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Post-Fire flood hazards as a cascading sustainability crisis: Integrated modelling, protection measures, economic assessment, and a governance roadmap through the SDG lens

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Post-Fire flood hazards as a cascading sustainability crisis: Integrated modelling, protection measures, economic assessment, and a governance roadmap through the SDG lens.

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Abstract: Climate change is intensifying wildfires, which in turn amplify flood hazards through altered soil infiltration, increased runoff, and debris-laden flows, forming a cascading crisis threatening multiple Sustainable Development Goals (SDGs). This chapter presents an interdisciplinary framework that integrates remote-sensing burn-severity mapping and atmospheric model-based storm simulation linked to 2D hydraulic-hydrodynamic modelling to represent real post-fire flash floods. An overview of the most common post-fire erosion and flood-protection treatments (PEFTs) is then provided. A typical Mediterranean catchment is used as an application example where the models run, and the PEFTs are designed, spatially mapped, and tested within the hydraulic model, demonstrating that they can fully offset fire-induced flooding increases. Economic analysis reveals that protection costs are a fraction of direct flood damages, establishing a compelling case for proactive investment. Drawing on an established governance framework (the values–rules–knowledge approach), the chapter diagnoses institutional barriers to PEFTs implementation and proposes a stakeholder capacity-building roadmap, linking findings to SDGs 1,2,3,6,9,11,13, and 15.

Keywords: post-fire floods, cascading hazards, flood protection, cost-effectiveness, governance, Sustainable Development Goals.

1. Introduction: Post-fire floods as a cascading sustainability crisis

Crises in the Anthropocene are multifaceted and interconnected, primarily driven by human activity. Environmental challenges such as climate change, pollution, and biodiversity loss trigger social and economic risks including food and water insecurity, displacement, and widening inequality (Alamanos, 2024a; Koundouri et al., 2024a). Together, these create a global polycrisis in which the failure of one system can trigger cascading disruptions across others, threatening progress toward the Sustainable Development Goals (SDGs). The SDGs provide the most comprehensive framework currently available for addressing the root causes of these crises and for building more resilient societies (Koundouri et al., 2024b). Yet achieving the SDGs requires navigating interconnected crises that span environmental, social, and economic domains simultaneously.

Among the most vivid illustrations of cascading environmental crises is the wildfire-to-flood sequence. Wildfires have become an increasingly pressing challenge, with climate change exacerbating their extent and severity worldwide (Nature Sustainability, 2023; Duane et al., 2021; Wang et al., 2021). This escalating trend threatens ecosystems and human communities alike, with far-reaching effects on economies, infrastructure, and natural resources (Liu et al., 2022; Alamanos & Koundouri, 2022). The Mediterranean region, a climate-change hotspot, has been particularly vulnerable to increasingly severe fire and flood events over recent years, while such threats are anticipated to become more frequent and intense in the future (Cos et al., 2022; Alamanos, 2024b; Ruffault et al., 2020). In Greece specifically, the trend has been alarmingly clear, with devastating fires in the Attica region (2018), Evia island (2021), and Thrace (2023), each followed by flooding of the burnt areas.

Critically, wildfires do not merely destroy vegetation and property; they fundamentally alter the hydrological behaviour of affected catchments. By removing organic litter and vegetation cover, fires reduce infiltration capacity, increase surface runoff, and mobilise vast quantities of sediment and debris. Depending on the burn severity and the fire duration, post-fire areas may have less than 10% ground vegetation cover remaining, resulting in increased soil erodibility, reduced soil infiltration capacity, and altered runoff generation processes (DeBano et al., 1998; Stavi, 2019). Surface runoff can increase by over 70% after a fire, while erosion can increase by three orders of magnitude (Robichaud et al., 2005). When subsequent precipitation events occur, the combination of altered soil properties, increased runoff, and debris-laden flows produces flash floods of far greater magnitude and destructiveness than would have occurred under pre-fire conditions (Brogan et al., 2019; Kemter et al., 2021; Hasan et al., 2020). In reality, cases of areas being burnt and then flooded, even repeatedly, are common worldwide, highlighting systematic failures in managing this cascading hazard.

This cascading crisis intersects with multiple SDGs. Direct threats to human lives and health relate to SDG 3 (Good Health and Well-Being). The economic devastation of post-fire floods undermines SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth). Agricultural losses threaten SDG 2 (Zero Hunger). Contamination and destruction of water systems compromise SDG 6 (Clean Water and Sanitation). Destruction of infrastructure and settlements conflicts with SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities). At its core, this hazard chain is driven by climate change (SDG 13), while biodiversity loss and land degradation connect to SDG 14 (Life Below Water) and SDG 15 (Life on Land). The interdisciplinary nature of the problem and the need for cross-sector collaboration underpin SDG 17 (Partnerships for the Goals).

Despite its importance, the post-fire flood problem has been studied in a fragmented way. Some studies have analysed post-fire flood risk factors using multi-criteria approaches (Yilmaz et al., 2023), post-fire hazards considering infrastructure sedimentation (Jong-Levinger et al., 2022), or future land-use impacts on flooding (Alamanos, 2024c). Others have explored flood mapping of burnt sites through hydraulic modelling: Godara et al. (2023) applied a rain-on-grid technique to explore the response of a steep catchment after a wildfire; Theochari and Baltas (2022) performed a holistic hydrological approach to a fire event in Evia, Greece; and Mitsopoulos et al. (2022) explored hypothetical flood protection works. However, most studies use typical design storms rather than the actual storm that caused a real event, and, to our knowledge, no study has combined: (i) an integrated, interdisciplinary simulation framework for post-fire floods using real storm data; (ii) the design and testing of post-fire protection measures within the hydraulic model; (iii) an economic assessment comparing protection costs with flood damage costs; and (iv) a governance analysis diagnosing why these protection measures are not applied in practice. This chapter addresses that gap. It presents an integrated modelling-to-governance framework applied to a real post-fire flood event in a Mediterranean catchment (Kineta, central Greece), and connects the findings to the SDG framework and the broader discourse on sustainability crisis management. The chapter is structured as follows. Section 2 introduces the case study. Sections 3-6 present the technical and economic components (Part A): the integrated modelling framework, the post-fire erosion and flood-protection treatments (PEFTs), scenario analysis, and cost-benefit assessment. Sections 7-8 address the governance dimension (Part B): why protection measures fail to be implemented, and how stakeholder engagement and capacity building can bridge this gap. Section 9 discusses the SDG implications in detail, and Section 10 concludes with policy recommendations.

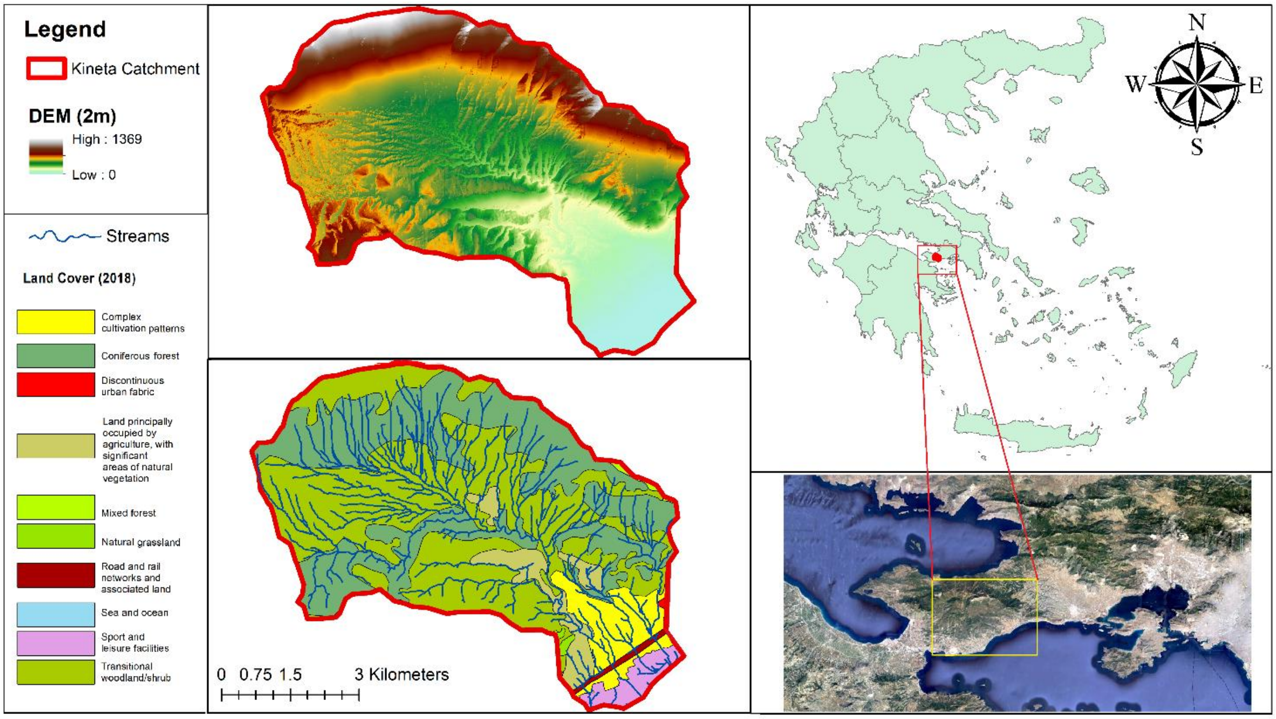
2. Case study: Post-fire flood in Kineta, central Greece

