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Innovative Methods for Mapping the Suitability of Nature-Based Solutions for Landslide Risk Reduction

Vishal Balaji Devanand [1], Adam Mubeen [1,2,*], Zoran Vojinovic [1], Arlex Sanchez Torres [1], Guido Paliaga [3], Ahmad Fikri Abdullah [4], João P. Leitão [5], Natasa Manojlovic [6] and Peter Fröhle [6]

1 Water Supply Sanitation Environmental Engineering Department, IHE Delft Institute for Water Education, Westvest 7, 2611 AX Delft, The Netherlands; vishaldevbalaji@gmail.com (V.B.D.); z.vojinovic@un-ihe.org (Z.V.); a.sanchez@un-ihe.org (A.S.T.)
2 Faculty of Applied Sciences, Delft University of Technology (TU Delft), Mekelweg 5, 2628 CD Delft, The Netherlands
3 GISIG Geographical Information Systems International Group, Via Piacenza 54, 16138 Genova, Italy; gpaliaga@gmail.com
4 International Institute of Aquaculture and Aquatic Sciences (I-AQUAS), Universiti Putra Malaysia, Port Dickson 70150, Malaysia; ahmadfikri@upm.edu.my
5 Swiss Federal Institute of Aquatic Science and Technology (Eawag), Überlandstrasse 133, CH-8600 Dübendorf, Switzerland
6 Institute of River and Coastal Engineering, Hamburg University of Technology (TUHH), Am Schwarzenberg-Campus 1, 21073 Hamburg, Germany; natasa.manojlovic@tuhh.de (N.M.); froehle@tuhh.de (P.F.)
* Correspondence: a.mubeen@tudelft.nl or adammubeen@live.com

Abstract: The impacts of climate change are becoming more widespread across the world, with hydro-meteorological extreme events on the rise, causing severe threats to nature and communities. Increasing trends in the frequency and intensity of floods and landslides have been projected by climate models. This necessitates the development of more effective measures such as nature-based solutions (NBS) which can complement grey infrastructures. Recent studies have identified knowledge gaps and limitations in existing research and tools that aid in spatial planning for the implementation of large-scale NBS and proposed new methodologies for the spatial allocation of large-scale NBS for flood risk reduction. This work presents a novel method for mapping the suitability of NBS addressing geo-hydrological hazards such as shallow landslides, debris flow, and rockfall, which are typically caused due to slope instability. This methodology incorporates landslide susceptibility mapping, and was used to create a toolbox ESRI ArcGIS environment to aid decision-makers in the planning and implementation of large-scale NBS. The spatial allocation toolbox was applied to the case study Portofino promontory, Liguria region, Italy, and 70% of the area was found to be highly susceptible to landslides. The produced suitability maps show that 41%, 33%, and 65% of the study area is suitable for the restoration of terraces, bio-engineering, and vegetative measures such as NBS for landslide risk reduction.

Keywords: nature-based solutions; climate change; afforestation; suitability mapping; landslide risk reduction

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1. Introduction

Global surface temperatures continue to rise at unprecedented rates, and these changes increase the intensity and frequency of hydro-meteorological extreme events all over the globe. The Intergovernmental Panel on Climate Change (IPCC) defines extreme events as the abnormal occurrence of a weather variables including rainfall or temperature above or below the threshold value near the upper or lower ends of the range of the observed value in a region [1]. The frequency and the intensity of these natural disasters can also be correlated with unsustainable socio-economic development, driven by rapid urbanization, booming populations, etc., which aggravates vulnerability by exposing an increasing proportion of the population to hazards [2]. The risks posed by these extreme events also rise with the probability of damage caused by natural hazards, and its interaction with the exposure, vulnerability, and ability of the ecosystems and communities to adapt [3].

The interaction between meteorological events and geological systems results in geo-hydrological hazards. Canuti et al., 2001 [4] categorized geo-hydrological hazards into three groups: hydraulic, landslides, and groundwater hazards. Landslides are the predominant hazard in mountainous and steep terrains, usually triggered by slope instability and rainfall [5], and have the potential to harm lives and damage infrastructure all over the globe, especially in the Mediterranean coastal regions. Mass movements of rocks and debris caused by slope instability on natural and man-made slopes are often triggered by hydro-meteorological events such as rainfall, snow melting, and earthquakes [6,7], resulting in the sliding, flowing, tumbling, rolling, and collapsing of masses of earth along these slopes. A study by Petley, 2012 [8], over a period of seven years, recorded 2620 intense landslides worldwide, causing a total of 32,322 fatalities. In addition, a study by Paliaga and Parodi, 2022 [9] showed the increasing trend of extreme events, meteorological variables, and climate-related disasters in the Mediterranean area between 1979 and 2018.

Since most of these events are fuelled by climatic parameters, the variations in the hydro-meteorological conditions imposed by climate change have a major influence on the intensity and frequency of these geo-hydrological hazards. The main factors that are expected to fuel this trend in the coming decades include rapid urbanization and increasing development in areas vulnerable to landslides, increased regional precipitation triggered by shifting climatic patterns, and continued deforestation of landslide-prone areas [10]. In the last few decades, resources have been invested to analyse the landslide hazards to provide maps that depict hazard zonation (spatial distribution) [11]. Several methods and strategies for assessing the hazards and risk of landslides have been suggested or evaluated [12,13], and they utilise assessment of landslide susceptibility as the first step. The approaches currently followed by the scientific community for the evaluation of landslide susceptibility are as follows: (1) a geomorphological approach involving a proficient analysis of landslide inventories, which requires technical expertise and completeness of data [14]; (2) a heuristic approach which depends on the understanding of the geomorphological processes and the interaction between the causative factors [15]; (3) physical-based approaches, which rely on a thorough understanding of the physical laws that govern slope stability [12]; and (4) statistical methods focused on the examination of functional associations between instability factors and the spatial distribution of past and present landslides [16]. These methods largely utilise the Geographical Information System (GIS) combined with data gathered using novel techniques such as satellite remote sensing and Light Detection and Ranging (LiDAR) images [17], thereby enabling visual presentation of the results in the form of landslide hazard and risk maps.

