SAFE-LAND

Mitigating the risk of flooding and landslides via artificial intelligence with a view to extreme climate events

Deliverable 3.3:
Reference guidelines

MITIGATING THE RISK OF FLOODING AND LANDSLIDES VIA ARTIFICIAL INTELLIGENCE WITH A VIEW TO EXTREME CLIMATE EVENTS

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Abstract	This document is the Deliverable 3.3 of the project "M*itigating the risk of flooding and landslides via artificial intelligence with a view to extreme climate events* (SAFE-LAND)". The aim of the technical activities of WP3 is to perform the landslide and flood risk assessment, the evaluation of people's risk awareness, and to suggest guidelines to mitigate the hydrogeological risk and to increase people's risk awareness for reference areas. This deliverable provides guidelines suggesting the most effective mitigation measures among all possible measures to reduce the hydrogeological hazard of the elements slope and river, and to raise risk awareness.
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1. INTRODUCTION

The first four tasks of WP3 aimed to:

- define representative reference elements, e.g., slopes, rivers, and people, and their element parameters (EPs);
- define the reference climate events (RCEs) and their climate parameters;
- select for each type of element appropriate damage parameters (DPs) able to quantify the effects of RCEs on the reference elements;
- evaluate the DPs values for each reference element and its risk level.

As a result of these activities, the knowledge base (KB) dataset to train the AI system is completely set up. Based on the KB dataset, mitigation measures can be proposed in order to reduce the landslide/flooding hazard and raise risk awareness.

This deliverable provides guidelines suggesting the most effective structural mitigation measures among possible solutions to reduce the landslide/flooding hazard of the reference slopes and rivers. The guidelines for the *reference* elements are used to train the AI system with the aim to suggest the most suitable mitigation measures for the *real* elements. The stabilization measures here described are engineering works aimed at reducing the possibility of occurrence of a landslide/flooding event. The document presents an overview of the technical and practical aspects of mitigation measures of landslide and flooding risk, offering preliminary guidance for selecting appropriate interventions during the initial phase of decision-making. The design and detailed implementation of the interventions should be managed individually by qualified professionals, taking into account the relevant regulations and local context-specific practices.

With reference to the “element” people, the consideration of the quality of risk perception and the psychological vulnerability of individuals in case of floods and landslides has led to the use of self-report psychological measures to implement the emergency management system through:

1. the promotion of effective preventive preparation and risk communication that support an adequate knowledge and awareness of risks and consequent functional and protective response in the event of a flood/landslide emergency

2. the promotion of early identification of the subjects most vulnerable to adverse psychological consequences in the event of floods/landslides in the post-event recovery phase.

The document is organized as follows. Section 2 and 3 describe the reference slopes/rivers stabilization measures and the procedure followed to suggest the most effective and applicable measures based on the DPs of the reference slopes and rivers, while Section 4 describes the guidelines on the effective preventive preparation/risk communication and early identification of people’s psychological vulnerability.

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2. SLOPES STABILIZATION MEASURES

This section aims to suggest guidelines on the slope stabilization measures, i.e., the structural measures that increase the factor of safety (FoS) of the *reference* slopes and reduce the likelihood of triggering the landslide addressed by the specific measure.

Independently of the peculiar conditions of a specific slope, the triggering factors of slope movements are:

a) reduction in shear strength, for example caused by the infiltration due to rainfall;
b) increase in driving shear stress, for example caused by an excavation at the toe or surcharging at the top of the slope.

Many processes affect both the shear strength and driving shear stresses, e.g., in case of basal erosion or excavations, which can cause both an increase in driving shear stresses, through increased slope angle and/or height, or a decrease in shear strength, through a reduction in total and effective stress. Therefore, to minimize the likelihood of triggering a landslide, mitigation strategies have to enhance resisting forces and/or diminish driving forces (Hutchinson, 1977).

In the following we consider five groups of slope stabilization measures which may be used singly or in combination and which are classified based on the physical process involved. The considered types of stabilization measures are:

1. surface erosion control strategies,
2. modification of slope geometry and/or mass distribution,
3. modification of the groundwater regime through drainage systems,
4. systems designed to transfer loads to more competent substrata,
5. retaining structures.

In case of unstable slopes (FoS ≤ 1), the selection of the most effective stabilization measure can be made using predefined *effectiveness matrices*. For each technique, an effectiveness matrix is set up that quantifies the degree of stabilization by using an effectiveness score based on the interaction between the values of the following DPs:

- the maximum depth of the potential sliding surface (z_s);
- the maximum depth of the piezometric level ($z_{w\,max}$).

According to the LaRiMiT database (https://www.larimit.com/), adapted effectiveness scores are discretized as follows:

- 1 = high effective (green)
- 0,5 =quite effective (orange)
- 0,25 = moderately effective (yellow)
- 0 = ineffective (white).

When multiple stabilization measures achieve the same score, the selection requires inspecting the *applicability matrix.* This matrix considers additional practical aspects (reliability, feasibility,

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ease of implementation, and indicative cost) by assigning each intervention an applicability score (S).

- S> 3 (green): The measure is highly recommended.
- 2 > S ≥ 3 (orange): The measure is suggested.
- 1 > S ≥ 2 (yellow): The measure is poorly suitable.
- S < 2 (white): The measure is not recommended.

The following section overviews the five principal groups (G1 – G5) of slope stabilization measures considered in this document, along with their *effectiveness* and *applicability matrices*. These matrices set up for the *reference* slopes are used to train the AI system with the aim to suggest the most suitable slope stabilization measures for the *real* slopes.

2.1. G1 (Group 1): Erosion control

Erosive processes stem from multiple concurrent factors, with rainfall being the primary agent. Slope vegetation controls and mitigates water erosion processes. The protective role of vegetation in mitigating slope erosion has been extensively studied and documented. Depending on the vegetation type—arboreal and/or herbaceous—soil erosion can be partially inhibited by the absorption of raindrop kinetic energy, the reduction of runoff velocity, and the delay in reaching complete soil saturation. In recent years, different studies have quantitatively assessed the effects of vegetation on soil shear strength, either by direct shear testing of root-permeated soils or by incorporating vegetation effects into shear strength parameters. Recent contributions in this field include for example those by Leung et al. (2015), Kamchoom et al. (2022), Phan et al. (2025).

Five main sub-groups (G1.1 – G1.5) of erosion control measures are considered in this document:

- **G1.1 Hydroseeding**
- **G1.2 Turfing**
- **G1.3 Tree bushes direct/pit planting**
- **G1.4 Live/inert fascines and straw wattles**
- **G1.5 Brush mattresses**

G1.1. Hydroseeding consists in the application of a slurry composed of wood fiber, seeds, fertilizers, and a stabilizing emulsion using hydromulch equipment to protect exposed soils from water erosion. It is especially effective for large areas and is the most popular method to create vegetation at the surface where the accessibility is limited (Xiao et al., 2017). Hydroseeding reduces runoff and soil loss (Albaladejo Montoro et al., 2000). It can also be combined with biodegradable geotextiles to enhance erosion control measures. Table 2.1 is the effectiveness matrix set up for the hydroseeding technique.

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Table 2.1. Effectiveness matrix of G1.1.

G1.1 HYDROSEEDING			**Depth of piezometric level**		
			High	Low	Absent
			0,5	0,5	0,5
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**0,5**	**0,5**
	Shallow (1 to 3 m)	0,5	**0,25**	**0,25**	**0,25**
	Medium (3 to 8 m)	0	**0**	**0**	**0**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G1.2. **Turfing** consists in the direct application of grass with an established root system onto the slope surface. It is suggested to mitigate runoff and rainsplash erosion, as grass can intercept and absorb rainfall. Grass plants are lightweight, with approximately 90% of their biomass consisting of roots. Turfing can be a long-term solution for surface erosion control without spoiling the landscape. This method is very labour-intensive and usually only applied to gentle slopes for residual soil (Niroumand et al., 2012). Table 2.2 shows the effectiveness matrix set up for the turfing.

Table 2.2. Effectiveness matrix of G1.2.

G1.2 TURFING			**Depth of piezometric level**		
			High	Low	Absent
			0,5	0,5	0
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**0,5**	**0**
	Shallow (1 to 3 m)	0,5	**0,25**	**0,25**	**0**
	Medium (3 to 8 m)	0	**0**	**0**	**0**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G.1.3. Tree bushes direct/pit planting involves the planting of woody vegetation, including shrubs, plants, and trees, along slopes to mitigate erosion and reinforce soil stability. Live planting is among the most effective methods for establishing woody vegetation on challenging sites, as it bypasses the germination phase, providing a significant advantage over direct seeding. Trees are preferred to herbaceous species for slope stabilization even in steep slopes because the roots reinforce the soil and reduce the water content (Lyons, 2000).