A Mediterranean catchment was selected as the application area: Kineta, in western Attica, central Greece. The Kineta catchment covers approximately 40 km2 and is located between the municipalities of Megara and Agioi Theodoroi. The climate is typical Mediterranean, with hot, dry summers and mild, wet winters. The main land uses are forests (pine forest in the north, which was the main burnt area), agricultural land (olive groves and cultivated fields), and the coastal town of Kineta in the south, which is the main settlement and the area most affected by the flood.

The Kineta area faces recurring risks from fires. In May 2017, a fire broke out in the Panorama settlement in Agioi Theodoroi (northwest of Kineta), burning approximately 600 hectares of forest and shrubland. The fire was attributed to strong winds bringing power lines into contact, causing sparks that ignited dry grass. Approximately 14 months later, in July 2018, a larger and more severe wildfire occurred on the eastern side of the Kineta catchment. This fire burned a significant part of the pine forest, and there were also debates regarding the possibility of arson. The July 2018 fire was part of the broader wildfire disaster that affected the wider Attica region that summer, including the catastrophic Mati fire that killed over 100 people.

The following year, in November 2019, an extreme storm event named Girionis by meteorologists took place during 24-26 November and caused a destructive flash flood. The subsequent visual inspection attributed the flood damage to the combined effects of the preceding wildfires and the storm, noting particularly the role of debris flows that blocked stream drainage routes. Damages included destruction of residential homes, commercial buildings, road infrastructure (including sections of the Athens-Corinth highway), agricultural land, and private vehicles. However, until the present work, there had been no comprehensive, data-driven assessment investigating the mechanisms involved, the relative contribution of the fire to the flood magnitude, or the potential role of protection measures. This sequence of events makes Kineta an exemplary case of the cascading sustainability crisis that this chapter addresses.

Among the key findings of the subsequent visual inspection was the critical role of debris flows in exacerbating the flood. After the wildfires, the lack of vegetation and the destabilised soil produced large quantities of sediment and woody debris that were mobilised by the storm runoff. This debris blocked critical drainage infrastructure, particularly the Pika stream above the Olympia highway bridge and the underground culverts of two smaller streams. With these drainage routes blocked, floodwaters that would normally have been channelled towards the sea instead spread across the residential area, inundating homes, commercial buildings, agricultural fields, and sections of the Athens-Corinth highway. The damages included destruction or severe damage to dozens of residential properties, several hotels (Kineta is a coastal resort area), hundreds of private vehicles, and significant road and coastal infrastructure.



[Figure 1] *Map of the Kineta study area showing the catchment, Digital Elevation Model (DEM), river network, and pre-fire land cover (2018). Source:* Alamanos et al., 2024b.

3. The integrated modelling framework

The proposed framework combines four modelling components in sequence: (i) Remote Sensing (RS) for burn severity mapping and flood-extent delineation; (ii) the atmospheric model WRF-ARW for storm reconstruction; (iii) the 2D hydraulic-hydrodynamic model HEC-RAS for flood simulation; and (iv) spatial design and incorporation of PEFTs into the hydraulic model. This integrated approach is novel in that it chains together disciplines (remote sensing, atmospheric science, hydraulic engineering, and spatial planning) to provide a comprehensive picture of the post-fire flood process, from cause to consequence to solution.

3.1 Assessing burn severity through Remote Sensing

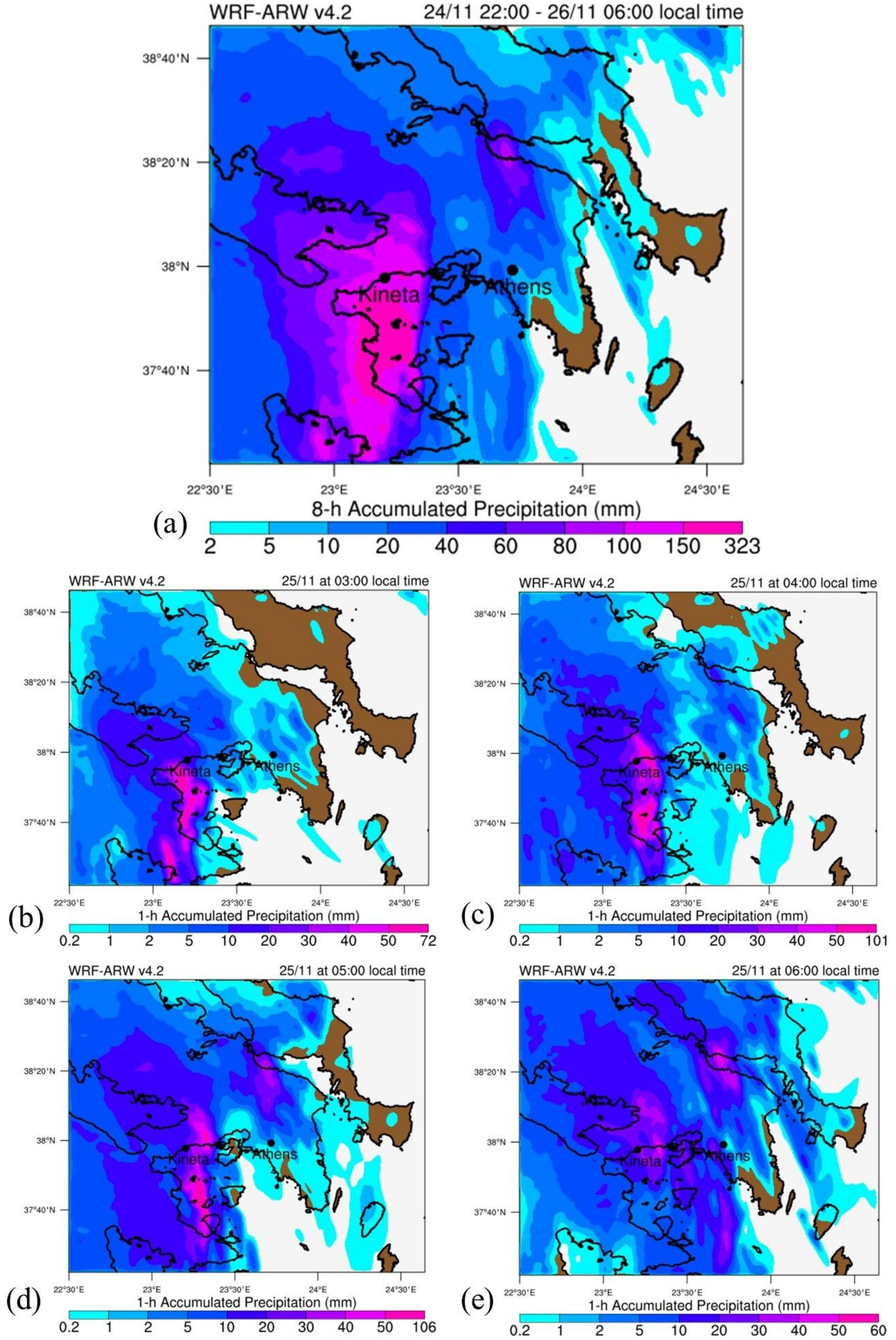
Remote sensing techniques are particularly useful for obtaining ready-to-use information about fire impacts that is not available through on-site observations alone. For the identification of the 2018 fire impacts, three Sentinel-2 satellite images (one pre-fire and two post-fire) were used. The study area was delineated using the shapefile of the Kineta catchment including adjacent watersheds. Burnt areas were mapped based on the Normalized Burn Ratio (NBR), which exploits the differences in reflectance between Near-Infrared (NIR, band B08) and Short-Wave Infrared (SWIR, band B12) bands. The Change in Normalized Burn Ratio (dNBR) was then calculated for two periods to highlight changes from the reference state: immediately post-fire (August 2018) and over a year later, before the flood (October 2019). A threshold value of +0.1 was applied to differentiate burnt from unburnt areas, and the resulting classification followed the USGS burn severity categories: unburned, low, low-moderate, moderate-high, and high severity.