Owing to hydrological and geo-mechanical processes, forests are considered to improve soil stability, thereby minimizing the risk of shallow landslides by reducing the run-off, increasing the soil strength, and preserving good biological processes [18]. In recent times, protection forests have attracted more focus globally as an efficient ecosystem-based approach for the reduction of geo-hydrological hazards, mainly those that occur at shallow strata [19]. Another widely used technique for improving slope stability is grading the terrain and cutting slope lengths using wattles, or constructing terraces and benches. The construction of terraces as a measure of soil and water conservation has been largely used in many mountainous areas of the world; it has enabled the practice of subsistence agriculture since ancient times, but may turn into a source of hazard if not properly maintained [20]. This technique not only contributes to slope stability, but also serves as a trap for the downward sliding or flowing masses, preventing down-hill damage. These types of slope modification techniques involve the construction of terraces with a proper drainage system, and reinforcement using organic structures such as tree branches, shrubs, etc. Additionally, the implementation of check dams and ponds could prevent against gully formation and other types of erosions [21]. Soil bio-engineering techniques are another type of sustainable slope stabilisation measure; they are widely adopted in locations wherein the landscape, ecosystem and environment should be preserved from hydrological risks [21]. Bio-engineering techniques make use of live plants combined with woods as a protective structure and form of reinforcement for the soil [22]. Some of the most common interventions involve slope plantings, live crib walls, planted pole walls, vegetated stone walls, and vegetated gabions. Among these, revegetation and live crib-walls are the commonly used measures in mountainous regions [23].

Using ecosystem-based adaptation (EbA) techniques has been proven to be more effective than conventional grey infrastructure approaches, as vegetation helps in mechanical support by stabilising the slope, and in the hydrological sense, by enhancing water drainage and reducing soil erosion. Additionally, re-vegetation helps to restore the ecosystem of the region if native species are being used and the aesthetic value of the landscape is also enhanced [23]. This calls for a shift to more sustainable measures that incorporate ecosystem functions. In Europe, such EbA measures are commonly referred to as nature-based solutions (NBS), which can be defined as actions that are inspired or supported by the nature. NBS allow communities to build resilience against extreme events, while simultaneously providing various benefits that will enrich the ecosystem and human well-being. NBS must be implemented after considering local knowledge in addition to hydro-meteorological, biophysical, geo-mechanical, and other site conditions.

Methodologies for the spatial allocation of NBS that address different hydrological hazards exist, but are limited to small-scale and more urban measures. Development of frameworks for the selection and spatial allocation of large-scale interventions would be advantageous for decision-makers [24]. Therefore, the development of a methodology or a framework that involves the spatial allocation of the NBS that address geo-hydrological extreme events would be of inestimable support to the decision-making process in disaster risk reduction. This study aims to develop a methodology and a corresponding GIS toolbox for mapping suitable locations for NBS for the reduction of geo-hydrological hazards such as shallow landslides, debris flow, etc.

2. Selection of Methodology for Landslide Susceptibility Mapping

As a first step to enable the spatial allocation of large-scale NBS for geo-hydrological hazards, a literature review was carried out to identify the different methodologies that have been adopted for mapping shallow landslide susceptibility, and the type of NBS used to address this hazard. The review was conducted from the openly available literature, using journal articles from online platforms including Research Gate, Google Scholar, Science Direct, and Scopus.

Since most susceptibility mapping methodologies work with GIS multiple criteria decision-making (MCDM) techniques, the main aspects that were analysed are predisposing factors considered (e.g., slope, land-use, lithology, etc.), the type of input data (raster or vector), and the type of integration (analytic hierarchy process (AHP), overlay, fuzzy logic, etc). From a precise literature review of eight articles, five types of methodologies were identified for landslide susceptibility determination, namely AHP with weighted linear sum (WLS), fuzzy logic, AHP with bivariate statistics, spatial probabilistic modelling and universal soil loss equation (USLE) techniques, and these are listed in Table 1. Based on these characteristics, the data availability, and the feasibility of replication in an Arc-GIS toolbox (which could be used for identifying the shallow landslide susceptibility of different case study regions), a methodology for mapping susceptibility was selected.

From the above reviewed methodologies, the methodology for shallow landslide susceptibility mapping using the analytical hierarchy process (AHP) and weighted linear sum (WLS), developed by Roccati et al., 2021 [17] for the case study of Portofino Promontory, Italy, was selected to be included in our developed methodology for the spatial allocation of NBS for shallow landslide risk reduction. The reasons for this choice are that the methodology incorporates all the commonly used landslide conditioning factors that, by contrast, were only adopted partially in the other reviewed articles. In addition, the methodology is characterised by a lower complexity, and the conditioning factors may be easily incorporated into an ArcGIS toolbox. Finally, the data were found to be easily accessible and available.

Table 1. Review of methodologies for landslide susceptibility mapping.

