did not. Inbar et al. [33] report that while considering the first rainstorm event in the short term, PAM can decrease soil loss and infiltration rate and increase runoff. However, in subsequent rainstorm events where the PAM is dissolved, the reduction in soil loss persists, but its effect on infiltration and runoff does not. The authors confirmed these findings in the post-burned Birya forest area of Israel.

Lessons learned

From the above examples, one can easily understand that the role of any PPT is to speed up the natural recovery of a burned watershed or at least minimize potential risks that arise from its deteriorated hydrological responses. In hydrological terms, we could say that PPTs try to bring the watershed's Curve Number as close as possible to its pre-fire status, increase the runoff lag-time, and increase the potential of sediment retention. The above examples also show that all PPTs played a positive role in the sites' recovery, bringing their functionality closer to the pre-fire conditions. This is the main common message from the cases described above. It is crucial to show the importance of such actions, even with simple PPTs, compared to a 'do-nothing' situation after a wildfire.

Moreover, it is evident that most of the existing studies on the topic have explored cases in the Mediterranean and the USA. Other studies also admit that no PPT works are described in the literature from other regions, such as Australia, South Africa, or South America [7]. However, the cases reviewed from the Mediterranean and the USA can provide an idea of some common and different factors that determine the effectiveness of PPTs. In the Mediterranean (Examples 1, 3, 4, 7), cover changes (such as mulching and seeding treatments) have been found to be more effective than barriers, as they provide immediate ground cover increase. This finding regarding the effectiveness of cover treatments compared to seeding and barrier treatments is also confirmed in the USA sites (Examples 2, 5, 6). However, these results may vary greatly due to factors such as installation quality, storm characteristics, and slopes. Dam treatments can be effective for lower-intensity rainfalls, both in the Mediterranean and the US, but require maintenance to ensure a stable performance over time. For cases where a fast recovery of high performance is needed, a combination of measures is the recommended strategy (e.g., mulching, barriers, seeding), along with the necessary installation and maintenance works.

4. Site Suitability and Effectiveness of Different Treatment Types

Although each treatment of the categories presented has case-specific factors and potentially different site suitability, we can draw a general conclusion regarding their effectiveness:

- Land treatments can generally reduce runoff and/or sediment yields during the first rainfall events. Still, their effectiveness depends on several factors, such as the application rates [7], the proper installation (e.g., log barrier installation is vital for the effectiveness of the treatment [50]), post-fire climatological conditions (e.g., rainfall amount and intensity [37]), slope length and steepness-terrain gradient [37], make/brand of tackifier [37], and the time (e.g., seeding does not provide instant protective effect, especially in the first year) [7].
- Channel treatments seem more efficient in gentle gradients and areas of low or moderate flows, as the risk of failure is lower. Moreover, channel treatment effectiveness is highly correlated with the adjacent areas' land treatments since these areas supply the channels with water and sediments [29]. However, specifically for check dams with finite storage capacity, their effectiveness is restricted due to their limited life expectancy (short-term sediment control solution) [51]. Moreover, channel treatment effectiveness is usually a function of the proper installation (e.g., log dams' installation is essential for the effectiveness of the treatment [50]), the appropriate positioning of the treatment (e.g., some channel treatments should be constructed in series), their maintenance (e.g., debris basin maintenance) [29], and the post-fire climatological conditions (e.g., rainfall amount and intensity affect the erosion, sediment transport, and deposition processes).
- Road and trail treatments may benefit road facilities and deliver less sediment into channels. However, similar to the channel treatment, the effectiveness of these treatments can be affected due to their poor installation and/or due to insufficient maintenance. On the other hand, limited data are documenting their effectiveness [52].

Overall, the effectiveness of all treatment types is subject to large uncertainties due to the difficulty in monitoring their actual effect and the multiple factors that can affect it. Even listing and documenting these factors is not easy, as it would be an attempt to generalize several site-specific cases. According to Robichaud et al. [37], these factors can be divided into not-fire-dependent and fire-dependent, as their combination determines the actual watershed response and, subsequently, the effectiveness of the post-fire treatments [53]. These factors are presented and further discussed in Table 2.

Table 2. An overview of some important factors affecting the effectiveness of post-fire treatments where all factors, except the "treatment implementation-installation", are based on the analysis of Robichaud et al. [37] and references therein.

Factors	Description
1. Factors Unrelated to Fire:	
Rainfall characteristics, especially rainfall intensity	a. Intense, short-duration storms with high rainfall intensity and low rainfall volumes cause high stream peak flows and substantial erosion episodes after wildfires. b. An increase in runoff, erosion rates, and stream flows means potentially lower effectiveness of any treatment.
Topography	a. Erosion rates are generally higher in bigger slopes and hillslope lengths (flow path). b. Drainage patterns and topographies that enhance erosion and peak flow concentration are more challenging for post-fire treatments.
Land use and management	a. In addition to natural elements such as rainfall and topography, the extent of a watershed's reaction to a hydrological event is also influenced by manmade activities such as road construction, fuel reduction, and timber harvesting. b. The cumulative effect of these anthropogenic activities can lead to the rise of runoff severity and, by extension, erosion, and flooding, posing important challenges for any treatment.
Treatment implementation-installation and design matters	a. The effectiveness of many post-fire treatments depends on the accuracy of the installation, the selected design type, the post-installation maintenance, and the level of experience of the personnel used for the treatments [7,50,54]. b. With proper treatment implementation, we can avoid failures and improve functionality and effectiveness over the long term.
2. Fire-Dependent Factors:	
Burn severity (also referred to as "fire severity")	a. Burn severity can be seen as a measure of damage to ecosystem properties. It is usually expressed by the degree of soil heating and/or vegetation mortality or precisely the degree of overstory plant mortality. b. In general, higher burn severity is translated into larger and quicker watershed responses to rainfall, being thus more challenging for the post-fire treatments.
Soil burn severity	a. Soil burn severity expresses the fire effects of soil heating and the soil's organic material consumption. Thus, higher soil burn severity leads to soil property alteration, resulting in soil infiltration reduction and high soil erodibility. b. Both these effects increase surface runoff, higher peak flows, flow concentration, sediment transport, and erosion.
Amount of bare soil	a. A crucial factor for burn severity mapping, which is positively related to postfire erosion rates. b. Land cover treatments, such as natural or straw mulching, can reduce post-fire erosion.
Soil water repellency	a. Post-fire soil water repellency is associated with soil burn severity and reduced infiltration. b. Although its effects vary over space, time, and soil type, most relevant treatments aim to rewet the soil to minimize the soil water repellency and its negative consequences since it depends on soil moisture (it is reduced or absent following prolonged wet conditions).
Soil erodibility	a. The treatments' effectiveness is largely dependent on runoff, sediment transport, and soil erosion. Moreover, soil texture, structure, and organic matter content are important factors considering erosion resistance. b. Soil texture (namely its inorganic particles by size, such as sand, silt, and clay) is ordinarily unaffected by the fire. On the other hand, soil structure is affected by fire (namely, the arrangement of primary particles into aggregates). Therefore, soil structure can become disaggregated, making soil more erodible and reducing its infiltration capacity.
Time since the fire	a. This factor refers to the ecosystem's natural recovery (soil structure, vegetation, microclimate, etc.). For example, more significant and faster vegetation recovery means smaller instant surface runoff rates and reduced erosion rates. b. As discussed above, timely action with post-fire treatments can improve watersheds' overall response and avoid post-fire negative consequences.