The two-fold calculation of the dNBR revealed notable vegetation regrowth between August 2018 and October 2019, with the percentages of unburnt areas and those characterised by low or low-moderate burn severity increasing, while the proportion of higher burn severity classes decreased. This is an important finding because it demonstrates that by the time of the flood (November 2019), approximately 16 months after the fire, some natural recovery had occurred. The actual post-fire flood conditions were therefore somewhat less severe than they would have been immediately after the fire. These burn severity maps served as critical inputs for both the hydraulic model parameterisation (informing Manning roughness values) and the spatial design of PEFTs (targeting the most severely burned and vulnerable areas).

3.2 Storm reconstruction through the atmospheric model WRF-ARW

A key challenge in post-fire flood studies is the accurate representation of the actual storm that caused the flood. Most existing studies rely on typical design storms derived from Intensity-Duration-Frequency (IDF) curves, which cannot capture the spatiotemporal variability of real extreme events. This is a significant limitation, as the exact spatial distribution of rainfall across a catchment critically affects where and how severely flooding occurs. In this work, the Advanced Weather Research and Forecasting (WRF-ARW) model v4.2 (Skamarock et al., 2021) was used to simulate the meteorological conditions that produced the heavy precipitation event in Kineta on 24-25 November 2019.

The simulation was initialised on 24 November at 00:00 UTC (02:00 local time) to capture atmospheric conditions prior to the flash flood, and ran for 48 hours up to 26 November at 00:00 UTC. A nested domain configuration with increasing spatial resolution was employed, reaching 1 km at the innermost domain. On 24-25 November, Greece was affected by severe weather conditions as a deep barometric low from the west brought heavy precipitation across many areas. A cold front accompanying the barometric low was the main trigger for the extreme rainfall. The WRF-ARW model estimated 182.6 mm of 2-day rainfall at the study area, in very good agreement with the ground-based measurements. Most of the rain was simulated during an intense 8-hour period from 24 November at 22:00 local time to 25 November at 06:00 local time. This detailed, hourly, spatially distributed rainfall output was used directly as input to the hydraulic model, providing a far more realistic representation of the actual event than any design storm approach could achieve (Varlas et al., 2024).



[Figure 2] *Simulated accumulated precipitation from the WRF-ARW model for the 8-hour peak period (24 November 22:00 to 25 November 06:00 local time) and hourly precipitation time series. Source: Alamanos et al., 2024b.*

3.3 Delineation of flood-inundated areas through Remote Sensing

A Sentinel-2 image of 25 November 2019 (processing level 1C, acquisition time 09:23 UTC) was used to map the actual flood-inundated areas in Kineta. Five water indices (WIs) were calculated, and the most representative threshold values for each index were selected through histogram analysis. Among these, the RSWIR2 index was found to be the most representative for mapping the flood extent in the study area. The resulting flood polygon at the location of Kineta town was used as the validation reference for the hydraulic model simulations, providing an independent check on model performance (Alamanos et al., 2024b).

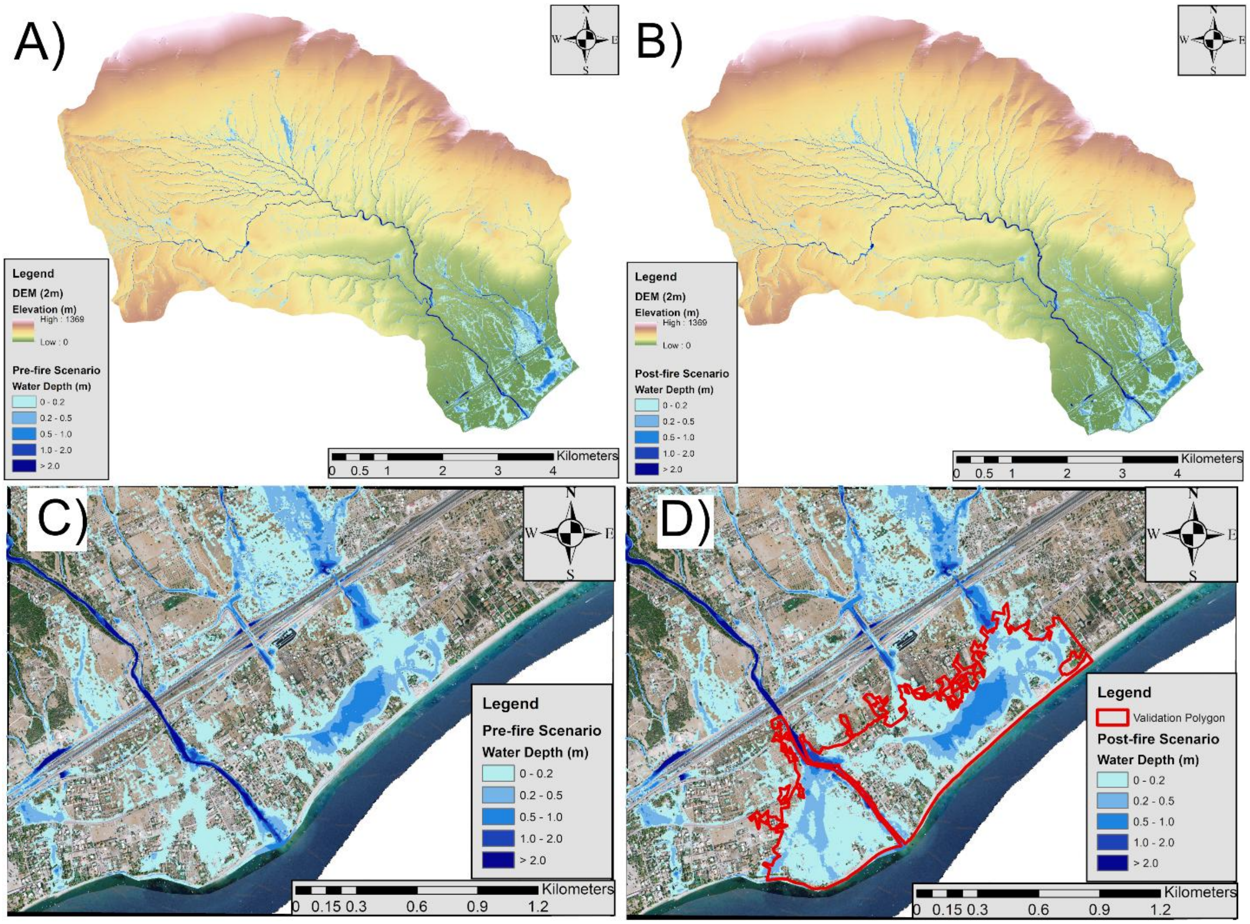
3.4 Flood simulation through hydraulic-hydrodynamic modelling

The 2D Hydrologic Engineering Center River Analysis System (HEC-RAS) (HEC, 2022), one of the most commonly used hydraulic-hydrodynamic models worldwide, was employed to simulate the flood inundation. Roughness is a key input in flood inundation modelling as it directly affects flow conditions. The most common approach for mapping Manning roughness coefficients (n) is the use of land-cover data. In this study, two sets of Manning values were used: pre-fire values based on the original land cover (e.g. n=0.10-0.15 for pine forest), and post-fire values reflecting the reduced vegetation and altered soil conditions (e.g. n=0.03-0.06 for burned areas). The 2D hydrodynamic calculations used a variable high-resolution mesh with small spacing especially around streams, buildings, and road infrastructure. The rain-on-grid technique was employed, applying the detailed spatiotemporal rainfall from the WRF-ARW simulation directly on each computational cell of the grid.

Crucially, the model also incorporated information from the visual inspection reports conducted after the fire and flood. After the fire, considerable amounts of rocks, mud, and wood mass blocked the drainage routes, most importantly the Pika stream above the Olympia highway (Athens-Corinth route) bridge and the underground culverts of two smaller streams. In the pre-fire scenario, the Pika stream was modelled as a typical open stream, and the other two streams had active orthogonal culverts (3x5 m) for water drainage to the sea. In the post-fire scenario, these were blocked using HEC-RAS terrain modification tools. It is worth noting how many houses had been built close to the streams, maximising exposure risks from any potential flood event.