Methodology	Conditioning Factors	Reference
AHP and weighted linear sum	Slope gradient Aspect Lithology Land use Distance to hydrographical network Distance to roads Distance to built-up area Existing landslides Location of terraces	[17,25]
Fuzzy logic	Slope gradient Aspect Lithology Distance to hydrographical network Distance to roads	[26]
AHP and bivariate statistics	Slope gradient Lithology Land use	[16]
Spatial probabilistic modelling	Slope Aspect Curvature Lithology Land use Terrain morphology Distance to hydrographical network Distance to roads	[27,28]
USLE technique	Rainfall erosivity factor Soil erodibility factor Slope length and steepness Vegetation factor Support practices factor	[29]

3. Methodology for Mapping the Spatial Suitability of Large-Scale NBS

Utilising the method for mapping landslide susceptibility as an initial step, a methodology was developed with the primary objective of aiding decision-makers in the spatial allocation of NBS measures for building resilience and reducing vulnerability to shallow landslides by (1) mapping landslide susceptibility, (2) selecting NBS for landslide risk reduction, (3) spatially allocating NBS for landslide risk reduction, (4) developing a landslide measures toolbox, and (5) applying the results to the RECONECT (Regenerating ECOsystems with Nature-based solutions for hydro-meteorological risk rEduCTion) project study area.

3.1. Mapping Landslide Susceptibility

The GIS-based methodology developed by Roccati et al., 2021 [17] usingAHP and WLS for the identification of the areas susceptible to landslides within Portofino Natural Park in Italy was identified from the literature review and used in this section. According to this methodology, nine sets of conditioning factors were selected, followed by the assignment of individual weights and rankings based on the pair-wise comparison performed by five experts using a semi-qualitative MCDM approach AHP. The spatial data of the selected factors were rasterized and then reclassified into their respective weights, after which the rasters were combined by a weighted linear sum to obtain the final susceptibility map.

3.1.1. Selected Conditioning Factors

The selected conditioning factors for the shallow landslide susceptibility mapping were slope, aspect, lithology, land use, distance from the hydrographical network, distance from man-made structures, distance from man-made factors, location of the terraces, and existing gravitational processes. The different attributes of the selected pre-disposing factors were rasterized into individual maps with different available classes.

3.1.2. Deriving Weightages and Rankings Using AHP

The weights and ranking of the conditioning factors were determined using the analytical hierarchy process (AHP) by arranging them in a pair-wise comparison matrix. For pair-wise comparisons, the AHP employs the eigenvalue approach and recommends a method for calibrating the numeric scale for both quantitative and qualitative performance evaluation [30]. This approach involves comparing each criterion with a help of a questionnaire, and calculating the geometric mean to arrive at the final solution. For a further understanding regarding weight and rank classification using AHP, articles such as that of Roccati et al., 2021 and Saaty, 2001 [17,30] may be referred to. A list of normalized eigenvectors for the conditioning factors and the sub-classes, drawn up Roccati et al., 2021 [17], was used in this study and is attached in Appendix A.

3.1.3. Development of the Landslide Susceptibility Map

After developing the rasterized maps of the conditioning factors and deriving the weightages, the rasterized maps were reclassified into their respective weightage, derived in the above sections using the RECLASSIFY algorithm developed within the SAGA plugin of QGIS. These reclassified maps were further combined using weighted linear sum, and were normalised so that the values ranged between 0 and 1, in order to obtain the landslide susceptibility map (LSM). The weighted linear sum and the normalization were carried out using the raster calculator in QGIS, and can be expressed as

$$\mathrm{LSM} = \left(\sum_{i=1}^{n} w_{ij} w_j\right) / \left(\sum_{i=1}^{n} w_{ij} w_j\right)_{\max}, \quad (1)$$

where W_{ij} is the weight factor of class i belonging to the conditioning factor j, and W_j is the weightage of the conditioning factor j.

Finally, the results of the raster calculation were classified into five classes of susceptibility from very low to very high based on the histogram distribution for identifying the intervals of each class. The same methodology for identifying the landslide susceptibility was adopted and incorporated into our methodology of spatial allocation using ESRI ArcGIS.

3.2. Selection of NBS for Landslide Risk Reduction

On examining the existing case studies and literature on the implementation of nature-based interventions for improving slope stability, a wide number of measures were identified to be applied in different locations. In the context of our selected case study, Turconi et al., 2020 [31] highlighted the types of geo-hazards, caused by slope instability, that frequently cause damage to the Portofino promontory in Italy, as in many areas along the coastlines of the Mediterranean Sea, and identified a possible set of interventions to be implemented along with the RECONECT project. In lieu of this, the following types of measures for shallow landslide risk reduction were selected in our methodology to be spatially allocated.

3.2.1. Vegetative Measures

Planting vegetation on a slope can be a very efficient way to stabilize it, because the plant roots tend to anchor the soil and minimize compaction, allowing rainwater to infiltrate instead of flowing down the slope [32]. However, the selection of appropriate species of vegetation is an important factor for the efficient functioning of the measure. The United States Department of Agriculture (USDA) recommends the plantation of native species of trees and plants for improving slope stability [32]. Vegetative measures also include the removal of species that are alien to the local ecosystem, and those that promote slope instability.

3.2.2. Bio-Engineering Techniques

For slope gradients of more than 50%, vegetative measures may not be highly efficient [32]. This calls for the bio-engineering techniques which provide more structural reinforcement to the soil through using organic materials such as tree trunks, branches, live plants, etc. Some examples of bio-engineering measures are vegetated live crib walls and vegetated gabions.

3.2.3. Restoration of Terraces

The presence of abandoned terraces was identified as one of the contributing factors for soil mass movements such as debris flow, shallow landslides, etc. [33,34]. Terraces that have been abandoned due to the changing socio-economic conditions have led to the instability of the soil strata; this means the soil strata is easily eroded by intense rain events, often adding their effects to those of flash flooding. This kind of instability is mainly observed in the Mediterranean catchments, wherein high-intensity rain events trigger shallow landslides and other geo-hydrological hazards [35]. Restoration of these terraces would improve the soil stability within them, thus making them hard to erode. This makes restoration an efficient nature-based solution to shallow landslides, and a way of protecting these cultural and aesthetic landscapes.