The factors in Table 2 are the main and more generic ones but are not the only ones relevant to the effectiveness of the post-fire treatments (for example, roughness also changes after a fire, affecting water retention and flow [55]). Finally, we should keep in mind that all these factors are interrelated, resulting in more complex cause–effect relations in terms of watershed responses (damage, runoff, erosion, etc.), and more complex relations between the treatment's impact and effectiveness.

5. Discussion

The sections above clarify that many PPT techniques mainly aim to improve the watershed's hydrological response. Improving ground cover, vegetation, roughness, 'cutting' the runoff and increasing the lag-times, and blocking the sediment movement passages, among other types of works, are common approaches.

It is difficult to determine which is the most efficient, and perhaps there is no point in seeking a sole answer. The application examples reviewed show that all treatments efficiently improve the post-fire hydrological and soil conditions to different degrees, always depending on site-specific factors. The most important ones, according to the studies reviewed, are:

- The burn severity and extent, as it determines the damages caused;
- The climatic conditions, especially rainfall intensity, and duration, as it determines the risk;
- The slopes and roughness; or, in general, the terrain morphology (geomorphology) of the areas, as they affect the runoff and sediment movements, as well as the accessibility for applying the treatments reviewed;
- The proper application—installation of the works and their monitoring over time (e.g., annual time step) to ensure maximum efficiency;
- Other site-specific factors, including social and behavioral aspects, that define the response to human interventions and other criteria such as costs and rehabilitation efforts.

Thus, a combination of techniques will be the most efficient way (and also necessary) to adequately mitigate and protect from erosion and flooding risks. The effectiveness of any intervention also heavily relies on their fast application, if possible, before the first rainfall events, to avoid any negative consequences [56].

The majority of the examined land treatments can reduce post-fire erosion [29] and support natural recovery, while only the cover (treatment that covers the area) and barrier-based (treatment that works as a barrier) PPTs can reduce the post-fire surface runoff [7]. Channel treatments, especially durable structures, can also reduce post-fire surface runoff, while check-dam treatments are more effective regarding sediment trapping, velocity reduction, and peak flow reduction [29].

The limitations of this study arise due to the limited information available on the role of each PPT type in the response of burned watersheds, as well as the limited studies exploring their cost-effectiveness. Thus, we were not able to provide a systemic literature review, but only a narrative review, summarizing the available knowledge. Moreover, the existing information is so poor that it prevents us from having a more structured typology in Tables 1 and 2. However, if a first step is taken to improve the understanding and encourage research on this topic, we believe this paper provides holistic and up-to-date information about PPTs, and especially their effectiveness, an overlooked issue of increasing importance in the future. We hope that this work will set the basis for further research to address the current gaps.

6. Conclusions

Wildfires are ecological destructions, affecting multiple ecosystem services and processes. In such extreme cases, intervention to mitigate the consequences is mandatory and urgent. This paper summarized the most common PPTs, analyzed them and their effectiveness, and provided examples from the existing literature. The literature is poor in assessing the impact of PPTs, so very little is known about their effectiveness. We found that cover changes were more effective than barriers, as they provided an immediate ground-cover increase in both Mediterranean and USA sites. What is certain is that PTTs should be prioritized in burned areas, as they can deliver multiple co-benefits by reducing the negative consequences of post-fire conditions. It is important to raise awareness and communicate the importance of the timely application of a PPT and/or the combination of some PPTs, as necessary action in burned sites.

Future studies should further explore the overlooked research area for finding ways to optimize the PPTs' performance and the overall watersheds' recovery. The limited number of published works on the topic, and in different regions of the world, indicates that more studies should be encouraged. Research should be conducted further to investigate the effectiveness and suitability of the different PPTs, also considering their combination, to optimize their results.

Future research should focus on:

- Raising awareness and promoting action through such treatments rather than doing nothing.
- Carrying out more studies, extending the geographical scope beyond the USA, Spain, and Portugal [7] and exploring more diverse conditions, such as large-scale and other possible treatments (e.g., complex bioengineering works, nature-based solutions, etc.).
- Increased monitoring, and data reporting, to expand the (very poor) existing data for post-fire conditions and conditions after the application of PPTs.
- Hydraulic and sediment transport models, as well as water quality monitoring and modeling in burned areas, should explore different scenarios assessing the potential impact of different PPTs.
- Improve assessment of post-wildfire erosion impact on soils and runoff, carbon release, air pollution, and nutrient losses, and soil loss [57].
- Improve the modeling tools for impact assessment at the watershed level, considering finer resolutions and scales. These improvements are possible, especially considering the advances in modeling technologies, but detailed and integrated data are necessary.
- Integrate the wildfire events and the counter-measures into the overall assessments for land degradation. All assessments should include minimum background data, field reviews, and other information. Assessing and mapping soil burn severity is the important first step in any analysis, forming the basis for subsequent soil erosion, hydrology, and geomorphic hazard assessments [58].

The implementation and success of most of the above recommendations depend on policy and the broader environmental management approach followed, with emphasis on social governance and sufficient funding [59]. Policy-makers also need to become more familiar with PPTs, and this will be an easier task if they realize the damages after wildfires, as well as the potential of PPTs to alleviate several negative consequences. For such purposes, economic tools from the environmental economics and ecosystem services valuation fields, have been proved particularly useful, since the conversion of damages and ecosystem benefits in monetary terms have the ability to influence policies [60,61]. The inability of decision-makers to realize the magnitude and extent of the post-fire consequences is often the reason behind the inaction or poor action with respect to PPTs [62].

The recovery of a burned site is an interdisciplinary problem that deteriorates the physical environment, natural processes, ecosystem, and socio-economic systems. Thus, it is crucial to support and develop policies in favor of high levels of fire protection, prioritization of post-fire recovery, seeking the timely and efficient application of PPTs, as well as encourage further research to improve the understanding of the mechanisms behind PPTs efficiency and improve their performance. Such policies will be of major importance in the coming years of drier climates and scarcer environmental resources.

Author Contributions: Conceptualization, G.P., A.A. and F.M.; methodology, G.P. and A.A.; investigation, G.P. and A.A.; writing—original draft preparation, G.P. and A.A.; writing—review and editing, G.P., A.A. and F.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Editor and the three anonymous reviewers for their constructive and useful comments, which contributed to an improved paper presentation.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Analysis of Post-Fire Protection Treatments (PPTs), their suggested suitable areas for application, and their effectiveness.