Seeding pits are dug along the slope to accommodate vegetation. The depth at which the cuttings are placed and the extent to which the roots penetrate the substrate are the

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determining factors for the effectiveness of this intervention. In Table 2.3 the effectiveness matrix of sub-group G1.3 is reported.

Table 2.3. Effectiveness matrix of G1.3.

G1.3 TREE BUSHES DIRECT/PIT PLANTING			**Depth of piezometric level**		
			High	Low	Absent
			1	0,5	0,5
Depth of sliding surface	Superficial (<1.0 m)	1	**1,0**	**0,5**	**0,5**
	Shallow (1 to 3 m)	0,5	**0,5**	**0,25**	**0,25**
	Medium (3 to 8 m)	0	**0**	**0**	**0**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G1.4. Live and inert fascines are elongated tubular bundles composed of cuttings from living woody plant material, strategically placed in trenches across a bank slope and secured with wooden stakes. Live fascines are designed to sprout, forming a root network that reinforces the soil and promoting top growth that enhances surface protection, while inert fascines are not intended to grow but serve to stabilize the toe of the streambank while other vegetation establishes. Fascines arrest soil erosion and enhance the slope stability (Punetha et al., 2018)

The technique of straw wattles is similar to live bundles, but they are made of recycled straw enclosed in biodegradable protective material that are placed in shallow trenches to intercept the surface runoff of water (Sotir & Fischenich, 2001). The effectiveness matrix of sub-group G1.4 is shown in Table 2.4.

Table 2.4. Effectiveness matrix of G1.4.

G1.4 LIVE/INERT FASCINES AND STRAW WATTLES			**Depth of piezometric level**		
			High	Low	Absent
			0,5	0,5	0
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**0,5**	**0**
	Shallow (1 to 3 m)	0,5	**0,25**	**0,25**	**0**
	Medium (3 to 8 m)	0	**0**	**0**	**0**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G1.5. Brush mattresses is a layer mattress of interlaced live branches placed on the slope surface to create a protective homogeneous living ground protecting against runoff and soil erosion, and stabilizing the slope (Allen & Fischenich, 2001) . Once fully developed, the brush mattress ensures complete vegetation coverage across the bank face, promoting natural infiltration and effectively functioning as a sediment trap. Brush mattresses reduce significantly

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soil erosion, by increasing the soil retention capability (Sokopp et al., 2022). Table 2.5 is the effectiveness matrix set up for the brush mattresses.

Table 2.5. Effectiveness matrix of G1.5.

G1.5 BRUSH MATTRESSES			Depth of piezometric level		
			High	Low	Absent
			1	0,5	0,5
Depth of sliding surface	Superficial (<1.0 m)	1	**1**	**0,5**	**0,5**
	Shallow (1 to 3 m)	0,5	**0,5**	**0,25**	**0,25**
	Medium (3 to 8 m)	0	**0**	**0**	**0**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

Table 2.6 shows the applicability matrix of the group G1 interventions with the applicability scores for each sub-group considering practical aspects such as reliability, feasibility, ease of implementation, and indicative cost. The applicability matrix can be used to select a type of intervention when two or more measures are characterized by the same level of effectiveness.

Table 2.6. Applicability matrix for measures of G1 group.

	G1.1	G1.2	G1.3	G1.4	G1.5
Reliability	1	1	1	1	1
Feasibility	1	1	1	1	1
Implementation	0,5	1	1	0,5	1
Typical cost	1	1	1	1	1
tot.	**3,5**	**4**	**4**	**3,5**	**4**

2.2. G2 (Group 2): Modification of slope geometry

Since the forces tending to cause movements downslope are essentially gravitational, a simple approach to increasing stability is to reduce the mass of soil involved in the slope. Measures such as the removal of unstable soil, toe weighting, reprofiling, excavation, and the use of lightweight fill at the head or gravity structures at the toe are aimed at modifying the balance between driving and resisting forces, thereby reducing landslide risk and potential impacts.

Cuts and fills are particularly effective as hazard mitigation measures for deep rotational and pseudo-rotational landslides, where the slip surface steeply falls at the head and significantly rises at the toe (Hutchinson, 1977). The effectiveness of a corrective cut or fill depends on its location, weight, and shape, as well as the characteristics of the actual or potential landslide being treated. Hutchinson (1977) proposed the "neutral line" concept to evaluate the effectiveness of performing cuts and/or fills at different locations on the slope. The neutral line represents a theoretical boundary within a slope where applied loads neither increase nor decrease the *FoS* of a potential failure surface. When a load is placed downslope, near the toe, it generally increases *FoS*, enhancing stability. Conversely, when a load is applied upslope, near the crest, it tends to decrease *FoS*, promoting instability. The neutral line marks the transition between these two effects.

Four main sub-groups (G2.1 – G2.4) of modification of slope geometry measures are considered in this document:

- **G2.1 Completely or partially remove unstable materials**
- **G2.2 Removal of material from driving area**
- **G2.3 Substitution of material in driving area with lightweight fill**
- **G2.4 Addition of material to the area maintaining stability**

G2.1. The complete/partial removal of an unstable or potentially unstable mass represents an effective and economically viable mitigation strategy, generally indicated only for small slopes, while large-scale excavation of extensive landslide-prone areas is typically discouraged due to economic constraints, environmental impacts, and the potential destabilization of adjacent slopes (Duncan, 2008; Hutchinson, 1977). Table 2.7 is the effectiveness matrix set up for the G2.1 measure.

Table 2.7. Effectiveness matrix of G2.1.

G2.1 COMPLETELY OR PARTIALLY REMOVE UNSTABLE MATERIALS			**Depth of piezometric level**		
			High	Low	Absent
			0,5	0,5	0,5
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**0,5**	**0,5**
	Shallow (1 to 3 m)	0,5	**0,25**	**0,25**	**0,25**
	Medium (3 to 8 m)	0,5	**0,25**	**0,25**	**0,25**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G2.2. The removal of material from the driving zone—or more generally, the regrading or flattening of slope geometry—reduces driving forces. This approach is most effective in cases where instability mechanisms are governed by rotational or pseudo-rotational sliding, and it is generally ineffective for translational slides. The excavation must be strategically positioned to ensure that the reduction in driving forces outweighs the loss of drag forces, taking into account the concept of a neutral line (Alonso et al., 1993). Drainage measures must be provided to prevent the infiltration of surface water into the landslide mass. Table 2.8 shows the effectiveness matrix for the removal of material from the driving zone.

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Table 2.8. Effectiveness matrix of G2.2.

G2.2 REMOVAL OF MATERIAL FROM DRIVING AREA			Depth of piezometric level		
			High	Low	Absent
			0,5	1	1
Depth of sliding surface	Superficial (<1.0 m)	0,5	**0,25**	**0,5**	**0,5**
	Shallow (1 to 3 m)	0,5	**0,25**	**0,5**	**0,5**
	Medium (3 to 8 m)	1	**0,5**	**1**	**1**
	Deep (8 to 15 m)	0,5	**0,25**	**0,5**	**0,5**
	Very deep (>15m)	0,5	**0,25**	**0,5**	**0,5**

G2.3. This mitigation strategy involves **digging the material out of the driving zone, followed by replacing it with a lightweight fill material**, reducing the driving forces acting on the surface of potential failure (Di Prisco, 2007; Dubreucq & Pezas, 2009). The infill material must have adequate shear strength while minimizing the additional load on the slope. This technique reduces the driving forces to a greater extent than the resisting forces through changes in the distribution of mass or load on the slope**.** This type of measure is particularly effective for rotational or pseudo-rotational sliding mechanisms, while it is generally ineffective for translational landslides. Table 2.9 shows the effectiveness matrix for the substitution of material in the driving area with lightweight fill.

Table 2.9. Effectiveness matrix of G2.3.