3.3. Spatial Allocation of NBS for Landslide Risk Reduction

Slope gradient was identified as an appropriate criterion for the spatial allocation of NBS. Within our methodology, slope was used as a criterion for spatial allocation to identify the feasibility of vegetative measures and bio-engineering techniques. Based on the recommendations for improving slope stability made by the Natural Resources Conservation Agency, USDA [32], a slope threshold of 50% was adopted for classifying vegetative and bio-engineering measures. Furthermore, the restoration of terraces measure was allocated to all the terraced locations. A list of the selected NBS and their respective constraints are tabulated in Table 2.

Table 2. Constraints considered for the spatial allocation of NBS.

NBS Measures	Constraints
Vegetative measures	Slope < 50%
Bio-engineering techniques	Slope $\geq$ 50%
Restoration of terraces	Location of terraces

The selected constraints are combined with the landslide susceptibility map developed in the previous sections for the final suitability map of the selected NBS. The locations with medium to very high susceptibility were identified and segregated, after which they were combined with the respective measure-specific criteria to spatially allocate the selected measures. The process of combining the susceptible zones with the slope criteria to obtain the NBS suitability map was carried out using the "AND" operator within the raster calculator. For example, the equation for allocation of bio-engineering techniques used was "Suitable locations for bio-engineering techniques" = "Medium − Very high susceptible locations" AND "Slope above 50%".

3.4. Development of the Landslide Measures Toolbox

The methodology of landslide susceptibility mapping and the spatial allocation of NBS were used to develop the toolbox for the spatial allocation of NBS for shallow landslides. The toolbox layout consists of two parts: (1) landslide susceptibility mapping and (2) the spatial allocation of NBS.

The toolboxes were developed using the model builder within the ESRI ArcGIS environment. The model builder is a powerful GIS interface that helps us to generate a general workflow of our spatial analysis, using the spatial analyst and the other various tools available within ArcMap. The spatial analyst toolsets provide us with many efficient tools that may aid us in observing hydrological characteristics such as slope, aspect, watershed delineation, etc., and other spatial analysis tools such as the raster calculator, overlays, reclassification, etc. enable the use of the methodology in different study areas.

3.5. Application in the Case Study Area

The Portofino promontory (Figure 1), which is world famous for its attractive landscapes and cultural heritage, spans over an area of 18 km^2 in the eastern Liguria region of Northern Italy. It lies between the cities of Genoa and La Spezia. The terrain relief is oriented WNW-ESE, with an abrupt steep slope facing the sea. In the southern and western parts of the promontory, highly elevated mountains (up to about 600 m above sea level) and high cliffs with steepness ranging from 50–75% are present. On the contrary, the northern and the eastern borders and bounded with gentle hills ranging between 10–50% in steepness. Settlements of great value such as Camogli, San Fruttuoso, Portofino, Paraggi, and Santa Margherita are present at the foothills as boundaries along the coast. Due to its great cultural and environmental richness, the promontory has been protected since 1935 as the "Regional Natural Park of Portofino". Nowadays, more than 1 million tourists visit the promontory each year, and up to 80 km of footpaths have been created to facilitate 75,000 hikers per year [17].

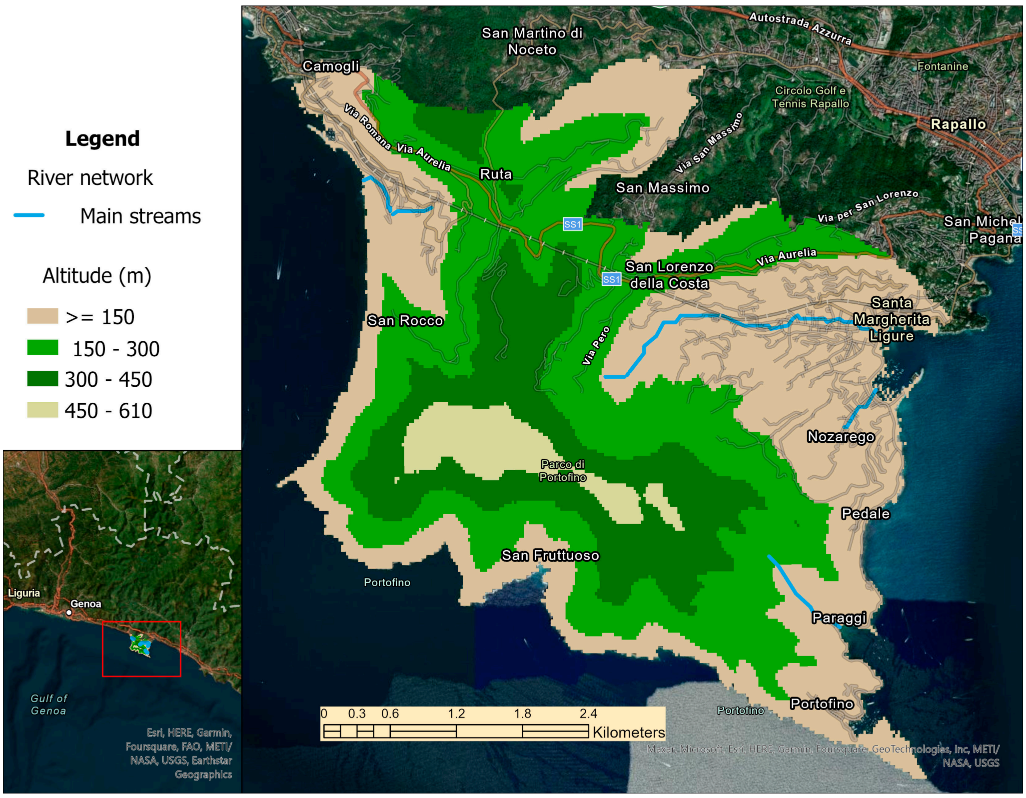

Figure 1. Location of the study area and the geographical setting of Portofino.