Two initial scenarios were simulated. The pre-fire scenario applied the Girionis storm to the catchment with pre-fire Manning coefficients and unblocked drainage. The post-fire scenario (representing reality) applied the same storm with post-fire Manning coefficients and blocked streams. The total simulated flood inundation area for the post-fire case was 595,246 m^2, covering almost 24% of the town residential area. The pre-fire simulation yielded 446,077 m^2 (inside the town: 411,177 m^2 versus 338,371 m^2). This demonstrates that the flood extent would have been reduced by 25.1% had the pine forest not been burned and the streams not been blocked by debris.

For model validation, the simulated post-fire flood extent was compared to the RS-derived flood polygon. The Critical Success Index (CSI), which considers correctly simulated flooded area (hits), false alarms, and misses, was calculated at 0.65, a satisfactory value since CSIs above 0.5 are generally considered acceptable. An interesting finding was that the Pika stream was not the main source of the flood; the water came principally from two smaller streams in the eastern part of the catchment, highlighting the critical and often overlooked role of intermittent rivers and ephemeral streams (IRES) in Mediterranean flash flooding.



[Figure 3] *Flood extent and depth results for the pre-fire scenario (A, C) and the real post-fire conditions (B, D), with the validation polygon from the RS-derived flood extent.*

4. Post-fire erosion and flood-protection treatments (PEFTs)

Watersheds receiving precipitation close to their average levels under good hydrologic conditions yield relatively small amounts of sediment and maintain stable baseflow. However, this behaviour significantly changes after fires. Fires affect all watershed characteristics critical to fundamental hydrologic processes: soils, vegetation, and land cover (DeBano et al., 1998; Moody & Martin, 2001; Swanson, 1981). Depending on burn severity and duration, post-fire areas have dramatically reduced organic litter and vegetation cover, resulting in increased soil erodibility, reduced soil infiltration capacity through hydrophobic layers, and altered runoff generation. Surface runoff can increase by over 70%, while erosion rates can increase by three orders of magnitude (Robichaud et al., 2005). After a fire, precipitation events produce higher peak flows with faster hydrograph responses and greater volumes of sediment-laden runoff. The post-fire peak flows are additionally characterised by greater amounts of sediment, including large woody debris and rocks, travelling downstream and increasing flood destructiveness (Santi et al., 2008; Langhans et al., 2017).

4.1 Types, effectiveness, and costs of PEFTs

PEFTs include several interventions that are case-specific depending on site physical characteristics, and the literature on their performance is not rich or concise. We conducted a comprehensive literature review (Papaioannou et al., 2023) and categorised PEFTs into three main types.

Land treatments stabilise burned areas by providing soil cover (reducing erosion), trapping sediment, and reducing water repellency. Common examples include log erosion barriers (LEBs), contour-felled logs, mulching (straw, wood, or hydromulch), seeding, and erosion blankets. These treatments can generally reduce runoff and sediment yields during first rainfall events, but their effectiveness depends on application rates, proper installation, and local conditions including slope, soil type, and rainfall intensity.

Channel treatments focus on mitigating post-fire effects on water quality, controlling water velocity, trapping sediment, and preserving channel characteristics. Examples include check dams (wooden or rock), channel debris clearing, and straw wattles. Channel treatments tend to be more efficient in gentle gradients and areas of low or moderate flows, as the risk of failure is lower. Their effectiveness is highly correlated with the sediment particle size and the amount of debris flow.

Road and trail treatments reduce post-fire effects on transportation infrastructure and prevent roads from becoming conduits for concentrated runoff. Combined with land and channel treatments, they help protect accessibility and reduce sediment delivery to streams. However, similar to channel treatments, their effectiveness can be compromised by extreme debris flow events.

The costs of PEFTs can vary widely depending on factors such as the size and severity of the burn area, the steepness and slope of the terrain, the types of treatments applied, and the local availability of materials and labour. A recent assessment based on 63 sites in Spain found that PEFTs are generally cost-effective at reducing post-fire erosion (Girona-Garcia et al., 2021).

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 involved. Even listing an approximate range of effectiveness is challenging, since literature values can range from negligible effects to significant reductions depending on specific conditions. The main factors affecting effectiveness include: burn severity and extent, climatic conditions (especially rainfall intensity and duration), terrain morphology, proper installation and monitoring over time, and site-specific social and behavioural factors.

[Table 1] *Different treatment types (land, channel, road/trail) with the most common works, comments on site suitability and effectiveness. Source: Papaioannou et al., 2023.*

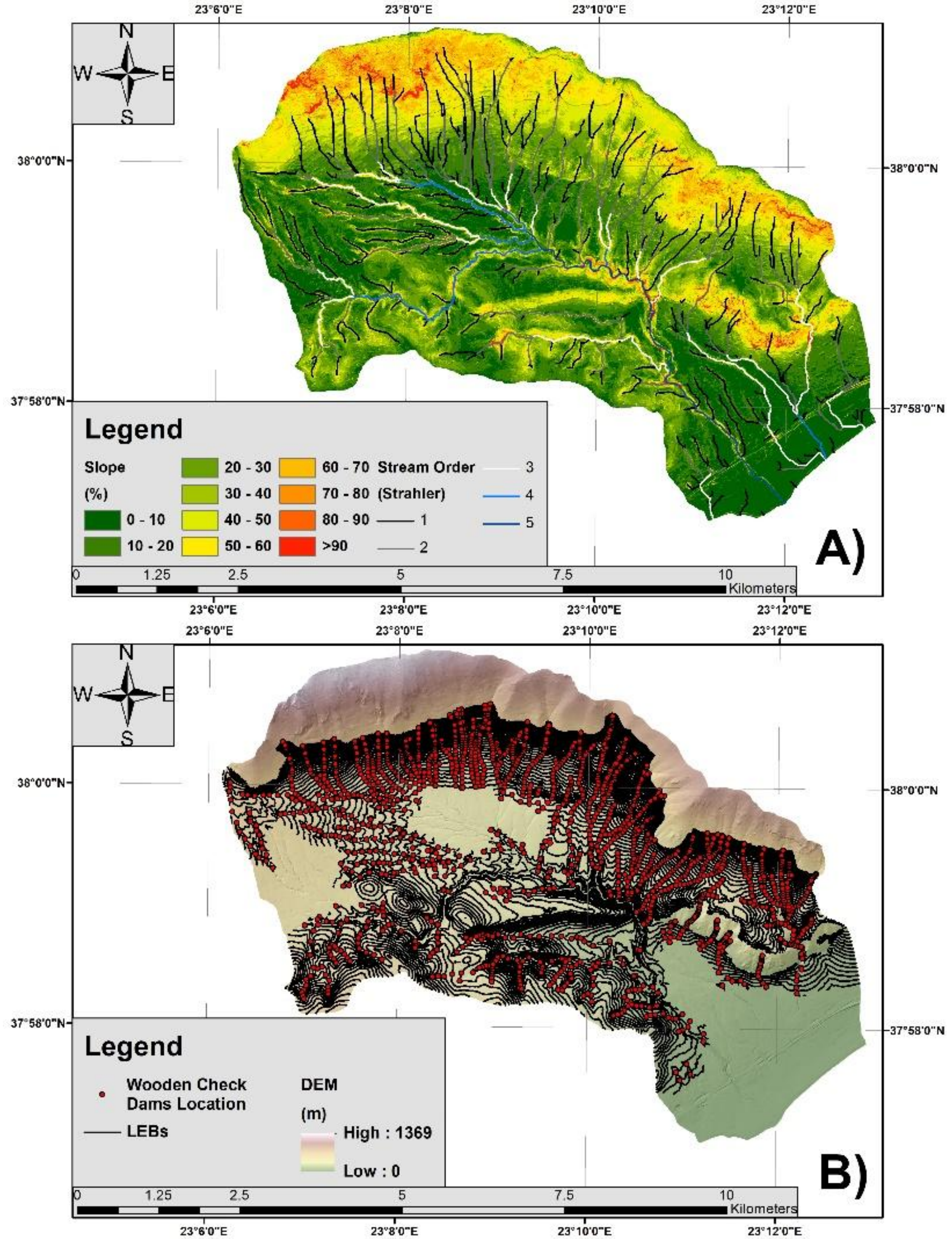
Type of Treatment	Typical works	Suitability and Effectiveness
Land – Cover-based	• Aerial Hydromulch • Ground Hydromulch • Straw Mulch • Slash Spreading • Erosion Control Mats, etc.	• Suitability: Areas with high-moderate burn severity; steep slopes; soils with high erodibility factor; low winds. • Effectiveness depends on: Proper installation, application rates, slope length and steepness, and wind conditions. Combinations of mulching and seeding 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. Erosion Control Mats are costly solutions, with limited information about their effectiveness.
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 only. Their maintenance requires significant effort and attention. Barrier construction remains a typical hillslope treatment with better effectiveness when combined with other treatments.
Land – Seeding	• Soil Scarification • Ploughing • Seeding, etc.	• Suitability: Areas with high-moderate burn severity and highly erodible slopes; vulnerable for invasive and noxious plants spreading. • Effectiveness: While there is limited available information, seeding is inefficient in reducing sediment yield compared to no treatment. 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 boost the vegetation development fast. • Effectiveness: Very few cases report their effectiveness, with no effects found on runoff and little erosion reduction achieved.