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Aerial Hydromulch	Land treatment	Cover-based	Aerial hydromulch is the hydromulch of an area using aerial means. Thus, soil stabilizers and fiber mulches that form a matrix on the surface when mixed with water are used to help erosion reduction and plant growth.	Areas: (1) without ground access, (2) with burn severity high-moderate, (3) with high erodibility factor (K) and soils with decreased infiltration capability, (4) sporadically forested with 25–50% slopes, (5) where adjacent or lowland areas from the treatment sites have high risk values, (6) that includes domestic water supply subwatersheds, (7) prone to vigorous winds.	It can decrease sediment yields in the short term, but its long-term effectiveness is unknown. It works better on short slopes than longer slopes because longer slopes are more susceptible to concentrated flows. Its effectiveness is influenced by various factors, including the application rates, slope length and steepness, and the type of tackifier used.
Ground Hydromulch	Land treatment	Cover-based	Hydromulch using ground means. Description of the hydromulch is presented in the Aerial Hydromulch description.	Areas: (1) with high-burn-severity soils, (2) with high erodible soils, (3) with steep slopes of 25–50% without cover, (4) with no litter or regrowth in the first year, (5) where adjacent or lowland areas from the treatment sites have high risk values, (6) with slopes lower from 25% with rocky surface and deeper than 20 cm soils.	Same as above. Hydromulch is wind resistant, but its effectiveness depends on multiple factors, as mentioned before.
Straw Mulch	Land treatment	Cover-based	Straw mulching using weed-free straw is implemented to cover vulnerable areas to erosion. The straw dispersion can be achieved using aerial (large areas) or ground means (small areas). Straw is dispersed until a specific percent of ground cover is achieved or applied in contour strips. Straw mulching is a well-known treatment because it can efficiently and rapidly treat large areas before rainfall events.	Areas: (1) with high-moderate burn severity, (2) with up to 65% slopes, (3) with no vigorous winds, (3) that are compatible for seeding, (4) with rare or sensitive plants should be dodged, (5) where high-moderate severity impacted the upper watershed, (6) where the surface roughness can hold mulch or located limbed trees.	Straw mulch is higly effective in reducing surface erosion with an application rate exceeding 60% of ground cover and may reduce runoff. High winds can reduce its effectiveness. A combination of mulching and seeding is more effective in germination but not necessarily in surface cover. Wood-based mulches are equally or more effective than straw mulch in reducing post-fire erosion.
Slash Spreading	Land treatment	Cover-based	Areas with high-moderate burn severity can be covered with slash spreading. Hillslope erosion can be decreased by covering the ground with slash spreading. Slash spreading can be generated using onsite materials involving felling, lopping, and scattering of sub-merchantable trees and brushes.	Areas: (1) with high-moderate burn severity, (2) that are burned but still exist onsite with available slash material, (3) that have high erodible-hazard rating soils.	The scattering of slash created by a chainsaw is generally not effective due to slow labor production rates and the large amount of material needed for soil cover. However, using mechanized equipment such as a hydro ax that masticates material is considered moderately effective.

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Erosion Control Mats	Land treatment	Cover-based	Until vegetation is established, soil stability can be achieved using rolled erosion control products (RECPs) or erosion control mats. Synthetic or organic materials are used for RECP construction and can be permanent or temporary. Organic and biodegradable RECPs are produced using several materials such as wood excelsior, coconut, or straw. Materials can be found with netting or netless with variable duration from months to years. Erosion by raindrops, as well as the overland flow absorption, can be treated using erosion control mats. Moreover, RECPs can help revegetation by conserving moisture and decreasing soil temperature. Erosion control mats are categorized as site-specific treatments.	Areas: (1) with effective soil cover loss and high burn severity, (2) with high risk values and small area size, (3) with a persistent hydrophobic layer, (4) that have highly erodible hazard rating soils, (5) where the threat by overland runoff is high.	Erosion Control Mats are costly solutions. There is limited information about their effectiveness, but they are reported to be effective when correctly installed.
Log Erosion Barriers	Land treatment	Barriers	Timbered areas with high-moderate burn severity hillslopes and fire-affected hillslope erosion rates can be treated using Log Erosion Barriers (LEBs). Logs are installed parallel to the contour lines within shallow trenches. The LEBs aim to slow runoff, trap sediment when arranged in a bricklayer pattern on hillslopes, and lead to localized ponding. The potential sediment volume that can be trapped depends on the proper installation of the logs, the length and size of the logs, and the slope of the terrain.	Areas: (1) with high-moderate burn severity hillslopes, (2) with 25–60% slopes, (3) with water repellent soils, (4) that have highly erodible hazard rating soils, (5) with high risk values at a watershed scale.	Log erosion barriers have limited effectiveness in high-intensity rain events but can reduce runoff, peak flows, and sediment yields during low-intensity events [30]. Sediment storage decreases with each rain event but proper implementation can still achieve effective sediment storage and create microsites, which depends on slope, tree size and length, frequency, and use of berm traps. On the other hand, barrier construction remains a typical hillslope treatment that could be useful for the runoff velocity reduction and have better effectiveness when combined with other treatments [7].

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Fiber Rolls or Wattles	Land treatment	Barriers	Fiber rolls or wattles are products made from coconut fiber, rice straw, or other fibers that are rolled into tubes or cylinders for use in erosion prevention and soil stabilization. The rolls are placed along the edge, in areas where the soil is prone to erosion, in areas with high burn severity, and where LEBs are impractical. Reduction of erosion using fiber rolls can be achieved due to the reduction of overland flow velocity and the slope length shortening. The fiber rolls can work as sediment traps, stabilize the soil, and help vegetation recovery.	Areas: (1) with high-moderate burn severity, (2) with 20–40% slopes, (3) with slopes less than 25 % surface rock, (4) with soils not less than 20 cm deep.	Similar to the previous one, these barriers may reduce runoff and sediment yields for low-intensity storms only. Wattles are reported to reduce total runoff and peak flow rates [30,37].
Silt Fences	Land treatment	Barriers	They are typically constructed with a series of metal or plastic posts driven into the ground and connected by a length of geotextile fabric. Silt fences are used as sediment traps and installed in high-risk areas where LEBs and Fiber Rolls may not be effective. Finally, silt fences are an effective tool for monitoring sediment movement during effectiveness monitoring.	Areas: (1) with high risk values, (2) where maintenance and inspection are accessible, (3) of specific interest such as heritage sites.	Silt fences have notably high effectiveness when properly installed and maintained. This requires them to be stably anchored into the soil, allowing water to pass through slowly while trapping sediment. Their maintenance requires significant effort and attention. Robichaud and Brown [63] measured their trap efficiency at over 90%.
Soil Scarification, Plouching	Land treatment	Seeding	Highly erodible areas with high burn severity can be treated using soil scarification. Soil scarification is used to improve the water infiltration of the burned soils, improve the vegetation recovery rate, and prepare the soil for seeding. Soil scarification breaks up the surface soil, exposes bare mineral soil to the elements, and reduces the risk of runoff, water infiltration, and soil erosion.	Areas: (1) with high-moderate burn severity, (2) highly erodible slopes, (3) with slopes <20% (mechanical equipment), (4) with slopes 20–40% (hand tools),	While there is limited available information, this treatment is not efficient in reducing sediment yield, as compared to no treatment [31].

