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Application of Bioengineering Techniques as Geo-Hydrological Risk Mitigation Measures in a Highly Valuable Cultural Landscape: Experiences from the Cinque Terre National Park (Italy)

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Abstract: In this work, experiences from the use of bioengineering techniques as geo-hydrological risk mitigation measures within the territory of Cinque Terre National Park (Eastern Liguria, Italy) after an extreme rainfall event that occurred on 25 October 2011 are described. This rainstorm was responsible for intense erosive processes and triggered numerous shallow landslides, causing severe structural and economic damage. After this disastrous event, many bioengineering interventions were planned to stabilize the most unstable slopes and the most problematic streams. Based on multidisciplinary studies and field surveys, an inventory of the executed bioengineering works was compiled. Subsequently, on the basis of expert judgement, both the efficiency and effectiveness of the works three years after their construction were examined. Furthermore, the compliance of the executed works with the design requirements was analysed. This study revealed that some of the investigated works lack post-intervention maintenance and require the adoption of remedial measures aimed at improving the biotechnical functions of live materials, which are often ineffective. This case study highlights the importance of technical aspects that should be considered during the design phase of bioengineering works, especially when implemented within protected areas. Specifically, it would be greatly helpful to define instructions for post-intervention maintenance and monitoring and to perform vegetational studies. Considering the great cultural and natural heritage of the study area, the obtained results are expected to provide useful information for the definition of guidelines for the best practices to be adopted when future bioengineering works are planned for geo-hydrological risk management purposes.

Keywords: bioengineering; Cinque Terre; cultural landscapes; geo-hydrological risk; shallow landslides; slope stabilization

1. Introduction

With its 55 locations of outstanding cultural and historical value, Italy dominates the list of World Heritage Sites provided by the United Nations Educational, Scientific and Cultural Organization (UNESCO) [1]. The high relevance of this patrimony is further enhanced by more than 200,000 sites widespread throughout the country [2], including a large amount of architectural (e.g., churches, palaces, castles, bridges), archaeological (e.g., caves and necropolis), cultural (e.g., museums and monuments) and natural (e.g., parks, protected areas, gardens) heritage sites. However, due to the peculiar geological and geomorphological setting of the Italian territory, many cultural sites are threatened by several natural hazards, such as earthquakes [3,4], landslides [5–9], floods [10–14] and subsidence processes [15,16]. Every year, the impact of geo-hazards on cultural heritage sites poses serious consequences in terms of economic losses and damage and risk to people [17–19], especially where cultural sites are located in densely populated areas or popular tourist destinations [20]. Among the natural events threatening cultural heritage sites, geo-hydrological phenomena, namely, rainfall-induced landslides, accelerated erosion processes and inundations, are the most common [21]. Furthermore, in recent decades, both the magnitude and frequency of geo-hydrological events have increased because of the effects of climate change [22,23]. In Italy, according to a recent report provided by the Italian Institute for Environmental Protection and Research [2], approximately 18% of the cultural sites are exposed to the effects of slope instabilities, while approximately 19% are located in areas prone to floods. These data highlight the urgent need for strategies to address the protection of this outstanding cultural and historical patrimony located in a such a fragile territory to preserve its identity for future generations.

The landscape shaped by agricultural terraces sustained by dry-stone walls has been recently recognized by UNESCO as a world cultural heritage site because of its inestimable environmental and historical value [24]. Slope terracing is among the most ancient land use practices and it represents one of the best expressions of the intimate relation between humans and the natural environment [25,26]. Since ancient times, the cultivation of agricultural terraces has played an important role in the social and economic development of different regions of the world [27,28]. Furthermore, terraces represent one of the most effective solutions to mitigate land degradation in hilly and mountainous landscapes [25]. Regrettably, terraced environments are increasingly threatened by the consequences of land abandonment correlated with the wide spectrum of economic, social and political changes that occurred during the twentieth century [29–32]. The cessation of agricultural activities has directly caused a lack of maintenance of terraced systems, which in turn has negatively affected their hydro-geomorphological functions, such as control of runoff and of water infiltration, soil protection and conservation [33–36]. These dynamics have progressively increased the vulnerability of terraced environments to mass movements and erosion processes, especially during extreme meteorological events [37–39].

In cultural landscapes and protected areas, geo-hydrological risk mitigation strategies should be directed as much as possible towards the adoption of approaches that allow mitigation of the impact of geo-hazards and, at the same time, preservation of the environmental, aesthetic and historic value [40–43]. In this sense, bioengineering techniques can represent a valid alternative to traditional structural measures as they reduce the environmental impact and provide beneficial effects in conservation of ecosystems and biodiversity. These techniques employ plants, or plant parts, either alone or in conjugation with inert materials (e.g., steel, concrete, rocks) to improve slope stability and to mitigate the effects of soil erosion [44,45]. Over the last 30 years, biotechnical engineering has been increasingly used as a geo-hydrological risk mitigation measure in hilly and mountainous environments [46–52]. However, as claimed by some researchers [53–55], the execution of effective bioengineering works requires accurate design procedures, based as much as possible on multidisciplinary approaches. Moreover, many practical experiences indicated that, in order to achieve the complete effectiveness of bioengineering interventions, it is of fundamental importance to schedule monitoring activities to be performed after the work realization [53–55].

This case study presents practical experience from the use of bioengineering techniques as geo-hydrological risk mitigation measures within two small terraced coastal basins located in Cinque Terre National Park (eastern Liguria, north-western Italy). This area is widely known worldwide for its great cultural and natural significance. Bioengineering works were performed to stabilize both slopes and streams that were severely affected by the consequences of an extreme rainfall event that occurred on 25 October 2011. In this paper, the outcomes of multidisciplinary studies promoted by the Geologic Risks Studies Center (GRSC) of Cinque Terre National Park on these bioengineering works are described. These studies were aimed at producing a detailed inventory of the executed bioengineering interventions as well as at examining their efficiency and effectiveness some years after construction. Furthermore, the compliance of these works with the design requirements and specifications was analysed.

2. General Setting of the Study Area

Liguria (Figure 1a) is included within the group of Italian regions that have the highest number of cultural sites located in areas classified as having high and very high landslide hazard and medium to high flood hazard [2]. This region is highly vulnerable to geo-hydrological processes because of its rugged morphology [56–60], which is characterized by prevalently hilly and mountainous-like slopes and small flood plains [61,62], and because of its peculiar climatic features, which favor the occurrence of high intensity rainfall [63–66]. Over the past centuries, large portions of steep slopes have been terraced by local inhabitants to develop agricultural activities [67–69]. Agricultural terraces have assumed a fundamental social and economic role, as they have compensated for the lack of suitable landscape morphologies for farming. For these reasons, terraced slopes have become one of most prominent geomorphological features of the landscape. Although no precise estimates exist, some authors have reported that more than 20% of the total region extension (approximately 5000 km^2) has been modified through slope terracing [70]. Starting from the 20th century, similar to many European hilly and mountainous landscapes, Liguria has experienced an extensive cessation of farming practices. These land use changes have produced extensive land degradation, radically transforming the landscape and making terraced slopes even more fragile and susceptible to geo-hydrological processes [71–73].