G2.3 SUBSTITUTION OF MATERIAL IN DRIVING AREA WITH LIGHTWEIGHT FILL			Depth of piezometric level		
			High	Low	Absent
			0,5	1	1
Depth of sliding surface	Superficial (<1.0 m)	0,5	**0,25**	**0,5**	**0,5**
	Shallow (1 to 3 m)	0,5	**0,25**	**0,5**	**0,5**
	Medium (3 to 8 m)	1	**0,5**	**1**	**1**
	Deep (8 to 15 m)	0,5	**0,25**	**0,5**	**0,5**
	Very deep (>15m)	0,5	**0,25**	**0,5**	**0,5**

G2.4. The addition of material to the area improves slope stability through increased drag forces. This approach provides adequate dead weight or structural reinforcement near the tip of the unstable slope, effectively counteracting driving forces and mitigating the risk of failure (Holtz & Shuster, 1996). The technique is effective for instability mechanisms characterized by rotational or pseudo-rotational sliding, and is generally ineffective for translational landslides. In the case of large slopes, this mitigation measure must be supplemented by drainage systems and other stabilization techniques to improve long-term effectiveness. When placing the fill material directly on a landslide body, it is crucial to take into account the simultaneous increase

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in driving forces. To ensure effective stabilization, the infill must be strategically positioned so that the resulting increase in drag forces outweighs the additional driving forces, taking into account the neutral line concept. Table 2.10 shows the effectiveness matrix for the sub-group G2.4.

Table 2.10. Effectiveness matrix of G2.4.

G2.4 ADDITION OF MATERIAL TO THE AREA MAINTAINING STABILITY			**Depth of piezometric level**		
			High	Low	Absent
			1	1	1
Depth of sliding surface	Superficial (<1.0 m)	0,5	**0,5**	**0,5**	**0,5**
	Shallow (1 to 3 m)	0,5	**0,5**	**0,5**	**0,5**
	Medium (3 to 8 m)	1	**1**	**1**	**1**
	Deep (8 to 15 m)	0,5	**0,5**	**0,5**	**0,5**
	Very deep (>15m)	0,5	**0,5**	**0,5**	**0,5**

Table 2.11 shows the applicability matrix of the measures of group G2 indicating the total applicability score for each intervention.

Table 2.11. Applicability matrix for measures of G2 group.

	G2.1	**G2.2**	**G2.3**	**G2.4**
Reliability	1	0,5	0,5	1
Feasibility	1	1	0,5	1
Implementation	1	1	0,5	1
Typical cost	0,5	1	0,5	1
tot.	**3,5**	**3,5**	**2**	**4**

2.3 G3 (Group 3): Drainage

Drainage interventions aim to remove surface and subsurface waters in the unstable slopes or foundational soils. In saturated soil, drainage systems are one of the most effective remedial measures against slope stability due to their capacity to reduce pore-water pressure in the subsoil, increasing the shear strength of the soil (D'Acunto & Urciuoli, 2006; Urciuoli & Pirone, 2013). Drainage both reduces the weight of the mass tending to cause the landslide and increases the strength of the soil in the slope.

Drainage interventions can be divided into two main categories:

- **Surface drainage works:** These include operations for the regulation and drainage of surface waters and first-response slope stabilization. They are quicker and easier to install

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and maintain, but are more prone to damage and require continuous maintenance.

- **Deep drainage works:** Typically designed as permanent solutions, these require more complex works and equipment for their installation and are more costly. However, despite these drawbacks, they ensure greater effectiveness in stabilizing landslide-prone slopes.

G.3A Surface water regime modification

By implementing surface drainage solutions, it is possible to mitigate the erosive impact of surface water and runoff, thereby improving slope stability and reducing the failure risks of subsidence.

Diversion ditches and interceptor drains are widely implemented as erosion control measures for surface drainage, particularly in scenarios where substantial runoff volumes are expected. Surface drainage allows surface water to be efficiently diverted away from the slope, increasing its safety. These are particularly important following a landslide event, as unsealed cracks and fissures behind the face of the escarpment can facilitate water infiltration into the rupture zone, potentially triggering reactivation.

Five main sub-groups (G3A.1 – G3A.5) of surface drainage measures are selected and described in this document:

- **G3A.1 Surface drainage works**
- **G3A.2 Local regrading to facilitate run-off**
- **G3A.3 Sealing tension cracks**
- **G3A.4 Impermeabilization**
- **G3A.5 Vegetation – hydrological effects**

G3A.1. Surface drainage works constructed on the main landslide body serve to manage local surface runoff and any water discharged from deep drainage systems. These drainage features play a critical role in preventing uncontrolled infiltration and reducing the risk of slope destabilization. Various ditch types are employed for surface runoff management. To minimize erosion and uncontrolled infiltration, drainage ditches should be properly lined. Rainfall infiltration is limited to a certain depth below which infiltration becomes insignificant (Rahardjo et al., 2003). Suitable lining materials include cast-in-place or prefabricated concrete, pitched stone, rip rap, gabion mattresses or baskets, specialty geotextiles or geocomposites, zinc-coated steel, or PVC half-pipes. Table 2.12 shows the effectiveness matrix for the surface drainage works.

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Table 2.12. Effectiveness matrix of G3A.1.

G3A.1 SURFACE DRAINAGE WORKS			Depth of piezometric level		
			High	Low	Absent
			0,5	0,5	0,5
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**0,5**	**0,5**
	Shallow (1 to 3 m)	1	**0,5**	**0,5**	**0,5**
	Medium (3 to 8 m)	0,5	**0,25**	**0,25**	**0,25**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G3A.2. Local regrading to facilitate run-off is a technique where the surface of the slope is smoothed to eliminate localized depressions in which stagnation could occur, minimizing the accumulation of water and reducing the risk of infiltration.

Any concave areas that hold standing water should be filled. These efforts should be supplemented with shallow and/or shallow drainage systems. The engineering approach should aim to preserve the overall mass distribution of the slope, avoiding substantial alterations unless explicitly required for stabilization purposes. In such cases, modifications should be executed ensuring structural integrity and long-term stability. In Table 2.13 the effectiveness matrix for the sub-group G3A.2 is reported.

Table 2.13. Effectiveness matrix of G3A.2.

G3A.2 LOCAL REGRADING TO FACILITATE RUN-OFF			Depth of piezometric level		
			High	Low	Absent
			0,5	0,5	0,5
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**0,5**	**0,5**
	Shallow (1 to 3 m)	1	**0,5**	**0,5**	**0,5**
	Medium (3 to 8 m)	0,5	**0,25**	**0,25**	**0,25**
	Deep (8 to 15 m)	0,5	**0,25**	**0,25**	**0,25**
	Very deep (>15m)	0	**0**	**0**	**0**

G3A.3 Sealing tension cracks is a technique that involves filling tension cracks with puddle clay or other impermeable materials. A practical approach is to dig a trench along the crack and fill it with the excavated impermeable soil, enriched with small amounts of bentonite or other natural materials to reduce its permeability. The existence of cracks on slopes usually provides an easy pathway for rainfall infiltration into soil, allowing rain to infiltrate deeper layers than the absence of cracks (Mukhlisin and Khiyon, 2018). In Table 2.14 the effectiveness matrix for the sealing tension cracks technique is shown.

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Table 2.14. Effectiveness matrix of G3A.3.

G3A.3 SEALING TENSION CRACKS			Depth of piezometric level		
			High	Low	Absent
			0,5	0,5	1
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**0,5**	**1**
	Shallow (1 to 3 m)	1	**0,5**	**0,5**	**1**
	Medium (3 to 8 m)	0,5	**0,25**	**0,25**	**0,5**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G3A.4 For **impermeabilization**, waterproof membranes are typically employed as short-term or emergency solutions to prevent an increase in piezometric levels within the unstable mass, which would result in a decrease in effective stress and the consequent decrease in shear strength along the sliding surface. Membranes help to avoid slope instability caused by precipitation penetration (Ma et al., 2023). Table 2.15 shows the effectiveness matrix for the G3A.4 interventions.

Table 2.15. Effectiveness matrix of G3A.4.

G3A.4 IMPERMEABILIZATION			Depth of piezometric level		
			High	Low	Absent
			0,5	1	1
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**1**	**1**
	Shallow (1 to 3 m)	1	**0,5**	**1**	**1**
	Medium (3 to 8 m)	0,5	**0,25**	**0,5**	**0,5**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G3A.5 Vegetation plays a crucial role in soil hydrology by improving the evapotranspiration process, which is actively managed by plants. This process leads to a reduction in volumetric water content, increasing suction in unsaturated soils. This results in a decrease in soil permeability and an increase in shear strength.
In addition, vegetation can reduce infiltration rates, depending on the type of vegetation, and the condition of the roots (Kamchoom et al., 2022, Phan et al., 2025). Table 2.16 shows the effectiveness matrix for the G3A.5 interventions.

Table 2.16. Effectiveness matrix of G3A.5.

G3A.5 VEGETATION			Depth of piezometric level		
			High	Low	Absent
			0,5	0,5	0,5
Depth of sliding surface	Superficial (<1.0 m)	0,5	**0,25**	**0,25**	**0,25**
	Shallow (1 to 3 m)	1	**0,5**	**0,5**	**0,5**
	Medium (3 to 8 m)	0,5	**0,25**	**0,25**	**0,25**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

Table 2.17 contains the applicability matrix set up for the measures of group G3A - Surface water regime modification.