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Seeding	Land treatment	Seeding	Spreading of seeds using aerial (large treatment areas) and/or ground means (small treatment areas). Hillslope erosion and wind erosion can be treated using seeding (vegetation cover). Moreover, seeding can be used in areas vulnerable to spreading invasive and noxious plants.	Areas: (1) with high burn severity, (2) with high risk value, (3) with high erodible soils, (4) with slopes >60%, (5) that are vulnerable to invasive and noxious plants spreading.	Seeding (e.g., <60% surface cover) is not very effective in the first year after a fire and is neutral in the following seasons. Combining seeding with mulching may increase the potential for germination. Sterile annual and cereal grain seeds can reduce soil erosion but may introduce invasive and noxious species. Despite the ongoing debate about seeding effectiveness, it still remains a common measure followed for wildfire treatment [32]. Seeding often proved ineffective concerning soil erosion and some studies showed a trend of soil stabilization for unseeded and seeded sites after five (5) years [32]. Further investigation on the long-term effects of seeding should be conducted [32].
Invasive Plants	Land treatment	Other works	Noxious and invasive weeds are treated as not desired species that can disturb the ecosystem. The treatment of these species involves hand, mechanical, chemical, and biological or prevention-seeding applications	Areas: (1) with weed species, (2) that invasive weeds or noxious entered.	Invasive plants seriously threaten the ecosystems' stability and response, as they can eliminate other plants and their diversity. The effectiveness of removing invasive plants in preventing runoff and erosion has not been reported.
Polyacrylamides (PAM) and Other Polymers	Land treatment	Chemical treatments	Application of chemicals and fertilizers to speed up cover and vegetation growth. Only two examples are reported, highlighting the importance of wetting the PAM after application.	There is not adequate information to generalize. Areas with very mild rainfall events are preferred, as they quickly boost vegetation development.	In one case reported, PAM did not affect runoff but reduced erosion by 35–57% compared to the untreated plots [33]. The other example shows that PAM did not affect runoff or erosion [34].

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Check dams	Channel Treatment	Barriers	Check dams are used to trap and store the sediments, to reduce the water velocity and the peak flows. The construction materials can be logs, straw wattles, rock, etc., depending on the material availability.	Areas: (1) with smooth slopes where sediment storage can be achieved, (2) with high burn severity, (3) with high erodible soils, (4) with <20 % ground cover, (5) with high risk value, (6) <20,234 m^2 and catchments with small drainage areas.	Check dams are more effective when placed in gentle gradients, high in the watershed and used in series. To be effective, in-channel treatments must be used together with adjacent hillslope treatments [7]. On the other hand, the research of Badia et al. [45] showed that the performance of log dams was about 90% for soil erosion and roughly 52% for runoff. Generally, check dams have short-term effectiveness and can retain sediment yield behind the dams [35]. Finally, recent research on check dams that consist of an embankment and spillway or a single embankment showed that they can efficiently reduce the peak discharge, and the flood volume, as well as increase the runoff concentration time [64].
In-Channel Tree Felling	Channel Treatment	Barriers	Debris and sediments can be trapped within a channel using tree felling. Moreover, tree felling can work as a valuable habitat for fishes and other life forms and provide channel stability.	Areas: (1) with high burn severity (consumed woody material sites), (2) high risk value (road crossing, sensitive aquatic species), (3) prone to high sediment load and unstable bedload, (4) where energy dissipation is essential within the channel	Same as in the previous case, the main drivers of the effectiveness of these barriers are the slope and the magnitude of the storm.
Grade Stabilizers	Channel Treatment	Barriers	Channel downcutting and incising can be prevented using grade stabilizers. The main construction materials are logs, rocks, or plant materials. Grade stabilizers are also used for the reduction of channel scouring.	Areas: (1) with channels with stability issues, (2) with high burn severity, (3) with stream slope <6%, (4) with intermittent streams that have moderate to low flows, (5) where debris flow and soil cover loss exist, (6) that exist persistent hydrophobic conditions, (7) where the downstream uses are very beneficial.	The effectiveness of grade stabilizers is uncertain due to the lack of quantitative data, but they may work well for low to moderate-flow areas. They are recommended to be implemented in gentle gradients, high in the watershed, and placed in series. However, grade stabilizers may fail during large storms, and in-channel treatments without adjacent hillslope treatments are ineffective.

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Stream Channel Armoring	Channel Treatment	Barriers	Stream Channel Armoring is the reinforcement of the streambank using a protective covering such as riprap, gabions, boulders placement, etc. Thus, such protection covering can reduce bank erosion and cutting because of the high peak flows observed after a wildfire event.	Areas: (1) with streambanks vulnerable to erosion, (2) with high risk values	The effectiveness of streambank armoring has not been quantitatively monitored. This treatment is more likely to work better in gentle gradients, high in the watershed, and placed in series. However, there may be problems such as complete structure failure from large storms. It is also ineffective as an in-channel treatment without adjacent hillslope treatments.
Channel Deflectors	Channel Treatment	Barriers	Channel deflectors are used for protecting infrastructure or a structure because of the high streamflows observed after a wildfire event. Such protection treatment is composed of structures such as rock barbs, j-hooks, and double- or single-wing deflectors. Therefore, channel deflectors divert the flow and velocity from non-stable banks and areas with high risk value and protect structures (e.g., hydraulic works, transportation infrastructures) from high streamflow and/or flooding.	Areas: (1) where roads are located parallel to the stream, (2) where facilities or structures are vulnerable to flooding or streambank erosion	Similar to the previous case, there is limited information for this treatment. It is more effective in gentle gradients and mild storms.
Debris Basins	Channel Treatment	Barriers	Debris basins are emergency structures designed for the storage of important amounts of sediments and runoff. These structures are used where the probability of human life threats and property is high. On the other hand, the construction cost and maintenance are high, while the construction time is demanding since it is needed timeframes for engineered design and permit approvals. Debris basins have variable sizes and types and can be installed within the channel or off-channel. Their design, construction and operation, and reclamation needs are influenced by the selected type.	Areas: (1) with burn severity high-moderate, (2) that were prone to landslides and debris flow even before wildfire event, (3) of specific interest with high-value resources, (4) that have locations where there is enough space to storage important amounts of sediments, (5) where construction, maintenance, and inspection are accessible.	Debris basins are expensive treatments. Thus, they are the last resort option. No quantitative information is available on their effectiveness, and they require long-term maintenance following runoff events.