The meteorological setup of Portofino is characterised by a typical Mediterranean climate, with temperatures reaching up to 21–27 °C in summer, and between 5° and 11° in the winters. In any season, rainfall is reasonably widespread, with a mean annual rainfall of 1300 mm. The region is prone to high-intensity rain events that are usually triggered by the low-pressure system known as the Genoa Gulf cyclogenesis. Such intense rain events usually occur within the months of August to November, with higher intensities ranging up to 50 mm/h within six hours.

The geology of region consists of sedimentary rock masses made up of conglomerates and flysch. These conglomerates are mainly observed in the southern part of the promontory along steep slopes; they comprise several faults and fractures, oriented mainly in the NW-SE and NE-SW directions. Similarly, the flysch occupy the central and northern parts of the promontory and the outcrops along the western slopes, with WNW-ESE orientations. The distribution of the lithology over the promontory can be understood with the help of Figure 2. The high contrast between the resistance to folding between the conglomerate and flysch causes some landslides to form along the contact points between them. The landscape of the region is majorly constituted by terraces (both abandoned and active) created for agriculture, mainly olive plantations.

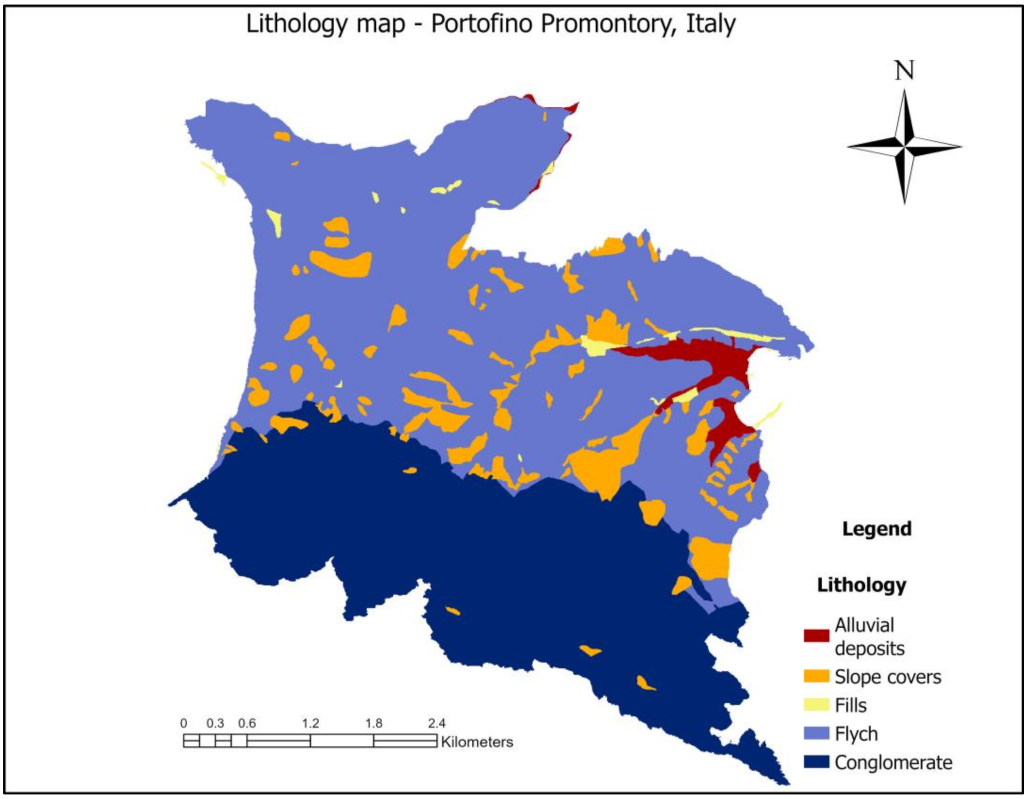

Figure 2. Lithology map of Portofino Natural Park.

The promontory's distinct geomorphological characteristics combined with its meteorological setup has led pre-dominantly to instability processes, resulting in geo-hydrological hazards such as shallow landslides, rock-falls, and mud/debris flows. These mass movements usually occur along the points of contact of the conglomerates and flysch formations. Twenty such severe incidents have been recorded since 1900 up to the present day, proving that this region is highly vulnerable to geo-hydrological hazards.

The toolboxes used within this study area and the suitability maps of the respective selected NBS were obtained. These suitability maps were further analysed based on the distribution of the suitable locations identified for each measure per catchment, as identified using the toolbox.

Furthermore, the suitability maps were overlaid on the satellite images to verify that the ideal locations determined by the toolbox do not overlap with any permanent structures within the urban landscape. Due to the exploratory nature of the research work, the results cannot be validated quantitatively.

4. Results

4.1. Landslide Susceptibility Mapping

The landslide susceptibility mapping was achieved using the selected methodology developed by Roccati et al., 2021 [17]. The GIS-based susceptibility mapping conducted for Portofino Natural Park in QGIS was adopted into the ArcGIS and converted into a model using the model builder plugin. The final landslide susceptibility map developed using the toolbox is presented in Figure 3.