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 is 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. 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. Debris basins are expensive treatments.
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.

4.2 Designing PEFTs for the Kineta catchment

For the case of Kineta, based on the literature review and the conditions of Mediterranean sites, the most commonly applied PEFTs were selected: Log Erosion Barriers (LEBs) and wooden check-dams. These were assessed according to the respective official Greek guidelines to specify their recommended installation strategy. The design criteria were as follows: LEBs are suitable for areas with high-moderate burn severity (at the time after the fire, to target the most vulnerable areas) and slopes between 20-50%, while it is also common to install them in slopes above 50%. Wooden check-dams are constructed along channels of 1st and 2nd order streams (the small tributaries), where they are more controllable in smaller channel openings due to the practicality of installation.

These criteria (burn severity categories from the RS analysis, stream slopes, and stream order) were spatially visualised over the DEM of the study area in GIS, allowing precise determination of treatment locations. LEBs were installed every 10 m along the contour lines following usual Greek practice. At spots where LEBs intersect a stream, a wooden check-dam was installed. This resulted in a total of 636,049 m of LEBs and 2,065 wooden check-dams across the catchment. The resulting spatial protection plan thus represents a practical, implementable design based on established guidelines and adapted to the specific conditions of the Kineta catchment.



[Figure 4] *Stream order and slope (A), and final map with the locations of LEBs and wooden check-dams designed for the Kineta catchment (B). Source: Alamanos et al., 2024.*

5. Scenario analysis: Quantifying the effectiveness of PEFTs

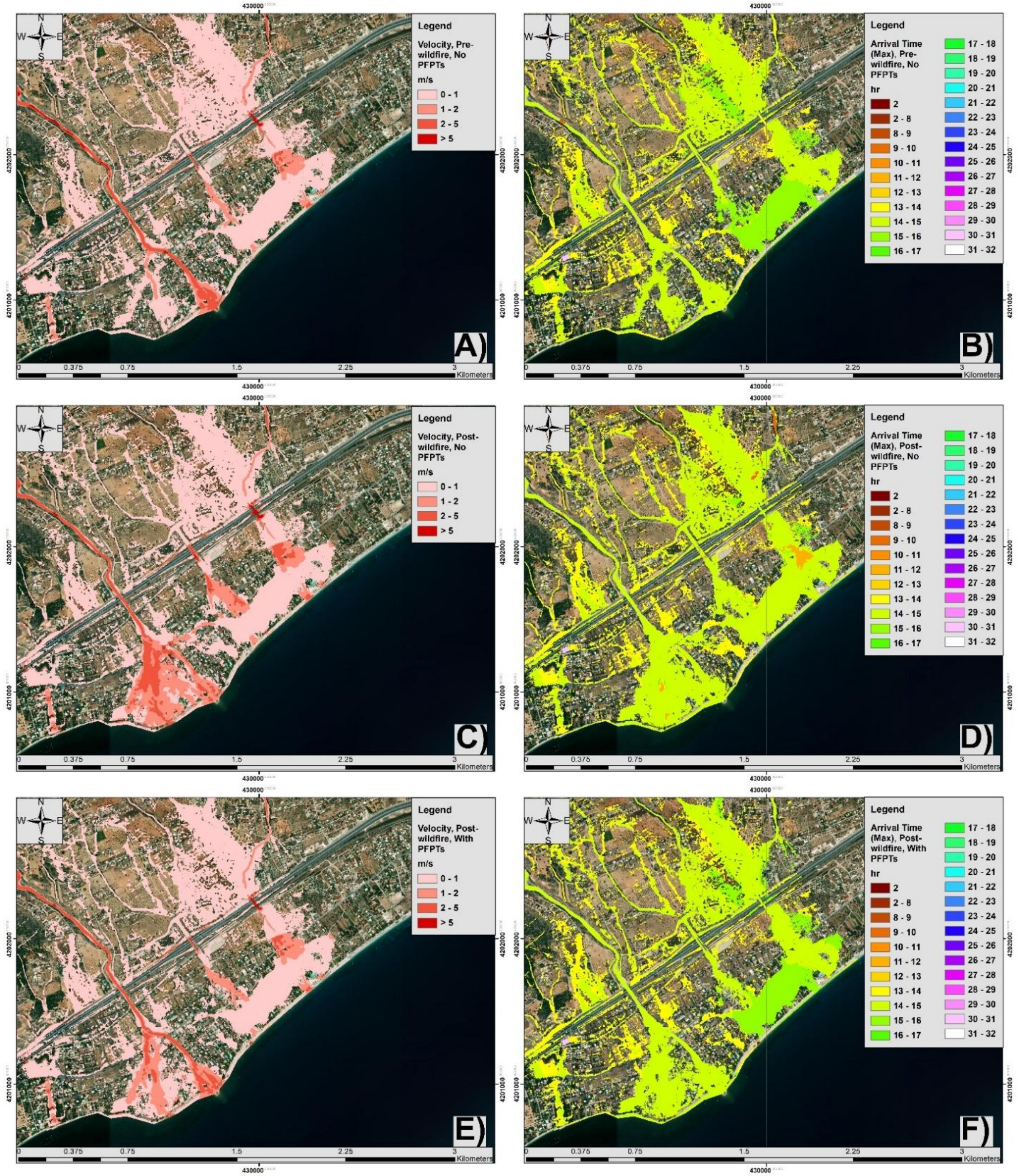
Beyond the pre-fire and post-fire scenarios described above, a flood-protection scenario was simulated to quantify the PEFTs effectiveness. This scenario considers the application of LEBs and wooden check-dams. Hydraulically, the LEBs were represented through increased Manning roughness values in areas of high-moderate burn severity (where LEBs were placed), as they essentially slow down the overland flow through physical barriers. The check-dams were represented as 2D-area hydraulic connections in HEC-RAS, simulating their function of retaining water and sediment within the stream channels. Additionally, the debris blocking the streams was assumed to be cleared as part of the protection measures. The three scenarios were thus:

Pre-fire (theoretical baseline): the same Girionis storm hits the catchment with pre-fire Manning coefficients and unblocked streams. Post-fire, No PEFTs (reality): the storm applies under post-fire conditions with altered roughness and blocked streams from debris. Post-fire, With PEFTs (protection scenario): the same storm under post-fire conditions, but with PEFTs installed (increased roughness from LEBs, check-dams as hydraulic connections, and unblocked streams assuming debris clearance as part of the intervention).

The results were compared in terms of flood extent, water depth, water velocity, and flood maximum arrival time. The total flood inundation area for the post-fire case without protection was 595,246 m^2. The pre-fire scenario yielded 446,077 m^2. If PEFTs had been in place, the flood extent would have been 447,575 m^2, a reduction of 24.8% compared to the reality scenario. This result is striking: the PEFTs scenario yields an extent nearly identical to the pre-fire case, indicating that the effect of the wildfire on flooding could have been entirely offset by the proposed protection measures.

The effects extended beyond flood extent. The proposed works offset significant portions of the water velocity acceleration caused by the fire. PEFTs were particularly effective along the main stream, where well-established flowpaths and gentle slopes allowed LEBs and check-dams to intercept and attenuate floodwater effectively. The PEFTs also introduced meaningful delays in flood wave arrival: peripheral urban areas and floodplain margins experienced delays of 0.4-1.5 hours (potentially critical for evacuation), while the core flood zone saw more modest delays of 0-0.4 hours. Areas where PEFTs show minimal effect (less than 0.4 hours delay or less than 0.1 m depth reduction) correspond to the steepest sub-catchments and the downstream floodplain directly adjacent to the coastline.

It should be noted that the November 2019 storm was a severe event that would have caused flooding under all scenarios, underscoring the inherent vulnerability of the area. While PEFTs effectively eliminate the fire-induced component of flooding, they cannot eliminate the baseline flood risk that exists even without a fire. For such extreme events, additional measures are needed to complement PEFTs: Early Warning Systems (EWS) to predict and warn for sudden floods; proper mapping of intermittent rivers and ephemeral streams (IRES), which were found to be the main flood contributors in Kineta; infrastructure planning and land-use regulation to reduce exposure; drainage and irrigation upgrades; and Nature-Based Solutions (NBS) such as restoring riverbanks and floodplains.