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Outsloping	Road and Trail Treatment	Other works	Outsloping is used in areas with high-moderate burn severity where runoff direction and storage can provide risk. Outsloping is when the road template is altered using machinery such as an excavator, dozer, and grader to reduce erosion and disperse the water. Usually is used on flat roads to disperse the surface flow to prevent runoff concentration on the road surface that can cause different types of erosion (e.g., rill, gully). Other road treatments are usually combined with outsloping such as armored crossing and rolling dips.	Areas: (1) prone to flow concentration, (2) with high-moderate burn severity, (3) with road slopes >10%, (4) that can be influenced and connected with adjacent burned areas.	No quantitative data exist for the effectiveness of outsloping roads, but informal observations suggest that they can provide both immediate and long-term benefits such as reduced sediment delivery to stream channels and less road maintenance. However, outsloping roads with unvegetated soils in highly erodible areas can increase erosion. Outsloping is typically used in conjunction with other road treatments such as rolling dips and armored crossings to manage water.
Rolling Dips	Road and Trail Treatment	Other works	Roadway dips alter the road drainage allowing surface flows to frequently scatter across the road. Dips can be used on sloped roads (removing the water from the inside of the road and allowing it to flow across the road), and on an outsloped road, where frequent rolling dips change the grade of dispersed flows.	Areas: (1) Important road infrastructure to maintain water flow control, (2) roads with a continuous grade and infrequent drainage structures, (3) culverts that have diversion potential, (4) roads where frequencies between inspection and maintenance May be limited after the fire, (5) roads with grades less than 12%, and (6) roads where outsloping is not feasible.	Rolling dips and outsloping are common treatments. There are no monitoring data on their effectiveness. They can be easily constructed but often are too short in length, or too shallow to contain the expected flows.
Overflow Structures	Road and Trail Treatment	Other works	Overflow structures (armored rolling dip, overside drain, or imbricated/overlapped rock-level spreader) are used on roads to control runoff and protect the road fill. They are placed in defined channels, or in areas between them, where increased storm runoff is predicted due to limited infiltration. The structure used depends on the road characteristics and conditions.	Areas: (1) Roads located below high and moderate burn severity areas, (2) road segments that have a long continuous grade and infrequent drainage, (3) sloped roads.	Armored rolling dips are effective and low-cost treatments when properly designed and implemented, but erosion problems can occur if they are too short or if insufficient riprap is used on the fill slope. Overside drains may fail if not designed, installed, and maintained properly. Imbricated rock-level spreaders were found to be effective in reducing erosion if they discharge directly onto a vegetated or wooded zone, according to initial qualitative monitoring data.

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Low-Water Stream Crossings (LWSC)	Road and Trail Treatment	Barriers	LWSCs protect transportation infrastructure, control water flows, and reduce water quality threats, by accommodating aquatic passages. They act as culverts under extreme watershed response conditions. The most common LWSC types are: Natural fords, Vented fords with pipes, and Low-water bridges.	Areas: (1) Roads crossing ephemeral or seasonally flowing channels, (2) where there is risk of interrupted traffic due to flooding, (3) when fisheries and water quality requirements allow vehicles to enter the stream, (4) when daily flow is less than 6 inches deep, (5) when expensive pipe sizes or pipes that do not fit the roadway cross section are required, (6) when culverts are at risk of plugging, (7) road crossings where high sediment delivery is expected.	Ford crossings effectively control water loss at road/stream crossings but must be properly designed and implemented to avoid damage to infrastructure and reduced water quality. Flexible structures are adaptable and not prone to undercutting, while boulder or riprap structures should be long enough to avoid being outflanked by high flows. Jersey barriers are not flexible and, therefore, less effective as an end wall material.
Culvert Modification	Road and Trail Treatment	Other works	Replacing or upgrading damaged culverts in a compatible way with road and trail management plans, forest plans, and guidelines for culvert sizing. The cost of upgrading should be less than the cost to repair damages after they occur. The culvert upgrading design and implementation should consider hydraulic capacity and requirements for aquatic species passage. The treatment must be quickly designed and implemented to maintain access and protect aquatic resources.	Areas: (1) High-burn-severity watersheds, (2) drainages with undersized culverts, (3) where road access is required.	There are only informal qualitative clues about the effectiveness of this treatment. It performs well when new culverts are installed before the first rain, but poorly when the upgrade is delayed or when culverts are still insufficient to manage runoff events.
Debris Rack and Deflectors	Road and Trail Treatment	Barriers	These are barriers that prevent large debris from passing through a culvert. They are designed for small and medium debris and must have enough storage area to retain debris expected in one storm. Debris racks can be made from rail, steel, wood, or chainlink fence material. Debris deflectors are V-shaped structures that divert medium and large debris and large rocks from the culvert inlet to a storage area where debris is removed after the flood subsides. Deflectors are suitable for high-velocity flows and heavy logs, stumps, or large boulders.	Areas/Cases: (1) Drainages at risk of plugging with debris, (2) culverts that can accommodate the storm runoff design capacity but may have increased bedload and debris, (3) movement of both bedload and debris, (4) identification of crossings where stream diversion is possible, (5) downstream infrastructure, public safety, or other resources are at risk.	Debris structures lack quantitative effectiveness data but may work if properly implemented and maintained according to anecdotal information. However, if the design structure is too small for the stormflows and associated debris, problems can occur.

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Riser Pipes	Road and Trail Treatment	Other works	These low-cost sediment storage systems prevent culverts from plugging with sediment and debris. They allow the accumulation of sediment and ash in the basin, which can be removed later, reducing downstream water quality impacts. Riser pipes reduce peak flows by storing water and sediment, providing sediment storage upstream of a crossing that would otherwise plug. Each riser is designed for a specific crossing and is quickly implemented.	Areas: (1) limited access at road crossings, (2) drainages with high burn severity and erosion predictions indicate a high risk of sediment delivery, (3) channels (confined) that have high bedload transport, (4) culverts that range from 18 to 48 inches, (5) paved roads, (6) channels that have high bedload transport capabilities, (7) seasonal channels.	There is no formal effectiveness monitoring data for risers. However, reports indicate that they perform well when maintained, but problems can occur if they are not routinely checked and debris is not removed from the basin. Risers are inexpensive, easy to install, and can be quickly disassembled when no longer needed.
Catchment-Basin Cleanout	Road and Trail Treatment	Other works	Catchment-basin cleanout removes sediment and debris from stream channels, culverts, and catchment basins to prevent blockages and flash floods. The frequency of cleanouts depends on the size of the basin and sediment sources.	Areas: (1) Road crossings where existing sediment reduces the culvert capacity, (2) streams where fish requirements are not a concern, (3) areas in high risk, (4) Locations where clearing can be done prior to the first damaging rain.	Almost no evidence is available for this case. Anecdotal information suggests that the treatment is effective.
Storm Inspection and Response	Road and Trail Treatment	Other works	Storm inspection and response aims to maintain the functionality of culvert and drainage structures by cleaning sediment and debris from the inlet during storm events. It ensures road access throughout the designated storm season and should meet safety considerations.	Areas: (1) Road crossings where loss of control of water or exceedance is identified, (2) Road access is necessary throughout the storm season, (3) road crossings where high sediment and debris is anticipated, (4) roads susceptible to landslides, (5) roads with all-season surfacing (aggregate or asphalt).	No formal data are available to evaluate the effectiveness of storm inspection and response. Informal observations suggest that timely clearing and cleaning of road crossings can be cost-effective in preventing road problems. However, maintaining a dedicated inspection team can be challenging, and inadequate coverage may result from excessive areas to patrol.
Trail Stabilization	Road and Trail Treatment	Barriers	Trail stabilization includes methods such as rolling dips, rubber belt water bars, rock water bars, and rock spillways used on trails lacking adequate drainage features for anticipated increased runoff. These methods aim to reduce trail erosion or damage and provide drainage and stability to reduce trail damage or downstream values at risk.	Areas -Trails: (1) within or below high-burn-severity areas, (2) with sustained grade through burned areas that lack adequate drainage, (3) segments that have the potential to deliver sediment to streams, (4) where previous drainage structures were damaged by the fire, (5) stream crossings with diversion potential.	No quantitative data available.