The study area is located in the easternmost section of the Liguria region (La Spezia Province) (Figure 1b), along the Cinque Terre coastal stretch, and it includes two small coastal basins belonging to the territory of the Monterosso al Mare municipality: the Pastanelli stream (3.2 km^2) and the Fosso Serra stream (0.1 km^2) catchments (Figure 1c). The Cinque Terre area is known worldwide for its terraced coastal landscape, which emphasizes the century-old equilibrium between human activity and the natural environment [74,75]. This coastal portion of Liguria, with its steep agricultural terraces rising from the shoreline, is an outstanding example of the intrinsic link between humankind and nature, and represents an environmental, historical and cultural heritage site for present and future generations [75]. For these reasons, in 1997, the Cinque Terre area was included on the list of World Heritage Sites by UNESCO, and in 1999 it was proclaimed to be a national park with the aim of protecting its peculiar man-made landscape. More than three million tourists annually visit this protected area to hike along several paths spreading out on the steep coastal terraced slopes [76,77].

The geology of the study basins consists of rocks related to the tectonic units involved in the Northern Apennines orogeny and can be grouped into four main geological formations (Figure 2a): the Macigno Fm. (Upper Oligocene—Tuscan Nappe), the Canetolo Shales and Limestones Fm. (Paleogene—Sub-Ligurian Domain), the Monte Veri Shales Fm. (Campanian—External Ligurides Domain) and an ophiolitic complex (Jurassic—Internal Ligurides Domain), only represented here by serpentinites [78]. The Macigno Fm. occupies the widest part of the study area by cropping out with the Riomaggiore Banded Sandstones lithofacies, which is characterized by the alternation of thin bedded fine-grained sandstones and siltstones. The serpentinitic bodies, together with the Canetolo Shales and Limestones Fm., which is mainly composed of claystones, limestones and silty sandstones, occupy a small amount of the upper sector of the Pastanelli stream catchment, whereas the Monte Veri Shales Fm., mostly composed of pelitic rocks, crops out along the western side of the study area (Figure 2a). The morphology of the study area is typically mountainous (Figure 1c) and is closely shaped by the geo-structural setting defined by the tectonic processes that affected this coastal stretch of the Apennines during the orogenic and post-orogenic phases [79]. The basins have a high relief outlined by steep slopes and several small V-shaped valleys, which are deeply incised by steep, straight and short channels arranged in a dense sub-dendritic pattern. The main water divides occur very close to the sea, reaching a maximum distance from the shoreline of approximately 2 km, with the highest elevation represented by the peak of Mt. Soviore (620 m a.s.l.). The final reaches of the valley floors are occupied by a small coastal plain while narrow belts of beach deposits occur at the stream mouths. In the past, the terminal tracts of the streams crossing the ancient hamlet of Monterosso al Mare were culverted.

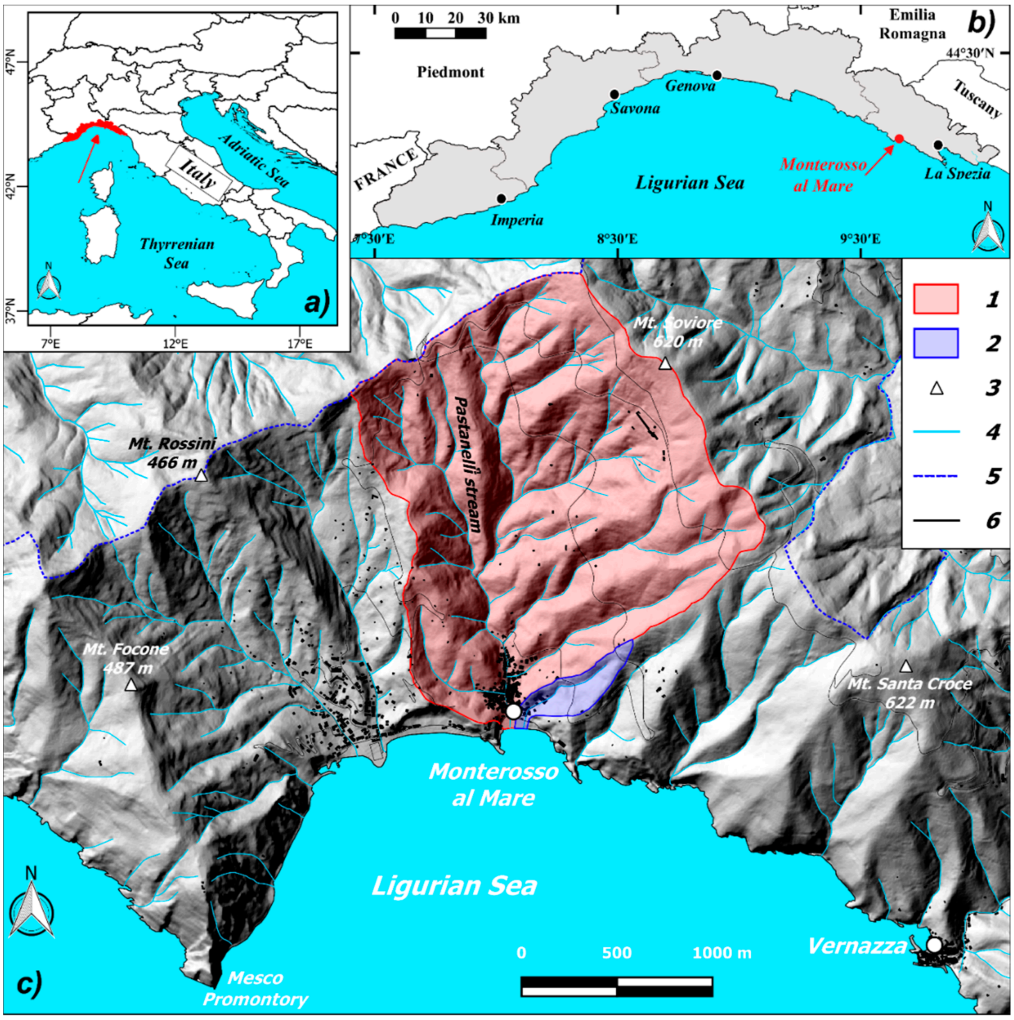


Figure 1. (**a**,**b**) Location of the study area; (**c**) Detailed view of the study area and of the surrounding Table 1. Pastanelli stream catchment; 2, Fosso Serra stream catchment; 3, main elevations; 4, hydrographic network; 5, Cinque Terre National Park boundary; 6, main road (base map derived from a 5 m cell-size Digital Elevation Model (DEM), source: Geoportale Regione Liguria [78]).