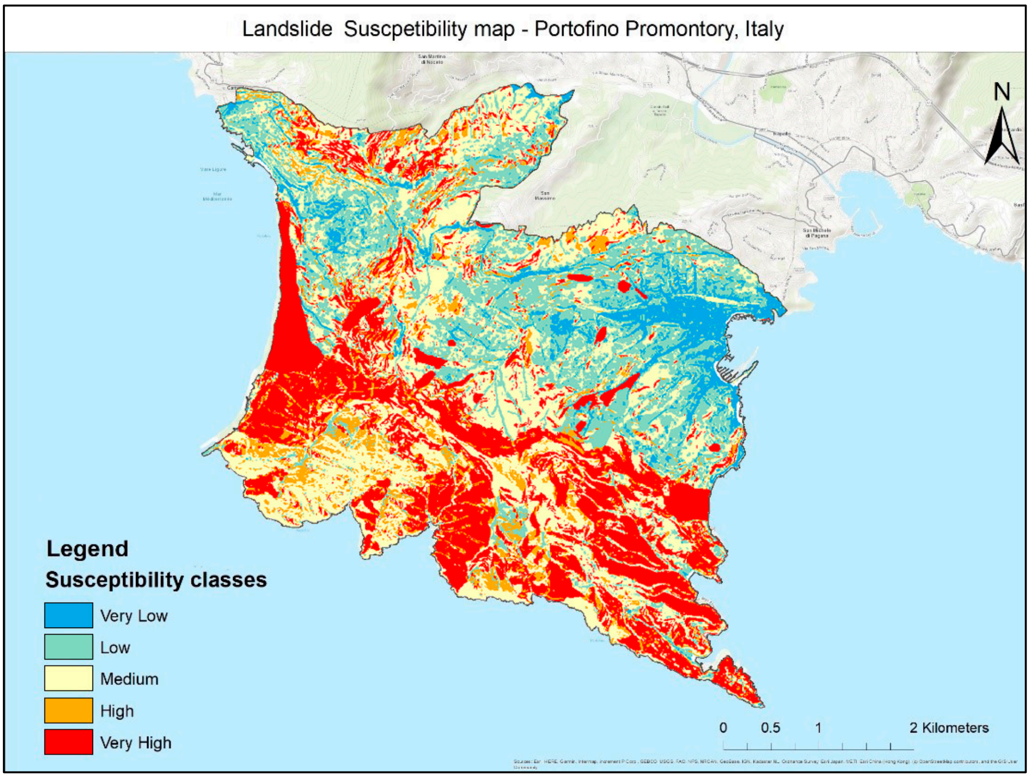

Figure 3. Landslide susceptibility map.

The developed landslide susceptibility map indicated that around 70% of the Portofino promontory is highly susceptible to shallow landslides, 34% is moderately susceptible, 9% is highly susceptible, and 27% is mapped as very highly susceptible to shallow landslides. Areas of low and very low susceptibility constituted 24% and 6% of the study area, respectively. The selected NBS measures were to be allocated within the moderate to very high susceptibility zones identified with the susceptibility map.

4.2. Spatial Allocation of NBS

From the landslide susceptibility map developed in the above section, the locations with medium to higher susceptibility values above 0.6 were segregated, to be allocated the selected NBS measures. A slope criteria of 50% was selected and used to classify the allocation of vegetative and soil bio-engineering measures to the selected susceptible locations (Figure 4).

The individual maps were then added with the reclassified rasterized map of the location of terraces for the allocation of the restoration of terraces measure.

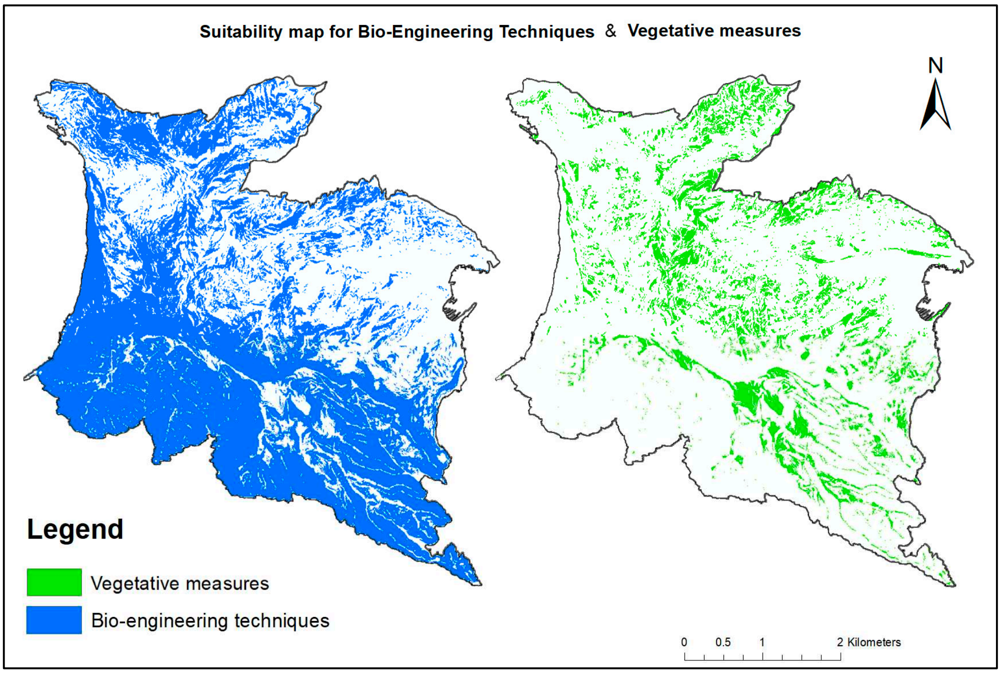

Figure 4. Individual suitability maps for bio-engineering and vegetative measures.

The final suitability maps of the individual measures were combined using raster sum after reclassifying the values: (0, 1)—vegetative measures, (0, 10)—bio-engineering techniques, and (0, 100)—location of terraces.