Table A1. *Cont.*

Work	Type of Treatment	Type of Works	Description	Suggested Suitable Sites	Specific Factors Regarding Appropriateness/Effectiveness
Road Decommissioning	Road and Trail Treatment	Other works	Road decommissioning involves restoring the original hillslope conditions, recontouring the road fill, restoring drainage through the road prism, and reducing hillslope erosion. Subsoiling with an excavator and/or dozer with rippers improves infiltration and breaks through compacted soil layers. The process also restores hillslope hydrology, reduces erosion of sidecast material, and improves drainage.	Areas: (1) with high burn severity and high soil-erosion potential, (2) destabilized roads by the fire through vegetation loss, (3) loss of stabilizing vegetation to hold soil and prevent erosion, (4) vegetative treatments are unlikely to be effective, (5) hillslope with multiple unclassified roads (jammer roads).	No quantitative data available. Observations from visual inspection reported that this treatment can efficiently improve infiltration and reduce erosion by restoring the slope.

References

1. Bailey, R.W.; Copeland, O.L. *Vegetation and Engineering Structures in Flood and Erosion Control*; U.S. Forest Service, Intermountain Forest and Range Experiment Station: Ogden, UT, USA, 1961.
2. DeBano, L.F.; Neary, D.G.; Ffolliott, P.F. *Fire Effects on Ecosystems*, 1st ed.; John Wiley & Sons: Hoboken, NJ, USA, 1998.
3. Moody, J.A.; Martin, D.A. Post-Fire, Rainfall Intensity-Peak Discharge Relations for Three Mountainous Watersheds in the Western USA. *Hydrol. Process* **2001**, *15*, 2981–2993. [CrossRef]
4. Blake, D.; Nyman, P.; Nice, H.; D'Souza, F.M.L.; Kavazos, C.R.J.; Horwitz, P. Assessment of Post-Wildfire Erosion Risk and Effects on Water Quality in South-Western Australia. *Int. J. Wildland Fire* **2020**, *29*, 240. [CrossRef]
5. Robichaud, P.R.; Beyers, J.L.; Neary, D.G. *Evaluating the Effectiveness of Postfire Rehabilitation Treatments*; US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2000.
6. Santi, P.M.; deWolfe, V.G.; Higgins, J.D.; Cannon, S.H.; Gartner, J.E. Sources of Debris Flow Material in Burned Areas. *Geomorphology* **2008**, *96*, 310–321. [CrossRef]
7. Girona-García, A.; Vieira, D.C.S.; Silva, J.; Fernández, C.; Robichaud, P.R.; Keizer, J.J. Effectiveness of Post-Fire Soil Erosion Mitigation Treatments: A Systematic Review and Meta-Analysis. *Earth Sci. Rev.* **2021**, *217*, 103611. [CrossRef]
8. Nasirzadehdizaji, R.; Akyuz, D.E. Predicting the Potential Impact of Forest Fires on Runoff and Sediment Loads Using a Distributed Hydrological Modeling Approach. *Ecol. Modell.* **2022**, *468*, 109959. [CrossRef]
9. Ebel, B.A.; Wagenbrenner, J.W.; Kinoshita, A.M.; Bladon, K.D. Hydrologic Recovery after Wildfire: A Framework of Approaches, Metrics, Criteria, Trajectories, and Timescales. *J. Hydrol. Hydromech.* **2022**, *70*, 388–400. [CrossRef]
10. Cheung, D.J.; Giardino, J.R. Debris Flow Occurrence under Changing Climate and Wildfire Regimes: A Southern California Perspective. *Geomorphology* **2023**, *422*, 108538. [CrossRef]
11. Sosa-Pérez, G.; MacDonald, L. Wildfire Effects on Road Surface Erosion, Deposition, and Road–Stream Connectivity. *Earth Surf. Process. Landf.* **2017**, *42*, 735–748. [CrossRef]
12. Kemter, M.; Fischer, M.; Luna, L.V.; Schönfeldt, E.; Vogel, J.; Banerjee, A.; Korup, O.; Thonicke, K. Cascading Hazards in the Aftermath of Australia's 2019/2020 Black Summer Wildfires. *Earths Future* **2021**, *9*, e2020EF001884. [CrossRef]
13. Nyman, P.; Yeates, P.; Langhans, C.; Schärer, C.; Noske, P.J.; Lane, P.N.J.; Haydon, S.; Sheridan, G.J. A Novel Approach for Determining Risk of Water Supply Disruptions Due to Post-Wildfire Debris Flows. In Proceedings of the 7th International Conference on Debris-Flow Hazards Mitigation, Golden, CO, USA, 10–13 June 2019.
14. Roering, J.J.; Gerber, M. Fire and the Evolution of Steep, Soil-Mantled Landscapes. *Geology* **2005**, *33*, 349–352. [CrossRef]
15. Stavi, I. Wildfires in Grasslands and Shrublands: A Review of Impacts on Vegetation, Soil, Hydrology, and Geomorphology. *Water* **2019**, *11*, 1042. [CrossRef]
16. Langhans, C.; Nyman, P.; Noske, P.J.; Van der Sant, R.E.; Lane, P.N.J.; Sheridan, G.J. Post-Fire Hillslope Debris Flows: Evidence of a Distinct Erosion Process. *Geomorphology* **2017**, *295*, 55–75. [CrossRef]
17. Scott', D.F.; Van Wyk, D.B. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. *J. Hydrol.* **1990**, *121*, 239–256. [CrossRef]
18. Andreu, V.; Imeson, A.C.; Rubio, J.L. Temporal Changes in Soil Aggregates and Water Erosion after a Wildfire in a Mediterranean Pine Forest. *Catena* **2001**, *44*, 69–84. [CrossRef]
19. Fernández, C.; Vega, J.A.; Jiménez, E.; Fonturbel, T. Effectiveness of Three Post-Fire Treatments at Reducing Soil Erosion in Galicia (NW Spain). *Int. J. Wildland Fire* **2011**, *20*, 104–114. [CrossRef]
20. Swanson, F.J. Fire and Geomorphic Processes. In Proceedings of the Fire Regimes and Ecosystem Properties, Honolulu, HI, USA, 11 December 1981; Mooney, H., Bonnicksen, T.M., Christensen, N.L., Lotan, J.E., Reiners, W.A., Eds.; U.S. Department of Agriculture, Forest Service: Washington, DC, USA, 1981; pp. 410–420.
21. Folador, L.; Cislaghi, A.; Vacchiano, G.; Masseroni, D. Integrating Remote and In-Situ Data to Assess the Hydrological Response of a Post-Fire Watershed. *Hydrology* **2021**, *8*, 169. [CrossRef]
22. Rust, A.J.; Hogue, T.S.; Saxe, S.; McCray, J. Post-Fire Water-Quality Response in the Western United States. *Int. J. Wildland Fire* **2018**, *27*, 203–216. [CrossRef]
23. Cook, D.G.; Hayes, M.P. Post-Fire Species Composition and Abundance of a Lentic-Breeding Amphibian Assemblage: Case Study of Ledson Marsh. *Calif. Fish Wildl. J.* **2020**, *106*, 110–128. [CrossRef]
24. Danilov, D.A.; Anisimova, I.M.; Belyaeva, N.V.; Kazi, I.A. Post-Fire Restoration of Tree Species in Various Soil Conditions after Surface Fires Zone. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *574*, 012019. [CrossRef]
25. Zituni, R.; Wittenberg, L.; Malkinson, D. The Effects of Post-Fire Forest Management on Soil Erosion Rates 3 and 4 Years after a Wildfire, Demonstrated on the 2010 Mount Carmel Fire. *Int. J. Wildland Fire* **2019**, *28*, 377. [CrossRef]
26. Błońska, E.; Bednarz, B.; Kacprzyk, M.; Piaszczyk, W.; Lasota, J. Effect of Scots Pine Forest Management on Soil Properties and Carabid Beetle Occurrence under Post-Fire Environmental Conditions—A Case Study from Central Europe. *For. Ecosyst.* **2020**, *7*, 28. [CrossRef]
27. Jolly, W.M.; Cochrane, M.A.; Freeborn, P.H.; Holden, Z.A.; Brown, T.J.; Williamson, G.J.; Bowman, D.M.J.S. Climate-Induced Variations in Global Wildfire Danger from 1979 to 2013. *Nat. Commun.* **2015**, *6*, 7535. [CrossRef] [PubMed]
28. Time to Recover. *Nat. Sustain.* **2023**, *6*, 1027. [CrossRef]
29. Napper, C. *Burned Area Emergency Response Treatments (BAER) Catalog*; US Forest Service: Washington, DC, USA; San Dimas Technology and Development Center: San Dimas, CA, USA, 2006.