[Figure 5] *The water velocity (A),(C),(E), and the flood maximum arrival time in the Kineta town (B),(D),(F). These are shown for the hypothetical Pre-fire scenario (A),(B); the real Post-fire, No*

PEFTs scenario (C),(D); and the hypothetical Post-fire, With PEFTs scenario (E),(F), respectively. Source: Papaioannou et al. 2026.

6. Economic assessment: Flood protection versus flood damage costs

From an engineering perspective, post-fire flood resilience relies on applying necessary protection measures. From an economic or policy perspective, however, the decision to invest depends on the balance between protection costs and expected flood damages. To our knowledge, such a comprehensive comparison had not been performed in the literature prior to this work. Yet the analysis can be highly valuable because the findings may be generalisable to similar cases in Mediterranean and other fire-prone regions globally.

6.1 Flood-protection costs

Cost estimations for PEFTs considered material and transportation costs, as well as installation and labour costs. Following the destructive fires in Thrace, Northern Greece during summer 2023, the Greek Ministry of Environment and Energy issued detailed studies with protection treatments and updated cost data (2023 values). Based on these official estimates, the unit costs for the Kineta PEFTs were 4.87 EUR per metre of LEBs installed and 49.25 EUR/m^2 of wooden check-dams. The total costs were thus: 4.87 EUR/m multiplied by 636,049 m of LEBs equals approximately 3.1 million EUR, plus 49.25 EUR/m^2 multiplied by 2,065 check-dams of 3.5 m^2 each equals approximately 356,000 EUR, for a grand total of approximately 3.45 million EUR.

6.2 Flood damage costs

Direct damage costs were estimated by synthesising the flood inundation results from the RS and hydraulic model with a semi-automated building footprint identification approach. The AI tool Segment Anything Model (SAM) was used to classify building footprints in the flooded area, which were then cross-checked with Google Street View navigation to ensure completeness and accuracy before counting and categorising elements.

Damage categories included: residential homes (estimated using depth-damage functions from a European flood damage database), commercial buildings primarily hotels (given Kineta is a coastal resort area), private vehicles (based on reported average vehicles per household and standard vehicle damage values from insurance data), agricultural fields (clean-up expenses, as no direct production loss was incurred due to the season), and road infrastructure (the Athens-Corinth highway closure, estimated using a general model accounting for daily traffic volumes, detour distances, vehicle operating costs, and time costs). The total estimated direct damage cost for the reality scenario summed to approximately 3.57 million EUR for property, vehicles, and agricultural damages. This value closely matches the reported government reimbursements of 3.5 million EUR for the Kineta flood, providing independent validation.

Adding significant infrastructure damages (stream cleaning from increased sediment volumes, road network repairs, and coastline restoration), the total flood damage was estimated at approximately 25.2 million EUR. The same estimation process was applied to the other two scenarios for comparison.

[Table 2] *Estimates of direct flood damage costs under the three scenarios: Pre-fire, Post-fire No PEFTs (reality), and Post-fire With PEFTs (protection). Source: Papaioannou et al., 2026.*

Affected Properties and infrastructure	**Pre-fire, No PEFTs (wildfire effect scenario)**		**Post-fire, No PEFTs (reality scenario)**		**Post-fire, With PEFTs (protection scenario)**	
	Quantity / Extent	**Estimated value (€ of 2023)**	**Quantity / Extent**	**Estimated value (€ of 2023)**	**Quantity / Extent**	**Estimated value (€ of 2023)**
Residential homes	412	1,595,857	541	2,095,531	405	1,568,743
Commercial buildings (hotels)	16	387,285	16	387,285	14	338,874
Private Vehicles	495	320,055	650	714,120	486	315,511
Agricultural fields	295,701 m^2	95,068	386,910 m^2	124,392	290,923 m^2	93,532
Blocked highway	2 days	260,500	2 days	260,500	2 days	260,500
Infrastructure	Roads, streams, land, drainage	16,429,135	Roads, streams, land, drainage	21,643,068	Roads, streams, land, drainage	16,273,769
Total Damage Cost:		**19,087,901**		**25,224,897**		**18,850,929**

6.3 Protection costs versus damage costs

The comparison of PEFTs costs (3.45 million EUR) with total flood damage costs (approximately 25.2 million EUR in the reality scenario) reveals that the protection investment would have been roughly 7.3 times less than the damages incurred. This represents a compelling economic case for proactive protection. Furthermore, the damage estimate is conservative, including only direct costs. Indirect economic losses (business disruption, tourism revenue decline, long-term environmental degradation), health impacts, social displacement costs, and the economic value of lost ecosystem services were not quantified but would substantially increase the total cost of inaction. Our flood damage cost estimates are thus quite conservative, and in reality, total losses are likely significantly more than five times the investment needed for post-fire flood protection. The take-away message is that after wildfires, PEFTs are absolutely necessary and should be seen as a cost-saving decision: a relatively affordable investment achievable at local scales (e.g. municipal or regional level). This directly supports SDG 1 (avoiding poverty through disaster prevention), SDG 8 (protecting economic development), SDG 9 (resilient infrastructure), and SDG 11 (sustainable cities).

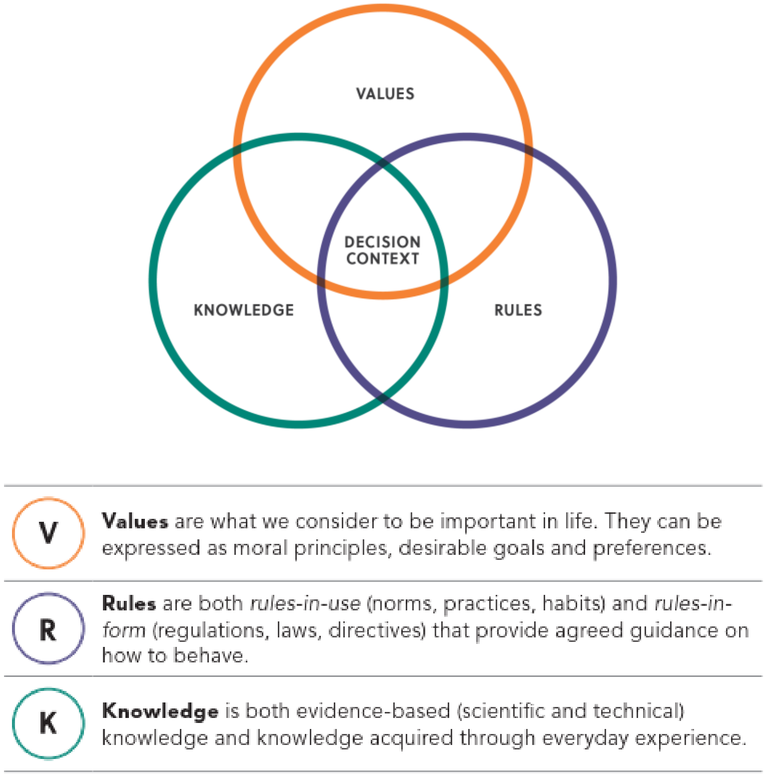
7. The governance problem: Why protection measures are not applied

Despite the clear technical and economic case for PEFTs, there is persistent inertia in adoption and implementation by local authorities responsible for natural hazard management. The response of local governance and the bridging of the science-policy gap is a significant and complex matter. It is vital to account for the decision contexts, defined by interconnected systems of values, rules, and knowledge, into which scientific information must be integrated for it to be credible, legitimate, and ultimately actionable. The situation in Kineta is illustrative: insufficient PEFTs were installed after the wildfire; no compensation was granted from government to regional authorities or affected residents; and by end of 2024, after extended protests, the case was brought to court, with the Former Regional Governor of Attica as primary defendant. This demonstrates a perverse outcome: holding officials accountable after the fact rather than investing in prevention that would have cost a fraction of the damages.

7.1 The values-rules-knowledge (VRK) governance framework and lessons from Australia

The need to bring model-driven insights into policy led us to augment the modelling approach with a governance framework developed and applied in Australia, which shares many relevant characteristics with Greece. Many fire-prone Australian regions have Mediterranean climates with hot, dry summers that promote fire weather, and steep coastal terrain where post-fire flooding can be devastating. The frequency, extent, and intensity of mega-fires have increased in both countries due to climate change, with Australia's 2019/20 Black Summer fires being a prominent example (Kemter et al., 2021). Both countries also have comparable multi-level governance structures with responsibilities shared between national and state/regional authorities, making comparisons of lessons directly relevant.