Table 2.17. Applicability matrix for measures of G3A group.

	G3A.1	G3A.2	G3A.3	G3A.4	G3A.5
Reliability	1	1	1	1	0,5
Feasibility	1	1	1	1	0,5
Implementation	1	1	1	1	1
Typical cost	1	1	1	1	1
tot.	**4**	**4**	**4**	**4**	**3**

G3B Sub-surface drainage (groundwater drainage)

Commonly applied and effective techniques for preventing and mitigating landslides involve, either wholly or partially, the management of groundwater. The increase in shear strength of the soil due to the decrease soil water pressures induced by the drainage processes, leads to an increase in the safety factor of the slope. Drainage is often the best remedial measure against slope instability in saturated soils, due to the important role played by pore-water pressure in reducing the shear strength of the soil.

Due to its cost-effectiveness combined with its high efficiency in stabilization, groundwater drainage is extensively implemented and is typically regarded as the most reliable stabilization technique. Furthermore, drainage remains applicable to a wide range of scenarios, even in cases of extremely deep landslides where structural interventions prove inadequate. Shallow and deep drain trenches and sub-horizontal drains are the most commonly used a drainage system in slope stabilizations, since wells and tunnels are costly and complex to construct (Urciuoli & Pirone, 2013)

Four main sub-groups (G3B.1 – G3B.4) of sub-surface drainage measures are selected and described in this document:

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- **G3B.1 Shallow and deep trenches filled with free-draining material**
- **G3B.2 Sub-horizontal drains**
- **G3B.3 Small diameter vertical wells**
- **G3B.4 Drainage tunnels**

These drainage systems predominantly rely on gravity-driven flow, though pumps may occasionally be utilized to extract water from low-elevation collector galleries or wells. The efficiency and regularity of use of different drainage methods depend significantly on hydrogeological and climatic factors.

G3B.1 Trench drains are narrow, deep-aligned drainage structures designed to minimize the risk of reactivating landslides. They typically reach depths of 4 to 6 meters and have widths ranging from 0.80 to 1.20 meters, oriented downslope for optimal drainage efficiency. Depending on site conditions, single drainage trenches perpendicular to the facility's centerline may suffice for water management, whereas interconnected drainage networks may be necessary in more complex scenarios. In case of deep trench drainage—such as difficulty in properly laying discharge pipes and the high volume of backfill material required—innovative technologies have been developed. Two key methods for deep trench drainage include narrow trench with high-capacity draining geocomposite, and deep trenches with aerated concrete panels. Both techniques significantly improve drainage efficiency and slope stabilization, while optimizing construction processes for deep trenches. The drainage effect is quantified using the average efficiency along the flow surface, which represents the difference between the initial and current average water pressure at a given time t, normalized to the initial value. Drains introduce a lower potential to the pore water which reduces the pore pressure in the sliding mass. This is why trenches are suitable for stabilizing shallow translational slides (Stanić, 1984; Desideri et al., 1997). Table 2.18 and 2.19 show the effectiveness matrix for shallow (G3B.1a) and deep (G3B.1b) trenches respectively.

Table 2.18. Effectiveness matrix of G3B.1a – shallow trenches.

G3B.1a SHALLOW TRENCHES			**Depth of piezometric level**		
			High	Low	Absent
			0,5	0	0
Depth of sliding surface	Superficial (<1.0 m)	1	**0,5**	**0**	**0**
	Shallow (1 to 3 m)	1	**0,5**	**0**	**0**
	Medium (3 to 8 m)	0,5	**0,25**	**0**	**0**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

Table 2.19. Effectiveness matrix of G3B.1b – deep trenches.

G3B.1b DEEP TRENCHES			**Depth of piezometric level**		
			High	Low	Absent
			1	0,5	0
Depth of sliding surface	Superficial (<1.0 m)	0,5	**0,5**	**0,25**	**0**
	Shallow (1 to 3 m)	0,5	**0,5**	**0,25**	**0**
	Medium (3 to 8 m)	0,5	**0,5**	**0,25**	**0**
	Deep (8 to 15 m)	0,5	**0,5**	**0,25**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G3B.2 Sub-horizontal drains (conventional drilling) are an effective stabilization technique for deep landslides, particularly those involving a circular slip surface. Horizontal drainage systems are typically installed on slightly rising gradients within slopes and equipped with perforated or porous liners to enhance groundwater control**.** Drainage pipes are typically micro-slotted PVC pipes with diameters ranging from 100 to 120 mm, installed in appropriately sized boreholes and inclined upward by 5°–15° to optimize water discharge. For large-scale landslides, horizontal drains can be strategically combined with other drainage systems to enhance slope stability and groundwater management. The design of horizontal drains can be carried out by quantifying the average efficiency using numerical analyses or easily by adopting design charts available in literature (see Desideri et al. 1997, Pun & Urciuoli 2008). Table 2.20 shows the effectiveness matrix for the sub-horizontal drains.

Table 2.20. Effectiveness matrix of G3B.2

G3B.2 SUB-HORIZONTAL DRAINS			**Depth of piezometric level**		
			High	Low	Absent
			0,5	1	0
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	0	**0**	**0**	**0**
	Medium (3 to 8 m)	0,5	**0,25**	**0,5**	**0**
	Deep (8 to 15 m)	0,5	**0,25**	**0,5**	**0**
	Very deep (>15m)	0,5	**0,25**	**0,5**	**0**

G3B.3 Small diameter vertical wells are deep drainage, being an effective solution for stabilizing slopes, particularly in cases where conventional drainage trenches are impractical due to excessive depth requirements. Sometimes the wells are drilled fairly close together, essentially

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to form a drainage gallery, and Large-diameter vertical wells, typically up to 50 meters deep and around 2 inches in diameter, are used to manage groundwater. Wells may be drilled close together to form a drainage gallery, enhancing overall efficiency. Well screens and riser pipes are commercially available in various materials, including black iron, galvanized iron, stainless steel, brass, bronze, fiberglass, and polyvinyl chloride (PVC). The performance of each material depends on strength, durability against servicing operations, and resistance to chemical interactions with groundwater. Either well-graded or uniform filter materials may be used, but the filter should consist of natural, hard, and durable particles to enhance longevity. Table 2.21 shows the effectiveness matrix for G3B.3 measures.

Table 2.21. Effectiveness matrix of G3B.3

G3B.3 SMALL DIAMETER VERTICAL WELLS			**Depth of piezometric level**		
			High	Low	Absent
			1	0,5	0
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	0,5	**0,5**	**0,25**	**0**
	Medium (3 to 8 m)	0,5	**0,5**	**0,25**	**0**
	Deep (8 to 15 m)	1	**1**	**0,5**	**0**
	Very deep (>15m)	0,5	**0,5**	**0,25**	**0**

G3B.4 Drainage tunnels, adits, galleries with secondary drains or as outlet for wells, are used when the depth to subsurface water is so great that drainage trenches or wells are prohibitively expensive (Urciuoli & Pirone, 2013**)**. Although expensive, they can be suitable for treating very large slides. Drainage galleries are strategically tunneled to intercept seepage sources, then extended along the water-bearing horizon to effectively lower piezometric pressures behind a slope. The section has minimal dimensions (height 1.80-2.00 m and width 1-2 m) such as to allow inspection and maintenance. The bottom of the excavation is lined with a concrete slab while the abutments are generally in masonry. The basis is located at a depth slightly greater than the average water level while the summit reaches and intercepts the level itself. In some cases, starting from the tunnels, a network of subhorizontal drains is developed to make the entire system more effective. Drainage shafts and tunnels can be left empty or filled with draining material. Table 2.22 shows the effectiveness matrix for G3B.3 measures.

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Table 2.22. Effectiveness matrix of G3B.4

G3B.4 DRAINAGE TUNNELS, ADITS, GALLERIES			**Depth of piezometric level**		
			High	Low	Absent
			1	1	0
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	0	**0**	**0**	**0**
	Medium (3 to 8 m)	0	**0**	**0**	**0**
	Deep (8 to 15 m)	0,5	**0,5**	**0,5**	**0**
	Very deep (>15m)	1	**1**	**1**	**0**

In Table 2.23 the applicability matrix for the measures of group G3B - Sub-surface drainage - is reported.

Table 2.23. Applicability matrix for measures of G3B group.