30. Robichaud, P.R.; Wagenbrenner, J.W.; Brown, R.E.; Wohlgemuth, P.M.; Beyers, J.L. Evaluating the Effectiveness of Contour-Felled Log Erosion Barriers as a Post-Fire Runoff and Erosion Mitigation Treatment in the Western United States. *Int. J. Wildland Fire* **2008**, *17*, 255–273. [CrossRef]
31. Robichaud, P.R.; Lewis, S.A.; Wagenbrenner, J.W.; Brown, R.E.; Pierson, F.B. Quantifying Long-Term Post-Fire Sediment Delivery and Erosion Mitigation Effectiveness. *Earth Surf. Process. Landf* **2020**, *45*, 771–782. [CrossRef]
32. Peppin, D.; Fulé, P.Z.; Sieg, C.H.; Beyers, J.L.; Hunter, M.E. Post-Wildfire Seeding in Forests of the Western United States: An Evidence-Based Review. *For. Ecol. Manag.* **2010**, *260*, 573–586. [CrossRef]
33. Inbar, A.; Ben-Hur, M.; Sternberg, M.; Lado, M. Using Polyacrylamide to Mitigate Post-Fire Soil Erosion. *Geoderma* **2015**, *239*, 107–114. [CrossRef]
34. Prats, S.A.; dos San tos Martins, M.A.; Malvar, M.C.; Ben-Hur, M.; Keizer, J.J. Polyacrylamide Application versus Forest Residue Mulching for Reducing Post-Fire Runoff and Soil Erosion. *Sci. Total Environ.* **2014**, *468–469*, 464–474. [CrossRef]
35. Boix-Fayos, C.; de Vente, J.; Martínez-Mena, M.; Barberá, G.G.; Castillo, V. The Impact of Land Use Change and Check-Dams on Catchment Sediment Yield. *Hydrol. Process* **2008**, *22*, 4922–4935. [CrossRef]
36. Girona-García, A.; Cretella, C.; Fernández, C.; Robichaud, P.R.; Vieira, D.C.S.; Keizer, J.J. How Much Does It Cost to Mitigate Soil Erosion after Wildfires? *J. Environ. Manag.* **2023**, *334*, 117478. [CrossRef]
37. Robichaud, P.R.; Ashmun, L.E.; Sims, B.D. *Post-Fire Treatment Effectiveness for Hillslope Stabilization*; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Washington, DC, USA, 2010.
38. Robichaud, P.R.; Lillybridge, T.R.; Wagenbrenner, J.W. Effects of Postfire Seeding and Fertilizing on Hillslope Erosion in North-Central Washington, USA. *Catena* **2006**, *67*, 56–67. [CrossRef]
39. Robichaud, P.R.; Lewis, S.A.; Wagenbrenner, J.W.; Ashmun, L.E.; Brown, R.E. Post-Fire Mulching for Runoff and Erosion Mitigation. Part I: Effectiveness at Reducing Hillslope Erosion Rates. *Catena* **2013**, *105*, 75–92. [CrossRef]
40. Lucas-Borja, M.E.; González-Romero, J.; Plaza-Álvarez, P.A.; Sagra, J.; Gómez, M.E.; Moya, D.; Cerdà, A.; de las Heras, J. The Impact of Straw Mulching and Salvage Logging on Post-Fire Runoff and Soil Erosion Generation under Mediterranean Climate Conditions. *Sci. Total Environ.* **2019**, *654*, 441–451. [CrossRef] [PubMed]
41. Fernández, C.; Vega, J.A.; Fontúrbel, T. Comparison of the Effectiveness of Needle Cast and Straw Helimulching for Reducing Soil Erosion after Wildfire in NW Spain. *J. Soils Sediments* **2020**, *20*, 535–541. [CrossRef]
42. Wagenbrenner, J.W.; MacDonald, L.H.; Rough, D. Effectiveness of Tree Post-Fire Rehabilitation Treatments in the Colorado Front Range. *Hydrol. Process* **2006**, *20*, 2989–3006. [CrossRef]
43. Lovreglio, R.; Giadrossich, F.; Scotti, R.; Murgia, I.; Tardío, G.; Mickovski, S.; García-Rodríguez, J.L. Observations on Different Post-Fire Bio-Engineering Interventions and Vegetation Response in a Pinus Canariensis C. Sm. Forest. *Ann. Silvic. Res.* **2020**, *45*, 83–91. [CrossRef]
44. Robichaud, P.R.; Storrar, K.A.; Wagenbrenner, J.W. Effectiveness of Straw Bale Check Dams at Reducing Post-Fire Sediment Yields from Steep Ephemeral Channels. *Sci. Total Environ.* **2019**, *676*, 721–731. [CrossRef]
45. Badía, D.; Sánchez, C.; Aznar, J.M.; Martí, C. Post-Fire Hillslope Log Debris Dams for Runoff and Erosion Mitigation in the Semiarid Ebro Basin. *Geoderma* **2015**, *237*, 298–307. [CrossRef]
46. Quiñonero-Rubio, J.M.; Nadeu, E.; Boix-Fayos, C.; de Vente, J. Evaluation of the Effectiveness of Forest Restoration and Check-Dams to Reduce Catchment Sediment Yield. *Land Degrad. Dev.* **2016**, *27*, 1018–1031. [CrossRef]
47. Shi, P.; Zhang, Y.; Ren, Z.; Yu, Y.; Li, P.; Gong, J. Land-Use Changes and Check Dams Reducing Runoff and Sediment Yield on the Loess Plateau of China. *Sci. Total Environ.* **2019**, *664*, 984–994. [CrossRef]
48. Groen, A.H.; Woods, S.W. Effectiveness of Aerial Seeding and Straw Mulch for Reducing Post-Wildfire Erosion, North-Western Montana, USA. *Int. J. Wildland Fire* **2008**, *17*, 559–571. [CrossRef]
49. Díaz-Raviña, M.; Martín, A.; Barreiro, A.; Lombao, A.; Iglesias, L.; Díaz-Fierros, F.; Carballas, T. Mulching and Seeding Treatments for Post-Fire Soil Stabilisation in NW Spain: Short-Term Effects and Effectiveness. *Geoderma* **2012**, *191*, 31–39. [CrossRef]
50. Kastridis, A.; Kamperidou, V. Evaluation of the Post-Fire Erosion and Flood Control Works in the Area of Cassandra (Chalkidiki, North Greece). *J. For. Res.* **2015**, *26*, 209–217. [CrossRef]
51. Margiorou, S.; Kastridis, A.; Sapountzis, M. Pre/Post-Fire Soil Erosion and Evaluation of Check-Dams Effectiveness in Mediterranean Suburban Catchments Based on Field Measurements and Modeling. *Land* **2022**, *11*, 1705. [CrossRef]
52. Foltz, R.B.; Robichaud, P.R.; Rhee, H. *A Synthesis of Postfire Road Treatments for BAER Teams: Methods, Treatment Effectiveness, and Decisionmaking Tools for Rehabilitation. Gen. Tech. Rep. MRS-GTR-228*; US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2009.
53. Reid, L.M. Understanding and Evaluating Cumulative Watershed Impacts. In *Cumulative Watershed Effects of Fuel Management in the Western United States. Gen. Tech. Rep. RMRS-GTR-231*; Elliot, W.J., Miller, I.S., Audin, L., Eds.; Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2010; pp. 277–298.
54. Maris, F.; Theofanous, N. The Main Problems Arousing during the Construction of Anti-Erosion Works after a Wildfire. The Case Study of Rhodes Island Forest Fire Occurred on July 2008. In *Scientific Annals of The Department of Forestry and Management of The Environment and Natural Resources—Democritus University of Thrace*; Maris, F., Ed.; Department of Forestry and Management of the Environment and Natural Resources—Democritus University of Thrace: Orestiada, Greece, 2012; Volume 3, ISBN 978-960-9698-01-6.