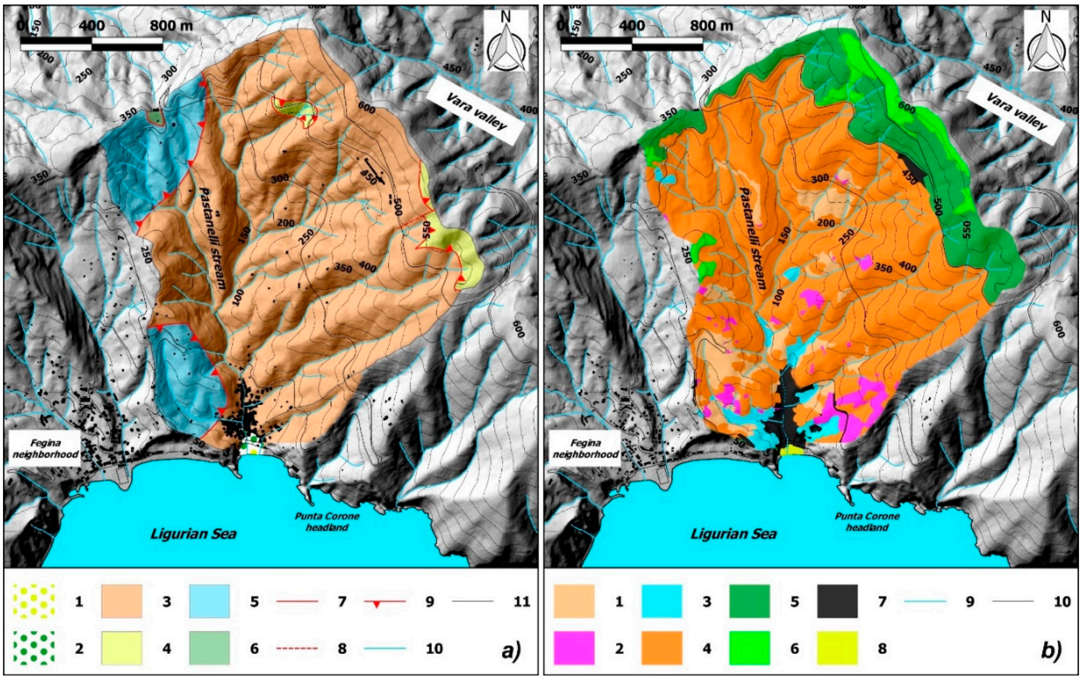


Figure 2. (**a**) Geologic map of the study area (data source Regione Liguria [78]): 1, beach deposits; 2, alluvial deposits; 3, Macigno Fm.; 4, Canetolo Shales and Limestones Fm.; 5, Monte Veri Shales Fm.; 6, serpentinites; 7, tectonic contact; 8, fault; 9, thrust; 10, hydrographic network; 11, main road. (**b**) Land use map of the study area (data from Schilirò et al. [80]): 1, cultivated terrace (olive groves); 2, cultivated terrace (vineyards); 3, cultivated terrace (orchards); 4, abandoned terrace; 5, wood; 6, scrubland; 7, urban area; 8, beach; 9, hydrographic network; 10, main road (base maps derived from a 5 m cell-size DEM, source: Geoportale Regione Liguria [78]).

The slopes of the basins are mantled by eluvial-colluvial deposits characterized by thicknesses ranging from less than 1 m to several meters, depending on the geological, geomorphological and land use conditions [80]. The slope deposits are prevalently coarse grained with abundant percentages of gravel and sand and minor fractions of silty and clayey soils [81,82]. The eluvial-colluvial soil covers were almost completely reworked by local farmers during the phases of slope terracing. The presence of agricultural terraces strongly influences the current land use setting of the basins (Figure 2b). Based on data reported from recent studies [80], 77.1% of the study area is covered by agricultural terraced slopes. However, only 15% of agricultural terraces are currently still cultivated: 4% with vineyards, 8.3% with olive groves and 2.7% with orchards. Generally, terraced slopes that have not been cultivated for a long time are characterized by a dense vegetation consisting of forest tree species (e.g., pines, chestnuts, oaks) and Mediterranean scrub, whereas those abandoned for a short time have herbaceous cover or shrubs. Wooded areas and scrublands occupy 15.1% and 4.7% of the study area, respectively, whereas the percentage of urban area is approximately 2.9%.

Because of the geomorphological setting characterizing the Cinque Terre coastal catchments, shallow landslides and erosive processes are recurrent phenomena, especially as a consequence of intense rainfall [71,80]. Moreover, the considerable abandonment of agricultural areas that occurred after World War II has resulted in a gradual decrease in land maintenance practices along with a lack of dry-stone wall restoration after collapses, giving rise to a significant disruption of terraced systems [75]. Over time, increasing land degradation has promoted increases in the magnitude of mass movements and fluvial and run-off-related phenomena induced by severe rainstorms [83–88]. These rainstorms, which usually occur between late summer and early winter, are the most distinct feature of the local Mediterranean climate and are characterized by large rainfall levels concentrated in a few hours [63]. According to the historical rainfall data (period 1954–2016) measured by the

Levanto rain gauge (located approximately 4 km W of the study area), the annual rainfall is on average 1040 mm, most of which is concentrated in autumn. The rainiest month is October (with a mean monthly precipitation of approximately 150 mm), while the driest month is July (with a mean monthly precipitation of approximately 28 mm). During extreme rainfall events, because of the large volumes of sediment mobilized from slopes and along streams, the village of Monterosso al Mare is particularly exposed to the risk of debris floods. Generally, the consequences of these extremely dangerous phenomena are strongly intensified by the dam effect produced by the covered tracts of the stream beds, as dramatically observed during the 25 October 2011 rainstorm and the disastrous flood that occurred on 2 October 1966 [80].

3. Materials and Methods

In autumn 2011, the Cinque Terre area was hit by a severe rainstorm, whose destructive consequences have heavily shaken the local population, further calling attention to the fragility of this territory [63]. In the Mediterranean area, this meteorological event is considered one of the most severe rainstorms in recent years in terms of both rainfall intensity and cumulative rain quantity [89]. Three years after the disaster, Cinque Terre National Park established the GRSC, whose main goal is to assist the park authority in the assessment, prevention and mitigation of natural hazards, with a special emphasis on geo-hydrological issues. Within the study catchments, bioengineering techniques have been extensively used to stabilize and secure the slopes and stream channels most seriously affected by the 25 October 2011 extreme rainfall. Recently, the GRSC has performed multidisciplinary studies with the purpose of investigating both the efficiency and effectiveness of these bioengineering works after their construction.

This section first presents the magnitude of the rainstorm and the rainfall-induced ground-effects in the study area. Subsequently, the methodology for inventorying, mapping and surveying the executed bioengineering interventions is described.

3.1. The 25 October 2011 Event and Rainfall—Induced Ground Effects

On 25 October 2011, the portion of the territory encompassing eastern Liguria and north-western Tuscany was affected by a one-day extreme rainfall event [63,90]. This severe rainstorm was characterized by highly localized and persistent precipitation generated by a back-building mesoscale convective system [64,89]. The rainstorm unleashed the largest part of its enormous energy over approximately 6 h (between 9 and 15 UTC—Universal Time Coordinate) [63,90]. The highest rainfall magnitude was recorded in the inland territories of Liguria, where the maximum cumulative rainfall levels exceeded 530 mm (Figure 3a). The force of the rainfall sequence was also severe along the coastal side of the region, especially in the Cinque Terre area, where the most affected zones were the municipalities of Monterosso al Mare [80] and Vernazza [71]. The rain gauge located at Monterosso al Mare recorded a cumulative rainfall height of 382 mm and an hourly intensity of 90 mm (Figure 3b). Because a significant amount of rainfall occurred in a few hours, the urban areas were impacted by a destructive debris flood (Figure 3c,d). The large quantity of transported sediments filled the covered tract of the Pastanelli stream, subsequently overwhelming roads and buildings and causing severe damage along with the interruption of essential services (i.e., electricity, gas, water, telephone and sewage). One casualty occurred, and many economic activities were devastated by the impact of the debris flood.