	G3B.1a	**G3B.1b**	**G3B.2**	**G3B.3**	**G3B.4**
Reliability	0,5	0,5	0,5	0,5	0,5
Feasibility	1	1	0,5	0,5	0,5
Implementation	0,5	0,5	0,5	0,5	0,5
Typical cost	0,5	0,5	0,5	0,5	0
tot.	**2,5**	**2,5**	**2**	**2**	**1,5**

2.4 G4 (Group 4): Transferring loads to competent ground

Mitigation measures in this category allow to increase the resistance of the potential sliding mass. This is achieved either by partially replacing the shear surface with more competent materials (e.g., shear keys, piles, etc) or by mechanically increasing the effective normal stress on the potential failure surface, thereby enhancing the shear resistance of the soil. Some systems operate on both principles simultaneously (e.g., passive anchors, soil nailing,). In all cases, these measures work by transferring part of the driving forces to the more competent, stable strata underlying the actual or potential sliding mass.

The effectiveness of these systems progressively decreases as the sliding mass transitions into a flowing mass. This can occur either through internal processes (e.g., loss of microstructure, particularly in saturated materials) or through mixing with additional water from surface runoff or groundwater. Instability-inducing loads can be mechanically redistributed, either fully or partially, to competent underlying ground through structural reinforcement elements. Applicable techniques include:

- **G4.1 Piles**
- **G4.2 Diaphragm walls**

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- **G4.3 Soil nailing**
- **G4.4 Strand anchors**

G4.1-G4.2 Piles and diaphragm wall elements (barrettes) are placed either at regular two-dimensional spacing over the entire slide or part of it to act as isolated dowels. More commonly, they are arranged at close spacing along one or more specific alignments to form embedded walls across the direction of movement. In such cases, they are often supplemented by anchors. Piles can considerably influence the stability of the slope (Cai & Ugai, 2000).
The effectiveness matrices for G4.1 (piles) and G4.2 (diaphragm walls) are shown in Tables 2.24 and 2.25 respectively.

Table 2.24. Effectiveness matrix of G4.1

G4.1 PILES			**Depth of piezometric level**		
			High	Low	Absent
			0,5	1	1
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	0,5	**0,25**	**0,5**	**0,5**
	Medium (3 to 8 m)	1	**0,5**	**1**	**1**
	Deep (8 to 15 m)	0,5	**0,25**	**0,5**	**0,5**
	Very deep (>15m)	0	**0**	**0**	**0**

Table 2.25. Effectiveness matrix of G4.2

G4.2 DIAPHRAGM WALLS			**Depth of piezometric level**		
			High	Low	Absent
			0,5	1	1
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	0	**0**	**0**	**0**
	Medium (3 to 8 m)	0,5	**0,25**	**0,5**	**0,5**
	Deep (8 to 15 m)	1	**0,5**	**1**	**1**
	Very deep (>15m)	0,5	**0,25**	**0,5**	**0,5**

G4.3 Soil nailing involves creating a stable block, inserting solid or hollow steel or glass fiber bars, grouted into the face of an excavation or an existing slope, by strengthening the in situ ground with soil nails (Pun & Urciuoli, 2008). The slope face is then protected using shotcrete and welded wire mesh, geogrid/geotextile sheets, and either cast-in-place concrete or prefabricated panels, depending on slope angle and ground conditions. The effectiveness matrix for G4.3 is shown in Table 2.26.

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Table 2.26. Effectiveness matrix of G4.3

G4.3 SOIL NAILING			Depth of piezometric level		
			High	Low	Absent
			0	0,5	1
Depth of sliding surface	Superficial (<1.0 m)	1	**0**	**0,5**	**1**
	Shallow (1 to 3 m)	1	**0**	**0,5**	**1**
	Medium (3 to 8 m)	0,5	**0**	**0,25**	**0,5**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G4.4 Strand anchors are installed and grouted in predrilled holes in soil or rock to transfer an applied tensile load into the ground. Typically made from high-strength, low-relaxation steel classified at 1860 MPa, they come in strands of 15.7 mm (0.6") diameter, with strand numbers typically ranging from three to eight. Their nominal maximum length is unrestricted since the strand can be manufactured and assembled in any length, then transported coiled. In practice, however, the maximum length is limited by drilling capabilities, with typical overall lengths ranging from 35 to 40 meters. The effectiveness matrix for G4.4 is reported in Table 2.27.

Table 2.27. Effectiveness matrix of G4.4

G4.4 STRAND ANCHORS			Depth of piezometric level		
			High	Low	Absent
			0,5	1	1
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	0	**0**	**0**	**0**
	Medium (3 to 8 m)	0,5	**0,25**	**0,5**	**0,5**
	Deep (8 to 15 m)	1	**0,5**	**1**	**1**
	Very deep (>15m)	0,5	**0,25**	**0,5**	**0,5**

Table 2.28 shows the applicability matrix for the measures of group G4 - Transferring loads to competent ground

Table 2.28. Applicability matrix for measures of G4 group.

	G4.1	**G4.2**	**G4.3**	**G4.4**
Reliability	1	1	0,5	0,5
Feasibility	1	1	0,5	0,5
Implementation	0,5	0,5	0,5	0,5
Typical cost	0,5	0,5	0,5	0,5
tot.	**3**	**3**	**2**	**2**

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2.5 G5 (Group 5): Retaining structures to improve the slope stability

Retaining structures are widely used and can be considered an additional class of hazard mitigation measures for preventing landslide triggering.
These structures offer a viable solution in cases where conventional toe-filling is impractical due to geometric constraints or interference with existing structures or infrastructure. Depending on their configuration and their positioning relative to the landslide mass, they allow for toe weighting with the transmission of horizontal forces to competent foundation materials located in front of the toe. The use of rigid restraining structures is generally less suitable than methods involving drainage or slope reshaping. However, when properly engineered, they can be useful, especially in areas with limited space. Among the applicable techniques, four main sub-groups (G5.1 – G5.4) are considered:

- **G5.1. Reinforced soil structures**
- **G5.2 Gabion walls**
- **G5.3 Cribb walls**
- **G5.4 Reinforced concrete stem walls**

G5.1 Reinforced soil structures consist of compacted layers of soil, typically ranging from 50 to 150 cm thick, with interposed reinforcing elements of appropriate length to enhance overall resistance. This kind of stabilization methods are simpler, easier and cheaper to implement compared to concrete and gravity walls. On the other hand, it is necessary to have large space behind the slope face and usually need a drainage system for ground nailing (Christopher et al., 1990). The external face of the structure is protected by a facing, which may include shotcrete and wire mesh, geogrid/geotextile sheets, modular facing blocks, cast-in-place or prefabricated panels, or similar materials. In reinforced soil structures, the reinforcing elements provide tensile strength to the overall system. The outward soil movement is resisted by the reinforcing elements, which develop tensile forces as frictional interactions occur along their length. The reinforcing elements in reinforced soil structures may include metallic or polymeric strips, geotextile sheets, geogrids or metallic grids. The effectiveness matrix for G5.1 is reported in Table 2.29.

Table 2.29. Effectiveness matrix of G5.1

G5.1 REINFORCED SOIL STRUCTURES			**Depth of piezometric level**		
			High	Low	Absent
			0,5	1	0,5
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	0,5	**0,25**	**0,5**	**0,25**
	Medium (3 to 8 m)	0,5	**0,25**	**0,5**	**0,25**
	Deep (8 to 15 m)	0,5	**0,25**	**0,5**	**0,25**
	Very deep (>15m)	0	**0**	**0**	**0**

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G5.2 Gabions are wire mesh boxes filled with stones, arranged side by side and securely laced together to form a gravity structure. Gabion walls can be constructed with either a stepped front or rear face. Where feasible, it is recommended to incline the wall 6 to 8° from the vertical, toward the backfill materials, to enhance stability. The materials used to fill gabions must be highly durable, ensuring resistance to erosion and frost. Gabion walls are constructed in courses ranging from 0.5 to 1 meter in height. Gabions are typically supplied flat and assembled on-site. Gabion walls are permeable, allowing retained fill to drain freely. They have been used for more than a century in numerous erosion control and bank protection projects and since they are environmentally sound and economical can also be used in small-scale slope stabilization (Kandaris, 1999). Where necessary, surface and/or deep drainage systems can be incorporated to prevent groundwater pressure buildup within the backfill materials. The effectiveness matrix for G5.2 is shown in Table 2.30.