The final output map of the toolbox consists of data belonging to four classes (0, 1, 10, 100–110). The locations of value 1 denote appropriate locations for vegetative measures, the locations of value 10 denote feasible areas for bio-engineering measures. The locations with values from 100–110 are grouped together, and represent the restoration of terraces measure. The final spatial allocation of the NBS for landslide risk reduction, obtained using the toolbox, is given in Figure 5 below.

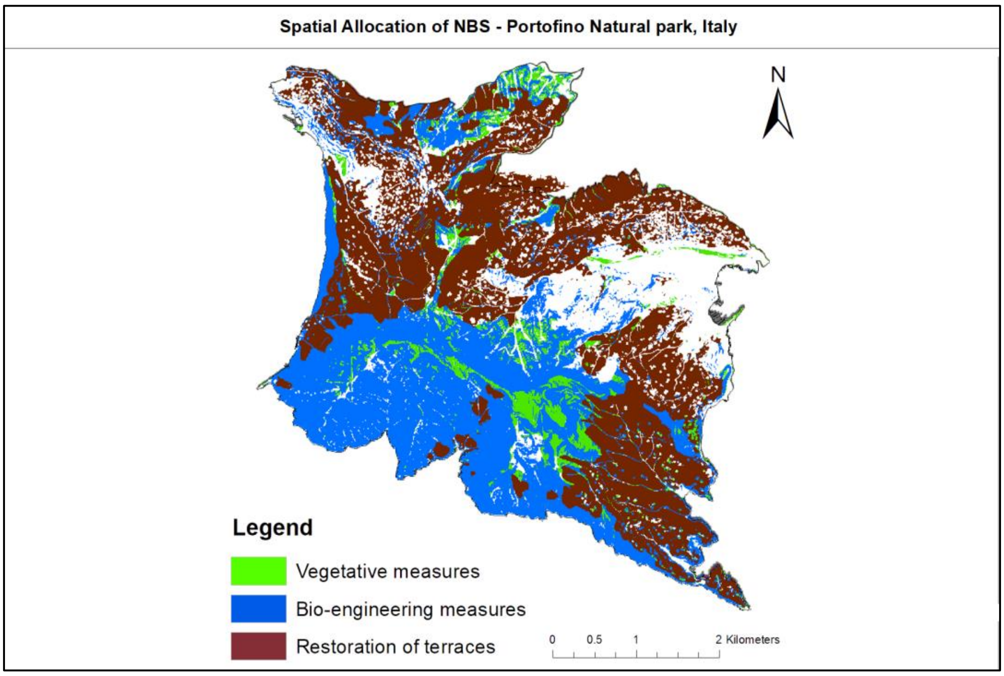

Figure 5. Spatial allocation of NBS for landslide risk reduction, Portofino Natural Park, Italy.

At the end of the final spatial allocation of NBS selected for the reduction of slope instability hazards in Portofino, vegetative measures and bio-engineering measures were found to be allocated each to about 6% (130 ha) and 33% (743 ha) of the park, respectively, and the restoration of terraces was found to be allocated to 41% (926 ha). After accounting for the restoration of terraces, 19% (433 ha) of the land does not fit any of the suitability criteria for the interventions considered in this study.

5. Discussion

The toolbox was developed in the model builder plugin of ArcMap. Although ESRI ArcGIS is a standard software, it is a proprietary software, and may not be accessible to individuals and smaller organisations interested in carrying out similar work. The methodology presented has the potential to be replicated in an open-source GIS environment such as QGIS. It must also be noted that ArcMap has its own limitations, including the presence of bugs that lead to the unexpected crashing of the software, and errors while running the toolbox.

The susceptibility map developed using the toolbox was compared with the final landslide susceptibility map published in the study by Roccati et al., 2021 [16] using Cohen's Kappa. The Kappa value was 0.932, and the correct fraction was 0.946. The difference in the results between the two studies can be attributed to the differences in weightages used for the conditioning factors, as the current research does not use the exact values of the previous work.

The spatial allocation toolbox can only serve the preliminary survey in the allocation of NBS, and the suitable locations can be finalised only after a physical survey of the selected locations. A comparison of the suitability with satellite images and digital images from Google Earth Pro, as shown in Figure 6a,b, shows that the areas suggested do not encroach on settlements. However, not all existing infrastructure within the study area is accounted for by the input used, and the suitability maps cannot be fully verified without the help of on-site surveys of the study area. The suitability maps are an initial input for the larger planning process, and have the potential to guide planners and decision makers on where interventions may be possible.

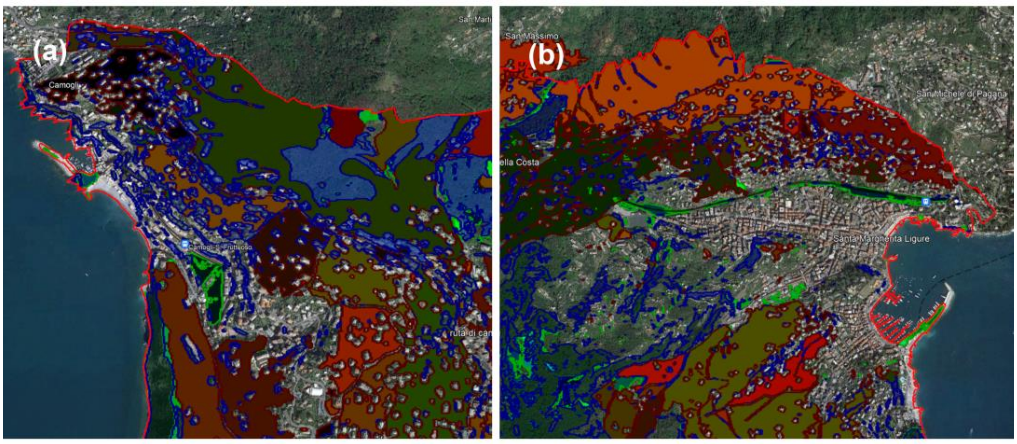

Figure 6. Comparison of suitability maps with digital images of areas in the (**a**) North Western and (**b**) Eastern sections of Portofino.