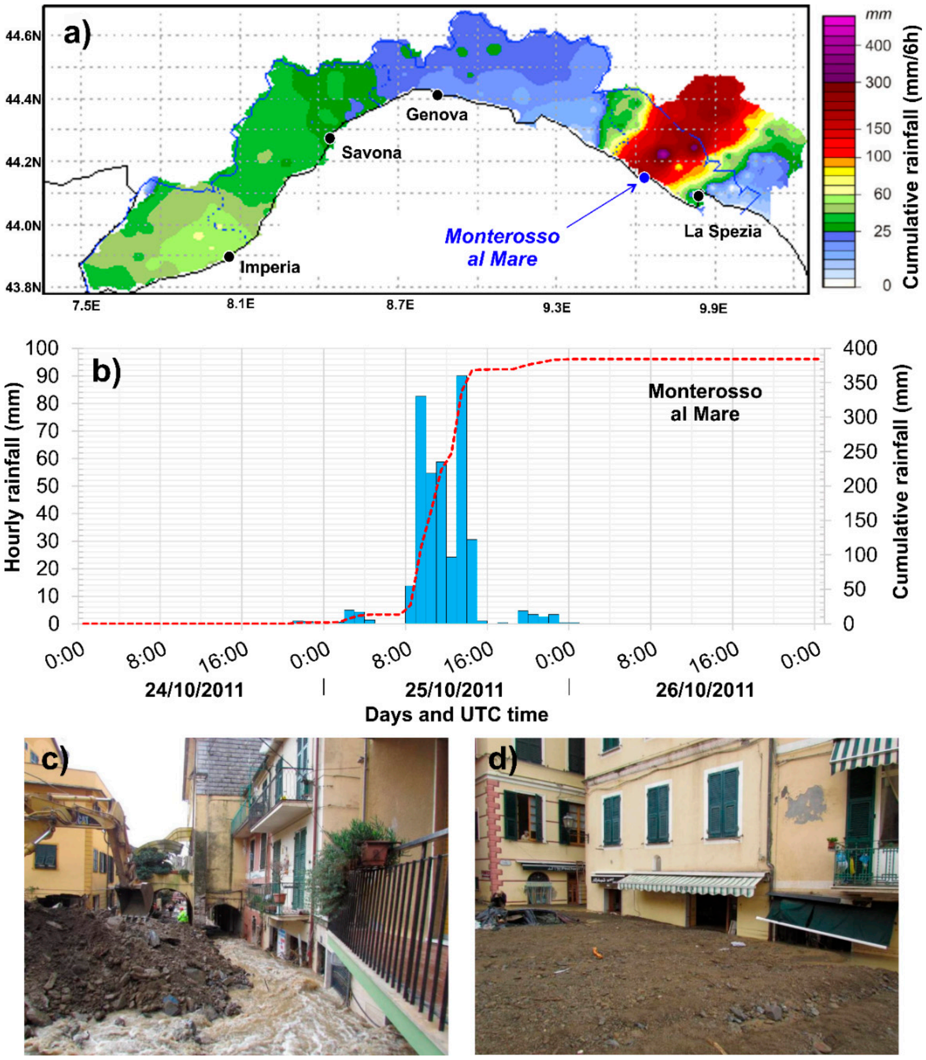


Figure 3. (**a**) Spatial distribution of the interpolated cumulative rainfall on 25 October 2011, between 10:00 UTC and 16:00 UTC (modified from ARPAL-CFMI-PC [90]). (**b**) Hourly (light blue bars) and cumulative (red dashed lines) rainfall recorded by the Monterosso al Mare rain gauge (data source: Regione Liguria [91], (**c**,**d**) View of some of the road sections of the historic centre of Monterosso al Mare buried by debris hours after the rainstorm (photos courtesy of Monterosso al Mare Municipality Administration).

On the slopes upstream of Monterosso al Mare village, several hundred rainfall-induced shallow landslides were triggered [80]. Moreover, widespread erosion processes occurred (e.g., gully and rill wash erosion), especially along fluvial channels that were deeply incised. According to the landslide inventory produced by Schilirò et al. [80], a total of 191 landslides were triggered within the study area (Figure 4a), the majority of which (179) affected the Pastanelli stream catchment, where a landslide density of 57.7 landslides/km^2 was calculated; the percentage of the basin area affected by landslides was 1.45%, corresponding to a total area of 4.51 hectares. The smallest slope failures involved surfaces of more than 10 m^2, while the largest mass movement covered an area of approximately 2500 m^2. Generally, shallow mass movements were triggered as debris slides affecting the thin veneers of eluvial-colluvial soils, also sometimes involving the most weathered/fractured horizons of the underlying bedrock (Figure 4b–d). In many cases, debris slides evolved into flow-like landslides, such as debris avalanches or, in a few cases, debris flows. Along channels, the significant rainfall triggered intense headward erosion and riverbank scouring, severely increasing the in-channel sediment supply (Figure 4e). Many antique artificial hydraulic works constructed by local farmers were swept away by the high stream power developed during the rainstorm.

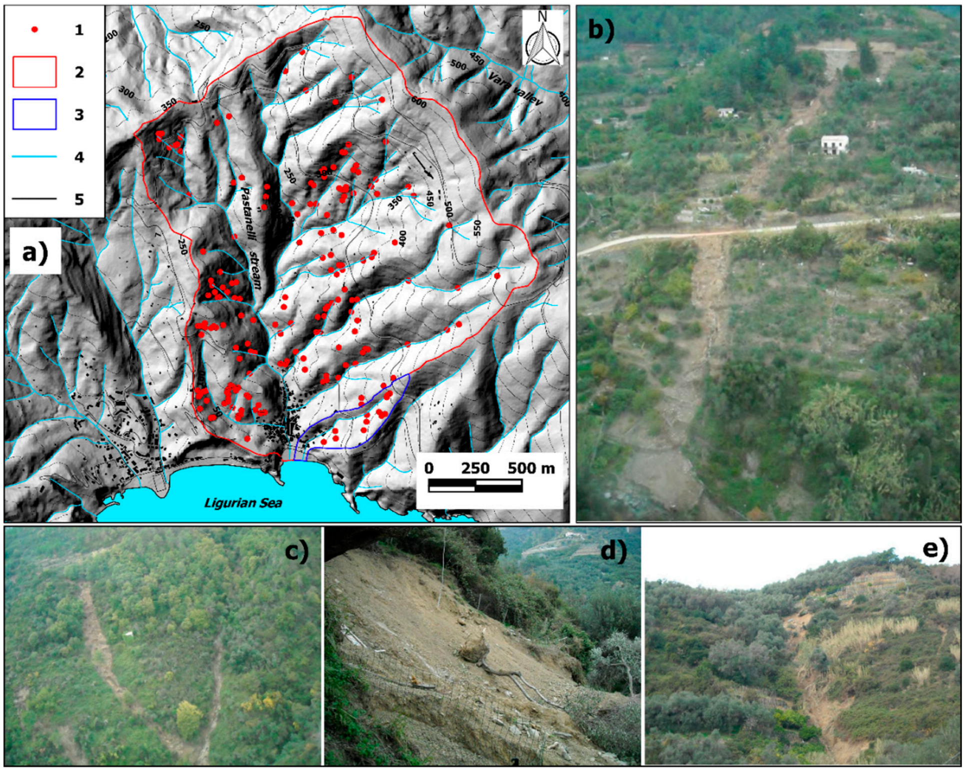
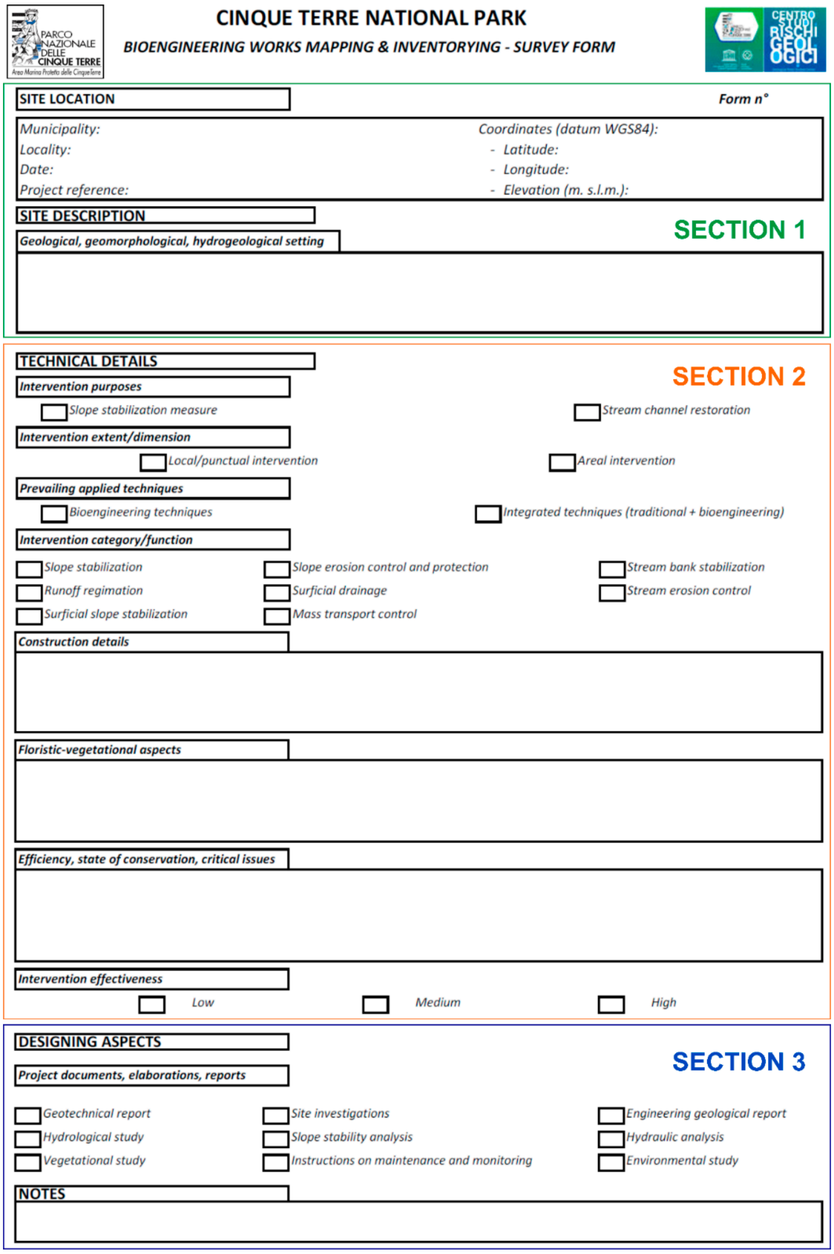