Table 2.30. Effectiveness matrix of G5.2

G5.2 GABION WALLS			**Depth of piezometric level**		
			High	Low	Absent
			1	1	1
Depth of sliding surface	Superficial (<1.0 m)	0,5	**0,5**	**0,5**	**0,5**
	Shallow (1 to 3 m)	1	**1**	**1**	**1**
	Medium (3 to 8 m)	0,5	**0,5**	**0,5**	**0,5**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G5.3 Crib walls are a type of gravity wall which comprises a system of interlocking header and stretcher blocks to retain granular fill that provides the necessary stabilizing mass to the wall (Manasa et al., 2021). The spaces within the grillage are filled with free-draining coarse-grained materials such as sand and gravel, which must be durable and resistant to erosion and frost. Crib walls are permeable, allowing retained fill to drain freely. Where necessary, surface and/or deep drainage systems can be incorporated to prevent groundwater pressure buildup within the backfill materials. Once the headers and stretchers have been erected, crib walls can be filled with lean mix concrete, making them more similar to masonry walls. The effectiveness matrix for G5.3 is shown in Table 2.31.

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Table 2.31. Effectiveness matrix of G5.3

G5.3 CRIBB WALLS			Depth of piezometric level		
			High	Low	Absent
			1	1	0,5
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	1	**1**	**1**	**0,5**
	Medium (3 to 8 m)	0,5	**0,5**	**0,5**	**0,25**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

G5.4 Cantilevered walls or gravity cantilevered walls are L-shaped or inverted T-shaped structures that rest on the ground and can be cast on site or prefabricated. From the point of view of geotechnical stability, they work in conjunction with the mass of the filler material retained above the foundation element.
A drainage layer is typically installed behind the wall to limit pressure on the stem. In addition, surface and/or deep drainage systems should be incorporated where necessary to prevent the build-up of groundwater pressure within the backfill materials. Table 2.32 shows the effectiveness matrix for G5.4.

Table 2.32. Effectiveness matrix of G5.4

G5.4 REINFORCED CONCRETE STEM WALLS			Depth of piezometric level		
			High	Low	Absent
			1	1	1
Depth of sliding surface	Superficial (<1.0 m)	0	**0**	**0**	**0**
	Shallow (1 to 3 m)	1	**1**	**1**	**1**
	Medium (3 to 8 m)	0,5	**0,5**	**0,5**	**0,5**
	Deep (8 to 15 m)	0	**0**	**0**	**0**
	Very deep (>15m)	0	**0**	**0**	**0**

Table 2.33 shows the applicability matrix for the measures of group G5 - Retaining structures.

Table 2.33. Applicability matrix for measures of G5 group.

	G5.1	G5.2	G5.3	G5.4
Reliability	1	1	1	0,5
Feasibility	1	1	1	1
Implementation	1	1	1	1
Typical cost	0,5	1	0,5	0,5
tot.	**3,5**	**4**	**3,5**	**3**

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3. FLOODING HAZARD MITIGATION MEASURES

3.1. Overview

As climate change accelerates, alongside increasing land use intensification and urban expansion, the frequency and severity of flood events continue to rise. These changes demand comprehensive and adaptive strategies to mitigate both hydraulic hazard and associated risk. In line with the principles set forth by the EU Floods Directive (2007/60/EC) and reinforced by international best practices, effective flood risk management should be built upon several foundational pillars. These include the risk management cycle, which encompasses prevention, protection, preparedness, response, and recovery (UNDRR, 2015); integrated river basin management, which promotes coordinated planning across hydrological boundaries; the precautionary principle and no-regret measures, which advocate proactive interventions even under uncertainty (IPCC, 2022); and multi-level governance, supported by broad stakeholder engagement (EC, 2017).

The following sections outline the main approaches for mitigating hydraulic risk across diverse environments—including river basins, floodplains, and urban areas. These approaches are grouped into three typologies: structural measures, non-structural measures, and nature-based solutions.

3.2. Structural Measures

Structural measures involve physical interventions in the landscape designed to control, divert, or contain floodwaters. While often capital-intensive, they remain central to risk management, particularly in high-exposure or densely populated areas.

In this frame, the most effective structural measures that should be implemented for reducing hydraulic risk are:

- Routine maintenance of watercourses, clearing and inspection of structures (e.g., culverts, bridges, ditches, drainage canals, etc.) (code SM1)

These basic interventions are essential to keep the hydraulic functionality of all watercourses and structures.

- Retention and Detention Basins (code SM2)

They serve as temporary reservoirs that store excess runoff during peak rainfall or river discharge events. By attenuating flow and reducing downstream pressure, they not only lower flood peaks but also support natural recharge and ecosystem integration (EC, 2017).

- Riverbed and Bank Stabilization (code SM3)

The use of riprap, gabions, vegetation reinforcement, and other revetments, aim to maintain the structural integrity of river channels. These interventions reduce erosion, preserve channel capacity, and contribute to sediment management (Pagliara and Palermo, 2013; Palermo and Pagliara, 2018).

- Dikes and Levees construction/reinforcement (code SM4)

They are among the most traditional forms of flood protection, creating elevated barriers along riverbanks to prevent inundation. While effective at protecting critical infrastructure and settlements, they require diligent maintenance and monitoring to avoid catastrophic failure, especially under climate-driven stressors (Mc Bain et al., 2010).

- Diversion Channels and Floodways (code SM5)

They are engineered conduits, either manmade or adapted from natural systems, that redirect surplus floodwater away from vulnerable areas. Their deployment is particularly effective in peri-urban zones, where they can reduce localized pressure on drainage systems (Mc Bain et al., 2010).

- Reservoirs and Dams (code SM6)

These structures offer substantial flood regulation through controlled water storage and release. They provide multiple benefits, including hydropower, irrigation, and drought management, but must be evaluated against their environmental and social impacts (UNESCO, 2012).

3.3. Non-Structural Measures

Non-structural measures focus on reducing vulnerability and exposure without significantly altering natural hydrological processes. They are essential complements to engineered systems and offer often more adaptable solutions.

The most effective non-structural measures include:

- Land Use Planning and Zoning (code NSM1)

  Correct planning of land use and zoning play an important role in long-term risk reduction by regulating development in flood-prone areas. Through strategic urban planning and zoning restrictions, authorities should limit exposure by steering high-risk activities away from vulnerable zones and promoting flood-compatible uses such as recreation or agriculture (European Parliament and Council, 2007).

- Flood Forecasting and Early Warning Systems (code NSM2)

  Relying on real-time data from rainfall, river levels, and hydrological models to anticipate flood events is becoming more and more strategic to mitigate the impact of adverse effects on the surrounding environment. Such systems should be paired with community outreach and preparedness campaigns, in order to enhance response capacity and reduce fatalities (UNDRR, 2015).

- Emergency Preparedness and Response Plans (code NSM3)

  One of the key aspects in crisis situations is to ensure coordinated action. Consequently, regularly updated protocols, simulations, and clearly defined evacuation routes and shelters are critical to minimizing impacts during flood events (UNDRR, 2015).

3.4. Nature-Based Solutions (NBS)

Nature-Based Solutions are increasingly recognized for their ability to mitigate flood risk while delivering co-benefits for ecosystems, climate resilience, and human well-being (EC, 2017).

These solutions include the following interventions:

- Restoration of Floodplains and Wetlands (code NBS1)

  They can re-establish natural flood buffers, allowing rivers to overflow into adjacent lowlands in a controlled manner. This reduces peak discharges and promotes groundwater recharge while enhancing biodiversity.

- Urban Green Infrastructure (code NBS2)

  Green roofs, bioswales, rain gardens, and permeable pavements are particularly effective in managing pluvial flooding in cities. By increasing infiltration and delaying runoff, green infrastructure contributes to both climate adaptation and urban livability (EC, 2017).

- Reforestation and Afforestation in Watersheds (code NBS3)

  These interventions aim at stabilizing soils, enhancing infiltration, and reducing the risk of rapid surface runoff and flash flooding. They are especially beneficial in upland and deforested catchments, where they help regulate basin hydrology.

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3.5. Specific measures for mitigating hydraulic risks

In this section, the recommended measures are detailed for different scenarios (i.e., for different combinations of slope class, type of basin, and hydraulic risk class of the target area), as defined in Deliverable 3.2 and illustrated in Table 3.3.

To this end, basins can be classified according to the criteria presented in Tables 3.1 and 3.2.

Specifically, basins are categorized into three main classes based on their average slope: low, medium, and high (Table 3.1). For each class, the typical orographic characteristics and expected speed of flood wave propagation are described.

Table 3.1. Classification of basins according to their average slope

Slope class	Average Basin Slope (%)	Description	Flood Wave Propagation Speed
High	> 10%	Steep terrain (e.g. mountain regions); fast runoff, high erosion potential.	Fast
Medium	2% – 10%	Hilly or undulating terrain; intermediate flow velocity and erosion.	Moderate
Low	< 2%	Flat or gently rolling plains; slower runoff, higher flood retention.	Slow

Similarly, Table 3.2 classifies basins into three types based on their size: small, intermediate, and large. For each type, a brief description of the basin scale is provided, along with typical slope classes and the dominant hazards. The hydrological homogeneity of the different basin types is also indicated.