The values-rules-knowledge (VRK) model (Gorddard et al., 2016) represents the decision context as the intersection of three societal systems: values (beliefs, priorities, and norms guiding choices), rules (formal and informal regulations, institutional arrangements, and procedures), and knowledge (scientific understanding, local experience, and technical capacity). When these three systems overlap well, decision-makers have a large, well-supported decision space enabling effective action. When they are misaligned, the decision space shrinks and inaction or inappropriate responses result. The VRK model assists in diagnosing constraints and barriers to interventions, particularly novel ones, and in identifying leverage points to overcome them. Its entailments for situations of emerging risks where novel solutions are needed include: (i) application as a diagnostic tool to identify the main V, R, or K barriers and indicate leverage points; and (ii) the need for proactive inclusive engagement with stakeholders that supports deliberative co-production of knowledge.



V	**Values** are what we consider to be important in life. They can be expressed as moral principles, desirable goals and preferences.
R	**Rules** are both *rules-in-use* (norms, practices, habits) and *rules-in-form* (regulations, laws, directives) that provide agreed guidance on how to behave.
K	**Knowledge** is both evidence-based (scientific and technical) knowledge and knowledge acquired through everyday experience.

[Figure 6] *Illustration of decision contexts as the intersection of the societal systems of values, rules, and knowledge (VRK). Source: Alamanos et al., 2026.*

7.2 Diagnosing governance gaps in Kineta

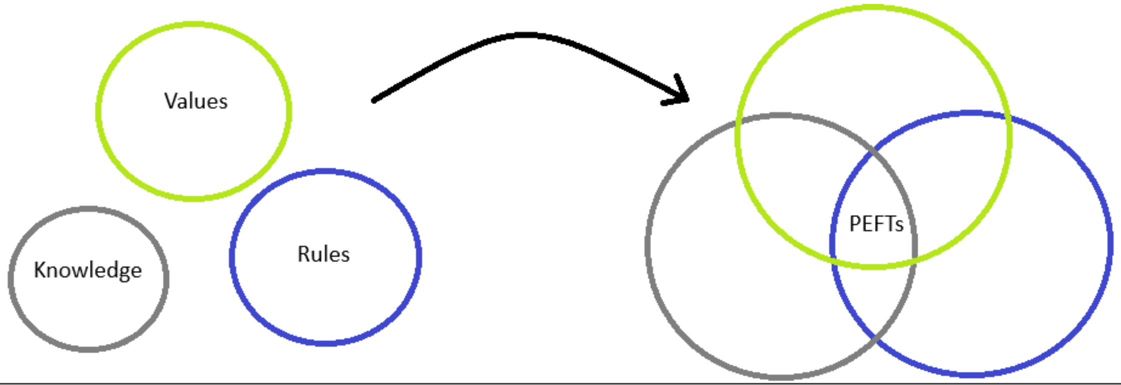
Applying the VRK framework to the Kineta case through informal communications with local authorities, we identified specific gaps in each domain. In the values domain: the perception that post-fire floods are rare exceptions rather than the new normal; low prioritisation of preventive investment compared to post-disaster relief; fragmented community awareness of cascading risks; and limited understanding of the long-term cost-effectiveness of proactive measures among local officials.

In the rules domain: unclear allocation of responsibilities between national and regional authorities for post-fire protection; lack of mandatory post-fire protection protocols; absence of dedicated funding mechanisms for PEFTs at the municipal level; and slow bureaucratic processes for approving and implementing protection works. In Greece, the Ministry of Environment provides national-level guidelines, but implementation responsibility falls to regional authorities who often lack dedicated resources.

In the knowledge domain: limited scientific information on PEFTs effectiveness at the local scale; insufficient technical capacity in regional authorities to interpret modelling results and design protection plans; lack of accessible tools for rapid post-fire risk assessment; and poor communication channels between researchers and local decision-makers. The separation of these three systems results in a narrow, ill-informed decision space. Bridging the existing science-policy and knowledge-action gaps requires participatory processes and knowledge co-production, including adaptive development and testing of modelling tools and PEFTs designs with input from local decision-makers.

[Table 3] *Factors limiting the VRK decision context for the Kineta case, organised by values, rules, and knowledge domains, with targeted recommendations for stakeholder engagement. Source: Alamanos et al., 2026.*

Factors reducing the VRK intersection spaces and hence constraining the decision context	**Intersection space limited**
Policymakers set low priorities (R & V) for PEFTs because they feel that they are unlikely to be widely publicised ("the media come for the disasters, but afterwards they don't care").	Values & Rules (VR)
Policymakers set low priorities (V) for PEFTs because their effectiveness will not be immediately evident (K) after implementation but after the first storms. In contrast, policymakers tend to prioritize (V) measures that have immediate results (K), to build their legacy quickly through advertising.	Values & Knowledge (VK)
Existing regulations (R) continue to require that flood-damaged infrastructure be restored to pre-disaster standards (R), which are generally based on outdated storm data (K) (+50 years ago) that no longer reflect the current and future (changing) climate (K).	Rules & Knowledge (RK)
The funding, staffing and training levels (V & K) of those responsible remain insufficient to support effective mitigation of the growing magnitude and frequency of the hazard risks.	Rules & Values (RK)
Unclear roles and responsibilities (i.e., accountability) (R) and siloed communications within and across organisations lead to uncoordinated decisions and inaction, particularly in diverse areas with uneven disaster impacts (V) and complex property rights (R & V). This is also often used as an excuse by local authorities that are responsible for implementing flood protection measures but feel unsure how to act.	Rules & Values (VR)
Although there are regulations (R) and national plans (R) for hazard mitigation and adaptation in place, there is little available information or assessments on the suitability and cost-effectiveness of PEFTs (K). This is especially the case in specific instances requiring novel PEFTs that are more effective at mitigating the changed hazard risk profiles. This knowledge gap (K) leads to generic regulations (R) around risk mitigation and leads to poor/limited implementation.	Knowledge & Rules (KR)
The widespread lack of awareness (K) about post-fire effects on the hydrological response of a burnt site to a subsequent storm or flood. The timely application of appropriate PEFTs can have many co-beneftisto flood protection (e.g. rapid recovery, reduced soil erosion, avoided damage etc.) but these are overlooked due to the lack of incentives (R) and awareness (K).	Rules & Knowledge (RK)
Local authorities continue with BAU mitigation practices (e.g., clearing the streams from sediment and rubbish) because these are associated with simple and easy implementation requirements (K) and levels of accountability (R), even though these are no longer as effective as they used to be.	Knowledge & Rules (KR)
Policymakers' ways of thinking and behaving (V, R & K) (i.e., prevailing poor or anachronistic understanding of compounding extreme hazards) have not changed to account for the "new normal" of radically different hazard behaviours under climate change (K). This is reflected in these 'extreme events' being considered exceptions and justifying BAU, which is hindering the adoption of necessary mitigation efforts.	Values, Rules & Knowledge (VRK)



Values - low priority for PEFTs	Potential argumentation on the benefits and the policy co-benefits (e.g. protection, small and easy local scale works of low cost, creation of local jobs, etc.
Rules - lack of accountability & poor integration of PEFTs in the regulations	Potential argumentation on enhancement of communication skills, clarification of the governance processes, and use of tools like the modelling framework, or previous applications for the design of PEFTs.
Knowledge - awareness for combined hazards	Use of modelling tools, such as the one presented, to raise awareness on the interactions among wildfires - extreme storms - floods - protection works

[Figure 7] *The values-rules-knowledge perspective on the Kineta decision context, showing separation of V, R, and K systems and the resulting narrow decision space. Source: Alamanos et al., 2026.*

8. Building capacity: A transformative roadmap for stakeholders

The insights from the modelling framework and governance diagnosis were used as inputs to a capacity-building exercise based on the Stakeholder Interaction Approach (SIA). The SIA is a process designed for capacity building and behavioural transition, consisting of: (a) selection of the stakeholder group and their assignment; (b) analysis of the problem; (c) analysis of existing solutions with strengths and weaknesses; (d) identification of tipping points to apply or create solutions; and (e) stakeholder collaboration for solutions implementation. For steps (a)-(c), the modelling framework outputs and broader scientific literature are integral inputs. Steps (d) and (e) involve analysis of both technical and policy gaps to serve as goals for the necessary capacity development.

A crucial starting point is understanding that combined fire-flood hazards are not exceptions but the new normal under climate change. Greece alone has experienced multiple such cascading events over recent years (fires and floods in Evia 2021, fires in northern Greece 2023 followed by flooding), each reinforcing the pattern. Capacity development has been recognised as a key component of SDG 6 implementation, as highlighted in the SDG 6 Global Acceleration Framework. Here, capacity refers to the ability of governments, organisations, and society to manage combined extremes successfully.