Figure 4. (**a**) Inventory map of the shallow landslides triggered within the study area during the 25 October 2011 rainstorm (data from Schilirò et al. [80]): 1, landslide source area; 2, Pastanelli stream basin; 3, Fosso Serra stream catchment; 4, hydrographic network; 5, main road. (**b**–**d**) Examples of rainfall-induced shallow landslides (photos courtesy of Monterosso al Mare Municipality Administration). (**e**) Example of the erosion processes and intense sediment mobilization that occurred along a steep stream channel (photos courtesy of Monterosso al Mare Municipality Administration).

3.2. Bioengineering Interventions Inventorying, Mapping and Surveying

After the disastrous event, the Monterosso al Mare municipality activated emergency procedures aimed at defining rapid and effective geo-hydrological risk mitigation programs. The first actions focused mainly on the restoration of urban areas through the removal of the enormous volumes of earth and debris that overran streets and obstructed the culverted reaches of the main streams, the reparation of the most important damage suffered from infrastructures and the reestablishment of essential services. Subsequently, in the upstream sections of the catchments, due to the difficult accessibility of sites because of the rugged morphology along with the need to preserve the environmental and cultural value of the landscape, numerous bioengineering interventions were planned and designed. Several projects were carried out to stabilize the most unstable slopes and problematic channels. Overall, the bioengineering works were executed starting in the early spring of 2012 and were completed between the end of 2013 and the beginning of 2014. As mentioned above, in 2016 the GRSC initiated multidisciplinary studies on the executed biotechnical stabilization measures. These studies involved different experts (i.e., engineering geologists and geomorphologists, geotechnical engineers, agronomists and foresters) and were developed in three steps. In the first step, an extensive collection of archive information, namely technical studies, reports and design documents, was compiled. Photos of individual project sites immediately after the rainstorm and after work completion were also collected. Unfortunately, representative photos showing the site conditions before the rainfall event were not found. However, such data allowed precise documentation of both the extent and the magnitude of the geo-hydrological processes at each project site and collection of fundamental information on the adopted design approaches and the selected biotechnical solutions. In the second step, accurate field activities were carried out by means of detailed topographic base maps (1:5000 scale) and a common GPS device to map the executed bioengineering works. During the field survey of the bioengineering works, using an ad-hoc survey form (Figure 5), a qualitative assessment of the following technical details was performed: i. efficiency, ii. effectiveness, iii. state of conservation and iv. floristic-vegetational aspects. The employed survey form consisted of three sections: i. site location and general setting; ii. technical details of the bioengineering intervention; and iii. designing aspects.


PARCO NAZIONALE DELLE CINQUE TERRE

CINQUE TERRE NATIONAL PARK

BIOENGINEERING WORKS MAPPING & INVENTORYING - SURVEY FORM

CENTRO STUDI RISCHI GEOLOGICI

SITE LOCATION

Form n°

Municipality:
Locality:
Date:
Project reference:

Coordinates (datum WGS84):
- Latitude:
- Longitude:
- Elevation (m. s.l.m.):

SITE DESCRIPTION

SECTION 1

Geological, geomorphological, hydrogeological setting

TECHNICAL DETAILS

SECTION 2

Intervention purposes
☐ Slope stabilization measure
☐ Stream channel restoration

Intervention extent/dimension
☐ Local/punctual intervention
☐ Areal intervention

Prevailing applied techniques
☐ Bioengineering techniques
☐ Integrated techniques (traditional + bioengineering)

Intervention category/function
☐ Slope stabilization
☐ Slope erosion control and protection
☐ Stream bank stabilization
☐ Runoff regimation
☐ Surficial drainage
☐ Stream erosion control
☐ Surficial slope stabilization
☐ Mass transport control

Construction details

Floristic-vegetational aspects

Efficiency, state of conservation, critical issues

Intervention effectiveness
☐ Low
☐ Medium
☐ High

DESIGNING ASPECTS

SECTION 3

Project documents, elaborations, reports
☐ Geotechnical report
☐ Site investigations
☐ Engineering geological report
☐ Hydrological study
☐ Slope stability analysis
☐ Hydraulic analysis
☐ Vegetational study
☐ Instructions on maintenance and monitoring
☐ Environmental study

NOTES

Figure 5. Survey form used during bioengineering works for mapping and field surveys.

The first section of the survey form includes some geographic information aimed at localizing each bioengineering intervention along with a brief description of the most important geological, geomorphological and hydrogeological features of the project site. The second section specifies the purpose of the risk mitigation measure (i.e., slope stabilization or stream channel restoration) along with summarizing some of the engineering specifics of the bioengineering intervention such as the function, construction details and vegetational aspects. In addition, qualitative information on the efficiency, state of conservation, critical issues and effectiveness of the interventions are reported. The third section outlines the design documents and reports (e.g., geotechnical reports, field investigations reports, stability analyses, environmental studies, etc.) available for the considered intervention.