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Table 3.2. Classification of basins according to their size

Basin Type	Typical Area (km²)	Description	Typical slope class	Hydrological Homogeneity	Dominant Hazards
Small	< 100	Often local watersheds; responds rapidly to rainfall events.	Low, Medium and High	High	Flash floods, debris flows
Intermediate	100 - 1000	Regional scale; both local and larger hydrological influences.	Low and Medium	Medium	Riverine floods, slope failures
Large	> 1000	Major river systems; long response times and complex hydrology.	Low	Low	Widespread inundation, overbank flow

To effectively mitigate hydraulic risk, the measures outlined above can be differentiated according to three main parameters: the hydraulic risk class of the target area (see Deliverable 3.2), and the size and average slope of the basin.

Table 3.3 summarizes the most effective measures, indicating the corresponding codes as defined in Sections 3.2–3.4.

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Table 3.3. Usually adopted measures (indicated by the corresponding codes) for different classes of hydraulic risk and basin characteristics

Type of basin		***Small***		***Intermediate***		***Large***
Slope class		***Low***	***From moderate to high***	***Low***	***Moderate***	***Low***
Class of Hydraulic Risk	**R1**	SM1	SM1, NBS3	SM1	SM1, NBS3	SM1, NBS3
	R2	SM1 , NSM1, NSM2, NSM3, NBS1, NBS2	SM1, NSM1, NSM2, NSM3, NBS1, NBS2, NBS3	SM1, SM3, NSM1, NSM2, NSM3, NBS1, NBS2	SM1, SM3, NSM1, NSM2, NSM3, NBS1, NBS2, NBS3	SM1, SM3, NSM1, NSM2, NSM3, NBS1, NBS2, NBS3
	R3	SM1, SM2, SM3, SM4, NSM1, NSM2, NSM3, NBS1, NBS2	SM1, SM2, SM3, SM4, NSM1, NSM2, NSM3, NBS1, NBS2, NBS3	SM1, SM2, SM3, SM4, SM5, NSM1, NSM2, NSM3, NBS1, NBS2	SM1, SM2, SM3, SM4, SM5, NSM 1, NSM2, NSM3, NBS1, NBS2, NBS3	SM1, SM2, SM3, SM4, SM5, SM6, NSM1, NSM2, NSM3, NBS1, NBS2, NBS3
	R4	SM1, SM2, SM3, SM4, SM5, NSM1, NSM2, NSM3, NBS1, NBS2	SM1, SM2, SM3, SM4, SM5, NSM1, NSM2, NSM3, NBS1, NB S2, NBS3	SM1, SM2, SM3, SM4, SM5, SM6, NSM1, NSM2, NSM3, NBS1, NBS2	SM1, SM2, SM3, SM4, SM5, SM6, NSM1, NSM2, NSM3, NBS1, NBS2, NBS3	SM1, SM2, SM3, SM4, SM5, SM6, NS M1, NSM2, NSM3, NBS1, NBS2, NBS3

To support the selection of the most effective measures among those listed in Table 3.3 for each scenario, quantitative indices are also provided.

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To this end, an effectiveness score is assigned to each measure. This score reflects the ability of the specific measure to reduce the hydraulic risk, which results from the combination of flood event likelihood (hazard) and the potential severity of its consequences (damage). The score ranges from 0.25 to 1, with higher values indicating greater effectiveness. It also serves as a quantitative criterion for prioritizing the various measures defined for each scenario. In other words, for each scenario, the most suitable measures to mitigate hydraulic risk are selected from those listed in Table 3.3, based on the scores provided in the *effectiveness matrices* (Tables 3.4–3.6). The following Tables 3.4-3.6 present the scores for each measure (identified by its corresponding code), grouped by typology, as outlined in Sections 3.2-3.4.

Table 3.4. Effectiveness score of structural measures (identified by their corresponding codes) in reducing hydraulic risk.

Measure	Code	Rationale	Effectiveness score
Routine maintenance of watercourses, clearing and inspection of structures	SM1	Ensures basic hydraulic functionality by preventing blockages and failures in watercourses.	0.6
Retention and Detention Basins	SM2	Stores excess runoff during peak events, thereby reducing flood hazard and protecting downstream areas. Supports risk reduction across both hazard and exposure axes.	0.75
Riverbed and Bank Stabilization	SM3	Controls erosion and stabilizes channels, preserving capacity and minimizing secondary risks (e.g. failure of banks).	0.65
Dikes and Levees construction/reinforcement	SM4	Acts as a primary defense, shielding people, assets, and infrastructure. Highly effective at reducing both flood hazard and vulnerability in protected areas.	1
Diversion Channels and Floodways	SM5	Redirects floodwaters away from at-risk zones, effectively reducing exposure and concentrating flow where impacts are lower. Especially useful in peri-urban regions.	0.85
Reservoirs and Dams	SM6	Allows system-wide flood control through planned storage and release. Effective in lowering hazard levels over large areas, especially in regulated river systems.	0.95

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Table 3.5. Effectiveness score of non-structural measures (identified by their corresponding codes) in reducing hydraulic risk

Measure	Code	Rationale	Effectiveness score
Land Use Planning and Zoning	NSM1	A correct planning of land use and zoning plays a pivotal role in long-term risk reduction by regulating development in flood-prone areas. It limits exposure by promoting flood-compatible uses.	0.5
Flood Forecasting and Early Warning Systems	NSM2	Uses real-time data and models to anticipate flood events. When paired with outreach and preparedness, it significantly enhances response capacity and reduces fatalities.	0.4
Emergency Preparedness and Response Plans	NSM3	Ensures coordinated action during crises through updated protocols, simulations, and evacuation planning. Critical for reducing impacts during flood events.	0.35

Table 3.6. Effectiveness score of nature-based solutions (identified by their corresponding codes) in reducing hydraulic risk

Measure	Code	Rationale	Effectiveness score
Restoration of Floodplains and Wetlands	NBS1	Restores natural flood buffers by allowing controlled overflows into lowlands, reducing peak discharges, recharging groundwater, and enhancing biodiversity.	0.45
Urban Green Infrastructure	NBS2	Implements urban features like green roofs and permeable pavements to manage pluvial flooding by increasing infiltration and delaying runoff in cities.	0.3
Reforestation and Afforestation in Watersheds	NBS3	Enhances soil stability and infiltration, reducing surface runoff and flash flood risks. Especially effective in upland or deforested catchments for hydrological regulation.	0.25

For completeness, we also considered other important aspects, including reliability, feasibility, ease of implementation, and indicative cost of each measure. Each criterion is scored on a scale from 0.25 to 1.0, with higher scores indicating greater reliability, feasibility, and ease of implementation, and a lower indicative cost.

To this end, applicability matrices are provided for all categories of measures (Tables 3.7-3.9). These matrices present the individual scores alongside an overall applicability score, calculated as the sum of the four components.

Table 3.7. Applicability matrix for structural measures (identified by their corresponding codes).

Measure	Code	Reliability	Feasibility	Ease of Implementation	Indicative Cost	Applicability score
Routine maintenance of watercourses, clearing and inspection of structures	SM1	0.4	1	1	0.45	2.85
Retention and Detention Basins	SM2	0.75	0.5	0.55	0.5	2.3
Riverbed and Bank Stabilization	SM3	0.6	0.75	0.75	0.55	2.65
Dikes and Levees construction/reinforcement	SM4	1	0.5	0.5	0.25	2.25
Diversion Channels and Floodways	SM5	0.8	0.4	0.45	0.4	2.05
Reservoirs and Dams	SM6	1	0.25	0.25	0.35	1.85

Table 3.8. Applicability matrix for non-structural measures (identified by their corresponding codes).

Measure	Code	Reliability	Feasibility	Ease of Implementation	Indicative Cost	Applicability score
Land Use Planning and Zoning	NSM1	0.75	0.6	0.5	0.55	2.4
Flood Forecasting and Early Warning Systems	NSM2	0.65	0.5	0.5	0.55	2.2
Emergency Preparedness and Response Plans	NSM3	0.5	0.75	0.55	0.6	2.4

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Table 3.9. Applicability matrix for nature-based solutions (identified by their corresponding codes).