55. Canfield, H.E.; Goodrich, D.C.; Burns, I.S. Selection of Parameters Values to Model Post-Fire Runoff and Sediment Transport at the Watershed Scale in Southwestern Forests. In Proceedings of the Managing Watersheds for Human and Natural Impacts, Reston, VA, USA, 13 July 2005; American Society of Civil Engineers: Reston, VA, USA, 2015; pp. 1–12.
56. Ferreira, A.J.D.; Alegre, S.P.; Coelho, C.O.A.; Shakesby, R.A.; Páscoa, F.M.; Ferreira, C.S.S.; Keizer, J.J.; Ritsema, C. Strategies to Prevent Forest Fires and Techniques to Reverse Degradation Processes in Burned Areas. *Catena* **2015**, *128*, 224–237. [CrossRef]
57. Shakesby, R.A. Post-Wildfire Soil Erosion in the Mediterranean: Review and Future Research Directions. *Earth Sci. Rev.* **2011**, *105*, 71–100. [CrossRef]
58. Hope, G.; Jordan, P.; Winkler, R.; Giles, T.; Curran, M.; Soneff, K.; Chapman, B. *Post-Wildfire Natural Hazards Risk Analysis in British Columbia. Prov. B.C., Victoria, B.C. Land Manag. Handb. 69*; Crown Publications: Hong Kong, China, 2015.
59. Haque, M.K.; Azad, M.A.K.; Hossain, M.Y.; Ahmed, T.; Uddin, M.; Hossain, M.M. Wildfire in Australia during 2019–2020, Its Impact on Health, Biodiversity and Environment with Some Proposals for Risk Management: A Review. *J. Environ. Prot.* **2021**, *12*, 391–414. [CrossRef]
60. Silvestro, R.; Saulino, L.; Cavallo, C.; Allevato, E.; Pindozzi, S.; Cervelli, E.; Conti, P.; Mazzoleni, S.; Saracino, A. The Footprint of Wildfires on Mediterranean Forest Ecosystem Services in Vesuvius National Park. *Fire* **2021**, *4*, 95. [CrossRef]
61. Chamberlain, J.L.; Jones, K.W. Sociocultural Mapping of Ecosystem Service Values Can Inform Where to Mitigate Wildfire Risk: A Case Study from Colorado. *J. Environ. Plan. Manag.* **2023**, 1–19. [CrossRef]
62. Misal, H.; Varela, E.; Grillakis, M.; Rovithakis, A.; Voulgarakis, A.; Kountouris, Y. Assessing Public Preferences for a Wildfire Mitigation Policy in Crete, Greece. *SSRN Electron. J.* **2022**. [CrossRef]
63. Robichaud, P.R.; Brown, R.E. *Silt Fences: An Economical Technique for Measuring Hillslope Soil Erosion*; US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2002.
64. Yuan, S.; Li, Z.; Chen, L.; Li, P.; Zhang, Z.; Zhang, J.; Wang, A.; Yu, K. Effects of a Check Dam System on the Runoff Generation and Concentration Processes of a Catchment on the Loess Plateau. *Int. Soil Water Conserv. Res.* **2022**, *10*, 86–98. [CrossRef]