In the third step, the data and information acquired during the previous two phases were organized in a Geographical Information System (GIS) to produce an inventory map of the executed bioengineering works along with an associated database. The slope areas and the river sections affected by these works were mapped as polygons, whereas single structures, such as vegetated palisades and check dams, were represented as points or linear features. Furthermore, the collected data were used to analyse the compliance of the bioengineering works with the design requirements and specifications. In this case, a comparison of photos taken immediately after the construction of the bioengineering works with those collected in 2016 was useful to investigate both the efficiency and effectiveness of the measures undertaken approximately three years after their construction.

4. Results

A total of 14 bioengineering works were inventoried and mapped by means of archive research and field activities: 12 interventions were implemented within the Pastanelli stream basin whereas two were implemented in the Fosso Serra catchment (Figure 6). The total area affected by the geo-hydrological risk mitigation measures through bioengineering techniques was approximately 4.4 hectares, corresponding to approximately 1.3% of the study area. The largest intervention covers an area of approximately 0.9 hectares while the smallest intervention has an extent of approximately 0.06 hectares.

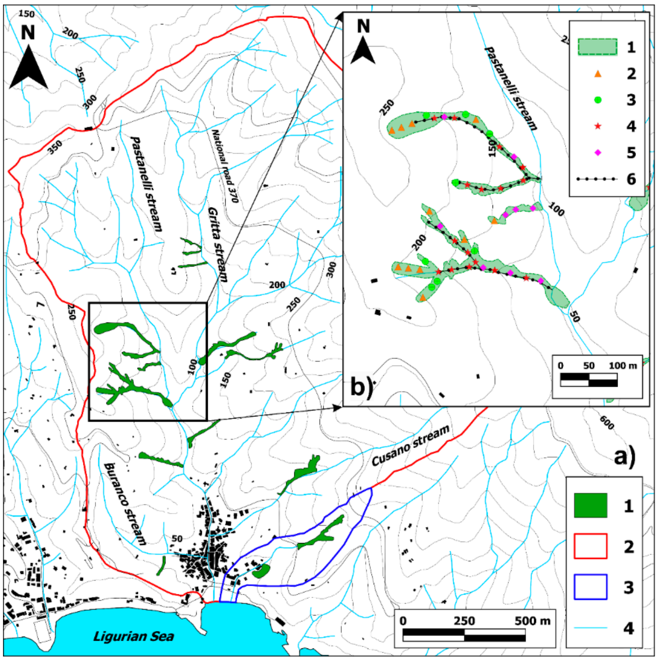


Figure 6. (**a**) Bioengineering works inventory map: 1, area affected by bioengineering works; 2, Pastanelli stream catchment; 3, Fosso Serra catchment; 4, hydrographic network. (**b**) Detailed view of the inventory map showing the location of some main structures: 1, area affected by bioengineering works; 2, double crib wall; 3, palisade; 4, log check dam; 5, single crib wall; 6, bed revetment.

Generally, the design approaches adopted for the restoration of the most problematic slopes involved the integration of a wide range of technical solutions aimed at preventing the retreat of landslide scarps, stabilizing displaced material and controlling rain-wash processes. In detail, slopes impacted by shallow mass movements were stabilized by means of grading works and through construction of a series of vegetated, single or double, crib walls (Figure 7); these structures were arranged as perpendicular as possible to the slope gradient whereas the foundation was placed over the bedrock surface and in a slight counter-slope. Crib walls were built using wooden logs held together with steel staples at the joints; the whole framework was anchored with steel bars (approximately 1.5–2 m long) into the bedrock and backfilled with eluvial-colluvial soils. The slope surface in the inter-zone between vegetated crib walls was further protected with alignments of vegetated palisades in combination with laying of coir nettings, which were carefully overlapped and arranged according to the direction of runoff (Figure 7c,d). The coir nettings were fixed into the ground with steel staples and were laid to provide both adequate resistance of the slope surface against rain-wash erosion and to promote the growth of natural vegetation.

Figure 7. Representative examples of slope stabilization and landslide mitigation bioengineering works: slope conditions pre-intervention (**a**,**b**) and post-intervention (**c**,**d**) (photos courtesy of Monterosso al Mare Municipality Administration).

To restore the herbaceous vegetation over the treated slope portions, mixtures of grass seeds were sown. Moreover, planting of shrubs belonging to Mediterranean scrub, prevalently broom plants (e.g., *Spartium junceum* and *Cytisus scoparius* species), was also implemented. The interventions on slopes were completed with the construction of surficial drainage works, consisting of open ditches lined with timber, which were placed at the head of the landslide area and along the landslide flanks (Figure 7c,d). Last, in the surrounding zones of intervention, collapsed and damaged dry-stone walls were reconstructed.

Concerning hydraulic works, both transversal and longitudinal measures were used (Figure 8). The different methods and techniques were aimed at improving water flow, reducing in-channel erosion, protecting riverbanks from erosion and improving their stability against failures. The first phases of the works focused on the restoration of the flow sections by removing sediments and wood elements mobilized by fluvial- and runoff-related processes that were triggered by the rainstorm; the hydraulic sections, where possible, were enlarged through excavations of both streambeds and banks. Subsequently, along the widest channels, the majority of design schemes involved the construction of sequences of log check dams to dissipate the energy of water discharge and to control in-channel erosion (Figure 8c). In terms of the construction details, log check dams consisting of alternate layers of wood and stones were built. During log check dam assembly, wooden beams were joined using steel bolts, and the voids within the wooden framework were carefully filled with stones packed as closely as possible (Figure 8c). The erosion control structures were set up over the bedrock and anchored with steel bars (approximately 1.5 m long) while shoulders were carefully tied into the flanks of the channels. In minor and steeper channels or short tributaries, the thalweg was shaped in gentle steps through the installation of small log check dams (Figure 8d).

Figure 8. Representative examples of stream channel stabilization and hydraulic bioengineering works: channel conditions pre-intervention (**a**,**b**) and post-intervention; (**c**,**d**) (photos courtesy of Monterosso al Mare Municipality Administration).

In some projects, this technical solution was coupled with bed revetment by placing wooden trunks parallel to the flow direction. Along the most critical or most damaged stream reaches, bank protection was achieved by means of vegetated palisades (Figure 8d); less frequently, stream banks were also protected using vegetated crib walls. However, in some cases, vegetated dry-stone walls and small longitudinal masonry walls were constructed. The set of geo-hydrological mitigation measures implemented along streams and channels were completed through interventions on the flanks to limit rain-wash erosion and improve their overall stability. Therefore, some series of vegetated palisades were positioned over the channel flanks in conjunction with jute meshes fixed using steel staples. Eventually, to improve the establishment of natural vegetation, grass seed mixtures were sown and shrubs belonging to the Mediterranean scrub were planted (i.e., *Spartium junceum* and *Cytisus scoparius* species) (Figure 9).