The weightages used in the landslide risk mitigation toolbox are based on local conditions specific to the case study of Portofino, and cannot be applied for other locations. The weights can only be derived by experts with knowledge about local landslide-triggering factors existing in the location if reliable results are to be obtained. Replication of the method is dependent on such expertise being available, along with the input data and the required maps being accessible.

The weights used in Roccati et al. (2021) [17] come from the statistics of the conditioning factors, considering more than 100 events that happened in the Portofino promontory; the model has been validated using a random 20% of these events. Such values are considered valid in similar conditions, i.e., in small steep catchments close to the promontory that share similar geomorphological and geological assets. The application of the method in a different context requests the prior calculation of proper statistics related to the conditioning factors, and the use of a statistically significant number of events. Then, after a proper calibration, this will allow the researcher to adapt and fine tune the weights to be used into the toolbox.

6. Conclusions

The main objective of this exploratory research study was to develop a GIS-based methodology for mapping the suitability of nature-based solutions to hydrological and geo-hydrological extreme events, making use of landslide susceptibility mapping. Out of five reviewed methods for mapping landslide risk, AHP and WLS by Roccati et al., 2021 [17] were used for the initial step of the suitability mapping process, followed by mapping the suitability of different risk reduction measures; vegetative measures, bioengineering techniques, and the restoration of terraces, based on slope conditions. The method was successfully implemented in the ESRI ArcMap work environment, thus producing a GIS toolbox.

The landslide risk reduction toolbox was applied to the case study area of Portofino promontory. The medium to highly susceptible locations for shallow landslides were identified via susceptibility mapping, and these areas were used in the following step for mapping the suitability of measures based on slope conditions. The presence of abandoned terraces in the selected case study acts as an important factor in slope instability and erosion-induced shallow landslides [35], and the restoration of terraces was also included as a potential intervention; this was allocated based on the location of existing structures.

The final resulting suitability maps for the three discussed NBS showed a good fit, and these maps can potentially be used for the planning of risk reduction measures and for prioritising areas that are most susceptible to landslide risk. Suitability maps can inform decision makers on where interventions are needed more urgently, in order to prevent further damage to the park and to reduce losses in the face of the changing risk landscape and the increasing frequency of extreme hydrometeorological events. Finally, this approach may be applied to similar situations in the Mediterranean area; in addition, the proposed methodology may be upscaled easily.

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Appendix A. List of Weights for Landslide Susceptibility Mapping

Following are the list of weightages/normalised eigenvectors used for landslide susceptibility mapping, derived using AHP by Roccati et al. (2021) [17].

Table A1. Weightage of each conditioning factor derived using AHP (Roccati et al., 2021, [17]).

Number	Conditioning Factor	Weight/Normalised Eigenvector
1	Lithology	0.155
2	Aspect	0.090
3	Acclivity	0.311
4	Land use	0.197
5	Terraced area	0.064
6	Distance hydrographic elements	0.034
7	Distance man-made cuts	0.031
8	Distance man-made structures	0.055
9	Existing landslides	0.063

Table A2. Weightage for each sub-class within each conditioning factor (Roccati et al., 2021, [17]).

Class Number	Conditioning Factor	Weight
	Lithography	
1	Alluvial deposits	0.031
2	Slope covers	0.093
3	Fills	0.061
4	Flysch	0.507
5	Conglomerate	0.308
	Aspect	**Weight**
1	NORD	0.0318
2	NORD-EST	0.0617
3	EST	0.2472
4	SUD-EST	0.0355
5	SUD-EST	0.0628
6	SUD-OVEST	0.111
7	OVEST	0.144
8	NORD-OVEST	0.285
9	ZENIT	0.021
	Slope	**Weight**
1	0–10%	0.033
2	11–20%	0.033
3	21–35%	0.09
4	36–50%	0.09
5	51–75%	0.331
6	76–100%	0.221
7	>100%	0.202
	Land use	**Weight**
1	Urban fabric	0.149
2	Industrial/commercial/transport units	0.038
3	Artificial non-agricultural areas	0.041
4	Arable land	0.034
5	Permanent crops	0.204
6	Pastures	0.034
7	Heterogeneous agricultural areas	0.038
8	Forests	0.358
9	Shrubs	0.064
10	Open space with little/no vegetation	0.04

Table A2. *Cont.*

Class Number	Conditioning Factor	Weight
	Terraced area	**Weight**
1	Area without terraces	0.261
2	Area with terraces	0.739
	Distance hydrographic elements	**Weight**
1	Watercourses, d > 10 m	0.394
2	Watercourses, d < 10 m	0.081
3	Springs, d > 10 m	0.471
4	Springs, d < 10 m	0.054
	Distance man-made cuts	**Weight**
1	Man-made cuts, d > 5 m	0.672
2	Trails, d < 5 m	0.127
3	Main roads, d < 5 m	0.122
4	Minor roads, d < 5 m	0.079
	Distance man-made structures	**Weight**
1	Man-made structures, d > 10 m	0.541
2	Buildings, d < 10 m	0.16
3	Other manufacts, d < 10 m	0.077
4	Retaining walls, d < 10 m	0.222
	Existing landslides	**Weight**
1	Inactive/stabilized	0.0438
2	Dormant	0.0597
3	Active/reactivated/suspended	0.1333
4	Area affected by widespread shallow landslides	0.0403
5	Assumed stable area, d > 50 m	0.4232
6	Assumed stable area, d < 50 m	0.2997

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