[Table 4] *Designing a capacity development exercise for flood protection, according to the Stakeholder Interaction Approach (SIA), with steps and corresponding activities.*

Step:	**Goal/ Expected Outcome**
a) Selection of the stakeholder group	Representatives from central and regional government, scientists, experts on floods, and experienced professionals on protection works, citizen scientists.
b) Analysis of the problem	Climate change, wildfires and impacts on catchments, extreme storms and flood risks. Inadequate infrastructure and (post-fire) flood protection action and basic design of flood protection works based on outdated data that cannot cope with future's climate. Unclear responsibility and accountability for remote areas. Issues identified in Table 3 (based on the VRK framework) should be core targets for behavioural change.
c) Analysis of existing solutions	Analysis of post-fire flood protection techniques, and implementation processes (logistics, economics, regulations). Solutions such as PEFTs should be suggested as counter-arguments to the obstacles of Table 3.
d) Identify/ design solutions	Behavioural changes (understand severity and frequency, and necessity to act). Non-protection risks vs protection benefits narrative (drawing insights from the techno-economic analysis of Part A). Building technical expertise. Collaboration/ coordination to apply proposed post-fire cleaning and flood protection works (drawing insights from the techno-economic analysis of Part A). Emphasis on local stakeholders, using available regional funds, and proactive action.
e) Solutions implementation	Boosting local economy with the application of the proposed measures from local timber and workers. Coordinative action and responsibilities sharing after wildfires, including installation and maintenance. Again, drawing motivation from the promising performance of the PEFTs analyzed in Part A.
f) Dissemination	An important element at this stage is the dissemination and publicity of such efforts. Since policymakers give particular weight to the public perception of their low-cost and highly effective actions in the short-term, this effort should be communicated as such. The journalistic narrative should stress the immediate / short-term benefits of PEFTs as restoration and resilience actions.

The major changes needed include: first, appropriate institutional arrangements supporting the new normal of frequent wildfires and flooding; second, central and regional government acquiring knowledge to understand new data, tools, and solutions, including the modelling framework presented here; third, behavioural change empowering society to adapt to new conditions, taking into consideration local context especially in vulnerable remote areas; and fourth, proper communication and argumentation on the cost-effectiveness and multiple benefits of PEFTs. Several notable examples from Australia demonstrate successful application of the VRK model with government and non-government stakeholders, supporting shifts towards more adaptive and inclusive decision contexts. These experiences are transferable to the Greek and broader Mediterranean context.

The combined use of the modelling insights and the VRK application can assist decision-makers in recognising the need to focus on certain actions required to alter the boundaries of their decision contexts. For instance, demonstrating the 1:7.3 cost ratio between protection and damages can shift values towards preventive investment. Clarifying institutional responsibilities and creating dedicated PEFTs funding lines can reform rules. And making modelling tools accessible and interpretable for non-specialist decision-makers can expand the knowledge base. However, more coordinated policies must be established by local, state, and national governments, as well as the private sector, focusing on redirecting funding mechanisms towards resilience planning, proactive risk reduction, and integrated natural hazard management. The engagement process needs to target the specific factors identified in the VRK diagnosis in ways that increase the overlaps between values, rules, and knowledge, thereby expanding the decision space available to those responsible for post-fire flood protection.

9. Implications for the Sustainable Development Goals

The presented framework, consisting of methodological advances for post-fire flood simulation, assessment of protection works, economic analysis, and a governance roadmap, has multiple layers of implications for sustainability, resilience, and science-supported policy. These implications span at least ten SDGs.

SDG 1 (No Poverty): Flood resilience is crucial for preventing economic deterioration of vulnerable communities. The estimated 25.2 million EUR in damages from a single event can devastate local economies, particularly in areas where livelihoods depend on agriculture and tourism, as in Kineta. SDG 2 (Zero Hunger): Post-fire floods threaten agricultural land through soil erosion, sedimentation, and crop destruction, endangering food production and agricultural livelihoods. SDG 3 (Good Health and Well-Being): The framework directly relates to protecting human lives and avoiding health impacts of floods including waterborne diseases, injuries, and mental health effects.

SDG 6 (Clean Water and Sanitation): Post-fire runoff carries ash, sediment, and contaminants that degrade water quality. Protection of municipal water supply, irrigation networks, and sanitation facilities ensures clean water availability. SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation and Infrastructure): The framework supports economic development through risk avoidance and strengthens research, innovation, and knowledge-based employment. SDG 11 (Sustainable Cities and Communities): The Kineta case vividly illustrates how proximity of settlements to streams maximises exposure, highlighting the need for resilient urban planning.

SDG 13 (Climate Action): The entire framework addresses climate change impact management, as the wildfire-flood cascade is fundamentally a climate-driven phenomenon. SDG 14 (Life Below Water) and SDG 15 (Life on Land): Avoidance of degradation, desertification, and coastal pollution through upstream protection preserves biodiversity and ecosystem integrity. SDG 17 (Partnerships for the Goals): The interdisciplinary nature of the proposal, combining modelling, economics, and governance with benefits spanning the SDGs above, can build cooperation bridges between scientific disciplines, government levels, and stakeholder groups.

It is worth emphasising that these SDG linkages are not merely academic classifications but reflect real, tangible consequences of action or inaction. In the Kineta case, the absence of PEFTs resulted in measurable impacts across nearly all of these SDG dimensions: economic losses affecting local livelihoods (SDG 1, 8), agricultural damage (SDG 2), health risks from floodwater and debris (SDG 3), water contamination (SDG 6), destruction of buildings and roads (SDG 9, 11), and degradation of the coastal environment (SDG 14, 15). The integrated framework presented here demonstrates that a single, relatively affordable intervention (PEFTs costing 3.45 million EUR) could have prevented or substantially reduced impacts across all these dimensions simultaneously, illustrating the potential for coordinated crisis management to deliver co-benefits across the SDG agenda.

10. Conclusions and policy recommendations

This chapter has presented an integrated modelling-to-governance framework for addressing post-fire floods as a cascading sustainability crisis, applied to a real case study in the Mediterranean and framed through the lens of the SDGs and sustainability crisis management. The findings argue strongly for proactive investment in the flood resilience of burnt sites.

The modelling results demonstrate that wildfires significantly exacerbate flood hazards: the post-fire flood extent in Kineta was 25% larger than under pre-fire conditions. The proposed PEFTs (LEBs and wooden check-dams) can fully offset this fire-induced increase, reducing flood extent by 24.8%, along with reductions in water velocity and meaningful delays in flood arrival time. The economic analysis reveals that PEFTs cost approximately 3.45 million EUR while flood damages reached an estimated 25.2 million EUR, a ratio of roughly 1:7.3 in favour of proactive investment. These measures were not applied in Kineta, and the VRK governance analysis reveals systemic barriers across values, rules, and knowledge domains.

The main policy recommendations are as follows. For post-fire flood management: PEFTs should be made mandatory after significant wildfires in fire-prone areas, with national and regional protocols specifying timelines and responsibilities. For modelling and data: investment in integrated modelling frameworks and mapping of intermittent rivers and ephemeral streams should be prioritised, as these were the main flood contributors in the case study. For governance reform: the VRK framework should be adopted as a diagnostic tool; stakeholder engagement and capacity building should be institutionalised; and dedicated funding mechanisms for post-fire protection should be established at municipal and regional levels. For broader resilience: combined fire-flood hazards must be recognised as the new normal, requiring integration into urban planning, land-use regulation, and infrastructure design, complemented by Early Warning Systems, Nature-Based Solutions, and drainage upgrades.

An additional insight from this research is the need for national-scale design storm inventories. The use of tools that facilitate fast and accurate storm assessments is essential for post-fire flood preparedness, as the standard Intensity-Duration-Frequency approaches may be inadequate given the spatial variability and non-linear scaling of design storms. We recommend that local and regional authorities invest in site-specific modelling rather than relying exclusively on national-level statistical parameters. Furthermore, the role of intermittent rivers and ephemeral streams (IRES) deserves particular attention: in the Kineta case, the two smaller, often-dry streams contributed more to the flood than the main Pika stream, yet such watercourses are frequently unmapped and excluded from flood risk assessments. Their systematic mapping and inclusion in hazard analyses is a practical, low-cost measure with high returns for flood risk reduction.

Building resilience to future cascading hazards requires a fundamental shift in how knowledge about problems and solutions is produced and used. Investing in protection is a cost-saving choice with multiple co-benefits across the SDGs. This chapter contributes to the broader discourse on sustainability crisis management by demonstrating that the gap between knowing what to do and actually doing it is fundamentally a governance challenge: one that requires aligning values, reforming rules, and co-producing knowledge with the stakeholders who must act.

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