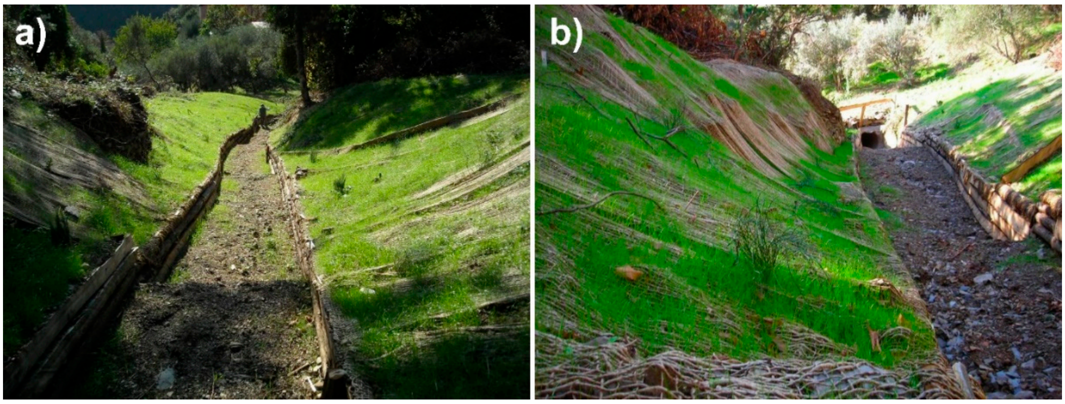


Figure 9. (**a**) Example of channel flanks stabilized with the combination of jute netting, grass sowing and shrub planting. (**b**) Detailed view of planted broom species on a stream bank (photos courtesy of Monterosso al Mare Municipality Administration).

Figure 10 summarizes the results of the data analysis of the multidisciplinary field surveys. On the basis of expert judgement, these surveys allowed qualitative assessment of the effectiveness along with the state of conservation of the bioengineering works approximately three years after their completion. The results reveal that approximately 30% of the mitigation measures are poorly effective, approximately 40% are characterized by medium effectiveness, and only 30% show high effectiveness (Figure 10). The bioengineering works classified at high and medium degrees of effectiveness exhibit a positive function both in biotechnical and environmental terms and have also achieved adequate aesthetic conditions (Figure 11a,b). On average, vegetated structures show a good state of conservation, structural elements are generally well anchored, single wooden logs are firmly connected to each other and inert materials within wooden frameworks are closely packed. Nevertheless, the results of this study indicate that the investigated works lack post-intervention maintenance, especially regarding live materials. It is worth highlighting that the main criticalities are related to the role played by the vegetation, namely, the biotechnical functions performed by the species sown or planted on slopes or stream flanks and by live materials positioned within crib walls, palisades and log check dams. In particular, it was observed that in the project sites characterized by the lowest efficiency, sowing and planting procedures were somewhat ineffective (Figure 11c) since several treated slopes and river flanks did not show continuous and dense shrub cover. This was often observed in project sites characterized by the most severe morphological conditions, such as very steep slopes or short tributaries. Moreover, in some interventions an extensive growth of unwanted vegetation was also noted. These field observations suggest that grass species germination has not adequately developed and that the vast majority of planted shrubs have not grown (Figure 12).

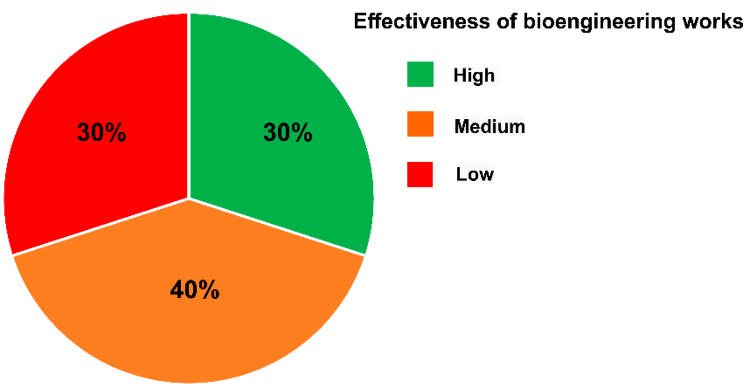


Figure 10. Graph summarizing the degree of effectiveness of the investigated bioengineering works.

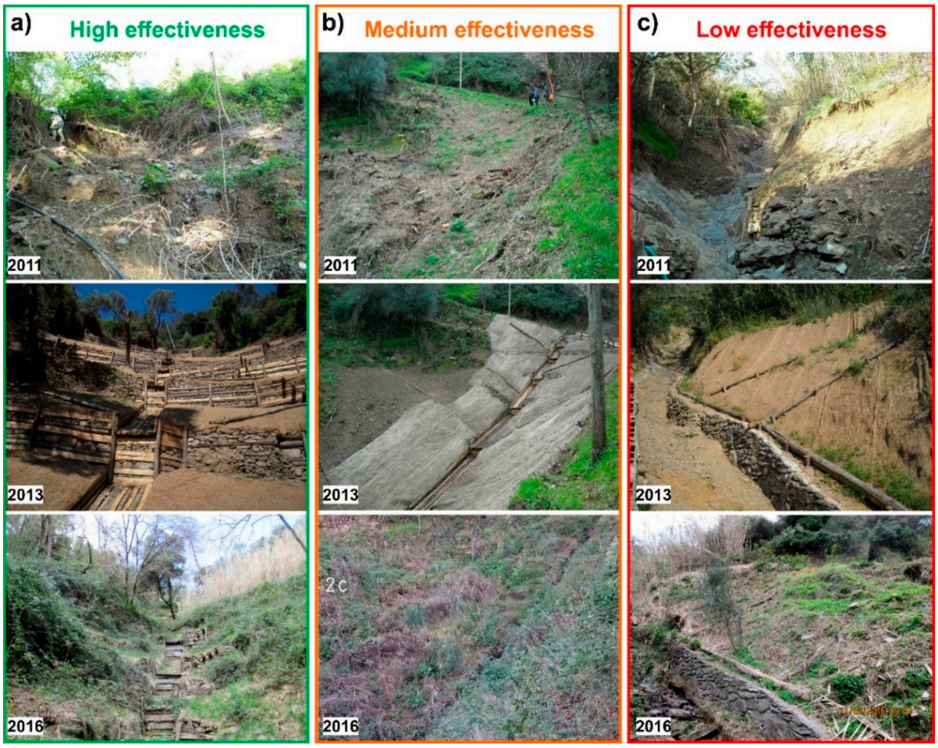


Figure 11. Representative examples of interventions classified at high (**a**), medium (**b**) and low (**c**) effectiveness. For each example, the site conditions immediately after the rainfall event, after stabilization work completion and three years after work execution are showed.

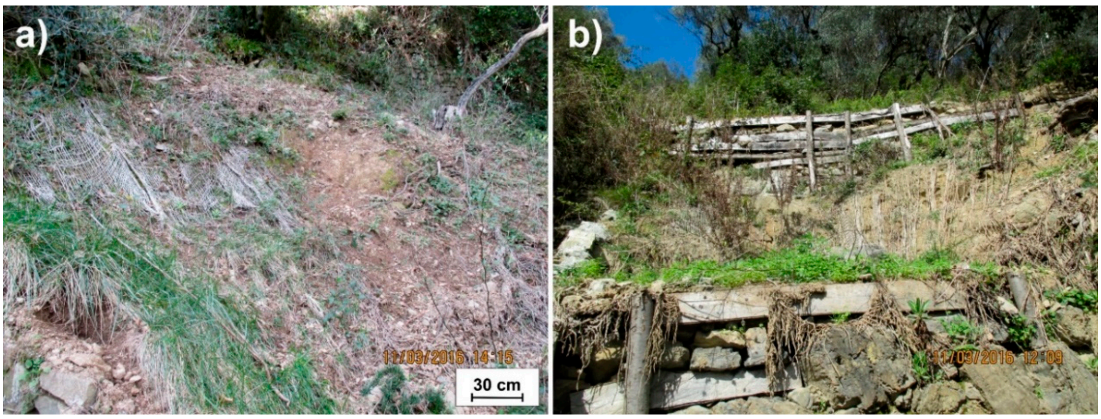


Figure 12. Examples of scarce vegetation cover development along a slope surface (**a**) and within single palisades (**b**).

The observations made in the field about the low quality of revegetation are supported by the analysis performed on technical studies, reports and design documents available for each project (Table 1). This analysis revealed that, during the design stage, site conditions were adequately investigated from the geological, geotechnical and hydraulic side. However, no vegetational and environmental studies were envisaged, and no post-intervention maintenance activities were scheduled (Table 1).

Table 1. Checklist of the designing documents envisaged during the design phases of the investigated bioengineering works.

Project Documents, Reports and Studies	Envisaged	Not Envisaged
Geotechnical reports	X	
Hydrological studies		X
Site investigations	X	
Slope stability analyses	X	
Engineering geological reports	X	
Hydraulic analyses	X	
Vegetational studies		X
Instructions on maintenance and monitoring		X
Environmental studies		X

5. Discussion

Within protected areas, the issues related to geo-hydrological risk can be addressed through the large variety of technical solutions offered by bioengineering. By exploiting the use of live plants in association with inert materials, this family of techniques allows protection of slopes and streams against erosion and shallow mass movements with environmentally compatible measures. This case study explores the efficiency and effectiveness of bioengineering works executed to stabilize 14 sites located within the territory of the Cinque Terre National Park. The results show that 30% of the investigated interventions are poorly effective three years after the implementation. The low functionality is mainly related to a scarce vegetation development. In these sites, a persistent plant cover has not established after sowing and planting operations. Therefore, neither the protective function against rain-wash nor surficial slope stabilization has been properly achieved. In these cases, the establishment of vegetation may have impeded by ongoing runoff and erosion processes. These processes may have removed fertile soil and organic matter, especially along the steepest slopes and channel flanks. As reported in the technical literature [92], the lack of dense vegetation turf does not allow full exploitation of some hydrological and mechanical benefits provided by vegetation, making slopes more unstable and more prone to erosion processes. The presence of vegetation reduces both runoff and rainfall infiltration [45,92], while the roots of grasses and shrubs increase the aggregation of soil particles, diminishing their susceptibility to erosion [93–97]. Moreover, the reinforcement provided by roots can play a significant role in the stabilization of shallow mass movements [94,98], especially in cohesionless and thin soil deposits such as those mantling the slopes of the study area [99]. Another significant issue was detected in some implemented works using live components in combination with inert and dead materials, such as vegetated crib walls and palisades. In some cases, field observations revealed that vegetation did not develop, since neither cuttings nor rooted plants placed into the frameworks took root, probably because of plant mortality. The weak spreading of plants within the structures can negatively influence both their current and future efficiency. It is known that the development of dense root architectures and intense root-soil interactions requires time and depends on several factors (e.g., climatic, environmental, pedological, etc.) [53,54,93,96]. However, once roots have been established, the live reinforcement of the vegetation used in bioengineering techniques increases with time [45,100]. Conversely, the effectiveness of dead materials gradually decreases over time, for example due to wood decay.

The results of this investigation highlight that no environmental monitoring or maintenance procedures were performed after completion of the works, which was confirmed by the examination of the project documents and reports, since neither maintenance nor monitoring of the executed works were envisaged. Moreover, no vegetational studies were performed to select the most appropriate plant and grass species to be used according to the floral and vegetational features of the study area. As noted by Giupponi et al. [55], during bioengineering work design, plant type and seed mixture are often not defined by experts with botanical and ecological skills. This implies that planted or sown species may not be suited for the environmental features of project area, negatively influencing the successful use of bioengineering.

Based on the results of this research, it is expected that both the efficiency and effectiveness of the most critical bioengineering works will further decrease with time. The outcomes of this case study are in accordance with the findings of Simon and Steinemann [101], who reported that the vulnerability of bioengineering projects is higher immediately after construction due to plant mortality. Many authors have claimed that the lack of maintenance strongly reduces the effectiveness of bioengineering works because it does not allow full exploitation of the biotechnical functions of live materials [53,54,93]. For these reasons, it is essential to schedule regular maintenance practices, such as mulching, vegetation enrichment, weeding of unwanted species and repair of non-vegetated structures (e.g., reinforcement of anchorages and replacement of degraded wooden logs). Moreover, to obtain an effective establishment of vegetation, post-intervention environmental monitoring is essential. Bioengineering maintenance and monitoring are even more important within cultural landscapes and protected areas, such as Cinque Terre National Park, where the aesthetic and environmental aspects should be maximized. In the Cinque Terre area, as demonstrated by Galve et al. [102] through landslide susceptibility models based on probabilistic approaches, bioengineering techniques represent one of the most suitable and effective structural measures to mitigate the risk from rainfall-induced shallow landslides. However, the adoption of these structural measures is feasible only at the local scale since the application over large areas implies great costs [42]. Therefore, at the basin scale, long-term strategies involving the integration between structural and non-structural measures are needed to protect and preserve the valuable cultural and environmental heritage site of the Cinque Terre area. By considering the close connection between humans and the natural environment that characterizes this area, land management strategies should include the participation of local inhabitants as much as possible.

6. Conclusions

Bioengineering can be considered one of the most suitable geo-hydrological risk mitigation measures to employ in areas of high environmental and cultural value. Within protected areas, this type of structural intervention, if properly executed, allows mitigation of the impact of geo-hydrological phenomena and, at the same time, meets environmental, aesthetic and cultural preservation demands.

In this case study, based on multidisciplinary studies and field surveys, both the efficiency and the effectiveness of 14 bioengineering works employed within two small coastal basins belonging to the territory of Cinque Terre National Park, known worldwide for its outstanding man-made landscape and declared a UNESCO heritage site, were investigated. These interventions were constructed to stabilize some slopes and streams that were severely affected by shallow landslides and concentrated erosion processes triggered by an extreme one-day rainstorm that occurred in October 2011. The investigation revealed that three years after execution, approximately 30% of the bioengineering works did not adequately comply with the design requirements. The main issues are related to the low effectiveness achieved by the biotechnical functions of live materials since sowing and planting procedures have been often ineffective. In these interventions, a scarce vegetation development has been observed on the treated slopes and stream banks and within structures such as crib walls and log check dams. This negatively influences the protective function against erosion processes and shallow slope movements. These observations have highlighted that the investigated bioengineering works require the adoption of maintenance programs to improve their functioning. In fact, the analysis of design documents and reports revealed that no instructions on post-intervention maintenance and monitoring were envisaged during the designing phases. Moreover, no vegetational studies were carried out to define the correct seed grass mixtures and plant species to use. These aspects play a crucial role in the successful application of bioengineering techniques since the correct development of the biotechnical characteristics allows the achievement of the highest effectiveness of the works through time.

This case study notes that multidisciplinary approaches have great importance in the design procedures of bioengineering techniques. Furthermore, the results represent a fundamental basis for the implementation of multitemporal monitoring activities aimed at analyzing the future evolution of the efficiency of the investigated bioengineering works. Finally, the outcomes of this study are expected to provide useful information for the definition of guidelines on the best practices to be adopted when future bioengineering works are planned within the Cinque Terre National Park for geo-hydrological risk management purposes.

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