Measure	Code	Reliability	Feasibility	Ease of Implementation	Indicative Cost	Applicability score
Restoration of Floodplains and Wetlands	NBS1	0.75	0.5	0.5	0.55	2.3
Urban Green Infrastructure	NBS2	0.25	0.5	0.75	1	2.5
Reforestation and Afforestation in Watersheds	NBS3	0.6	0.65	0.8	0.65	2.7

For the mitigation of the hydraulic risk, the measures usually adopted for different scenarios are already provided in Table 3.3. Therefore, the total score S, calculated as the product of the effectiveness score and the applicability score, helps distinguish between “recommended” and “highly recommended” measures. Specifically:

- $S \geq 1.5$: Highly recommended (green color)
- $S < 1.5$: Recommended (yellow color)

Note that the ranking of different measures based on the total score S is fully consistent with that derived from the effectiveness score alone, therefore it also serves as a quantitative criterion for prioritizing the various measures defined for each scenario. Table 3.10 presents the total score values for each measure.

Table 3.10. Total score values (S) for each measure

Measure	Code	Score effectiveness	Score applicability	Total score S	Note
Routine maintenance of watercourses, clearing and inspection of structures	SM1	0.6	2.85	1.71	Highly Reccommended
Retention and Detention Basins	SM2	0.75	2.3	1.73	Highly Reccommended
Riverbed and Bank Stabilization	SM3	0.65	2.65	1.72	Highly Reccommended
Dikes and Levees construction/reinforcement	SM4	1	2.25	2.25	Highly Reccommended
Diversion Channels and Floodways	SM5	0.85	2.05	1.74	Highly Reccommended
Reservoirs and Dams	SM6	0.95	1.85	1.76	Highly Reccommended
Land Use Planning and Zoning	NSM1	0.5	2.4	1.20	Reccommended
Flood Forecasting and Early Warning Systems	NSM2	0.4	2.2	0.88	Reccommended
Emergency Preparedness and Response Plans	NSM3	0.35	2.4	0.84	Reccommended
Restoration of Floodplains and Wetlands	NBS1	0.45	2.3	1.04	Reccommended
Urban Green Infrastructure	NBS2	0.3	2.5	0.75	Reccommended
Reforestation and Afforestation in Watersheds	NBS3	0.25	2.7	0.68	Reccommended

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4. RISK PERCEPTION INCREASING MEASURES

4.1. Floods and landslides risk perception: an introduction

Floods and landslides can cause significant adverse consequences in affected communities. In addition to economic and structural damage, these events can cause death, injury (CRED, 2024), and long-term adverse impacts on the mental health of survivors (Fernandez et al., 2015; Parel & Balamurugan, 2021). Moreover, in case of floods and landslides, people's risk perception could have a significant role because it affects how people prepare and react to hazards, influencing their personal vulnerability, exposure, and safety. Risk perception refers to subjective assessments of the perceived probability regarding the occurrence and severity of a hazard event, which influence the preparedness, response, and mitigation behaviors that precede, accompany, and follow the event (Bradford et al., 2012; Lechowska, 2022). Specifically, an adequate risk perception among the population can promote effective emergency management because risk perception is linked to the early recognition of real risks and subsequent timely implementation of appropriate protective behaviors (Marincioni, 2020). This response could increase self-efficacy and personal safety, reducing the risk of vulnerability and exposure, mitigating the impact of danger, and preventing more serious outcomes, including mental health consequences.

For example, people with adequate risk perception could have adequate knowledge and awareness about the hydrogeological hazards in their municipality (e.g., the most at-risk areas, if one's residence is located in an area at risk, the workplace evacuation plan), and they could adopt protective behaviors in case of an emergency. Consequently, in the case of a flood or landslide alert, they could pay attention to the early warning signs and have preventive and mitigation protective behaviors, such as monitoring the authorities' updates on local warnings and following their recommendations, taking refuge in safe places, and avoiding crossing and standing in risky areas (e.g., underpasses, flooded roads, basements, or paths prone to landslides).

Conversely, inadequate risk perception, both in terms of underestimation and overestimation, can interfere with effective emergency response and management (Lechowska, 2018), contributing to amplifying the level of personal exposure to hazards (Wachinger et al., 2010) and consequent possible repercussions on psychophysical vulnerability. Specifically, people with a low risk perception may engage in risky and reckless behaviors or reduce protective behaviors (Ding et al., 2020). For example, they may not be informed in advance concerning hydrogeological hazards in their municipality and may not know the protective behaviors to adopt in case of an emergency. In addition, in case of alert, they might underestimate or ignore local warnings to evacuate or move away from hazard areas, downplay warning signs, not follow the directions of local authorities, and delay taking preventive measures and protective behaviors. Underestimation of risk could be fueled by the belief that the information disseminated by the media or local advisories is exaggerated, that flooding or landslide events

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are rare and cannot really occur in one's area, or that the situation is not severe enough to follow the guidance disseminated. Conversely, people with high/heightened risk perception are generally more likely to know and adopt preventive and protective behaviors (Ding et al., 2020). However, they may have a greater vulnerability to intense and dysfunctional emotional reactions (Zhao et al., 2023), such as high anxiety and fear, panic, or impulsive behaviors. In emergency settings, such emotional reactions may hinder the ability to rationally assess the situation and make effective decisions, leading to the enactment of hasty, counterproductive, and potentially harmful and dangerous choices. For example, individuals experiencing anxiety, fear, and panic may overload emergency lines with requests for reassurance or updates already available through official channels, slowing the timeliness of responses and interventions in the most critical situations. Severe anxiety and panic could cause greater difficulty in remembering previously learned procedures, such as evacuation routes or actions to take to get to safety. Moved by the fear of possible imminent risks, these people might exhibit hyper-vigilance, act on impulse and preemptively move away from their homes or safe places without real official indications of evacuation or danger. Although motivated by protective intent, such behaviors may paradoxically increase individual vulnerability and secondary risks and compromise coordinated emergency management.

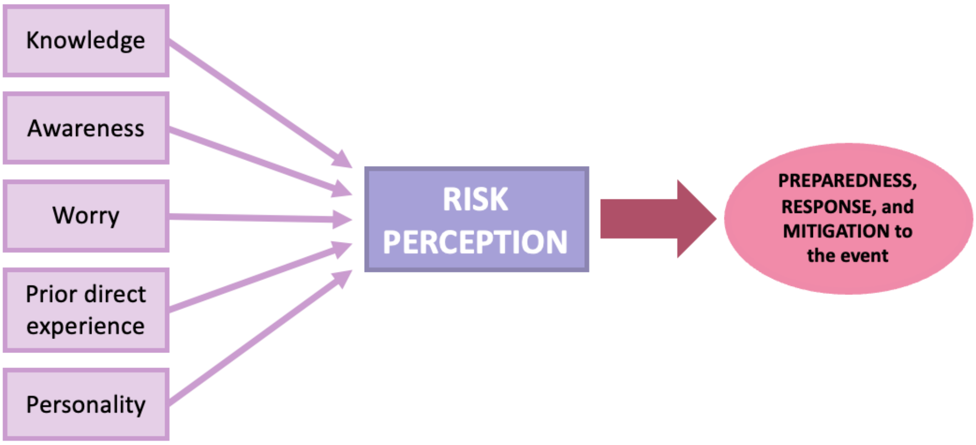
4.2. The assessment of risk perception and risk of vulnerability to adverse psychological consequences

Based on the above-cited literature, the psychological section of the SAFE-LAND Project aimed to assess both the risk perception of floods and landslides and the risk of vulnerability to adverse psychological consequences in case of floods and landslides.
As indicated in D3.2, preliminary study (pre-test) was conducted on a reference convenience sample (reference people) to collect preliminary data on the research protocol. Specifically, during this pre-test phase, a web survey was created on the Qualtrics platform and distributed to reference people through a QR-CODE/link via email and social media sites of the research staff. The web survey described the research protocol's objectives, and included informed consent and a series of self-report questionnaires to assess the risk perception of floods and landslides and the risk of vulnerability to adverse psychological consequences (For more details, see Table 4.1 in Deliverable D3.2). 124 subjects (79.5% females) – reference people - aged between 20 and 69 (mean value, M = 36.7; standard deviation, SD = 12.4) participated in the web survey (for more details on the demographic characteristics of the sample, see Table 4.2 in D3.2). As already mentioned in D3.2, the questionnaire continues to be sent to the sample population, and the database with the questionnaire responses is continuously updated, in order to build a larger and more representative sample.

The Assessment of Risk Perception

Based on the literature indications, assessing the risk perception of landslides and floods could become a significant factor in emergency management systems. Specifically, in the assessment of risk perception, the psychological section of SAFE-LAND considered the following factors: knowledge, awareness, worry, prior direct experience, and personality variables (Biernaki et al., 2009; Lechowska, 2018; Siegrist & Arval, 2020), see figure 4.1. More details were reported in D3.2).

Figure 4.1: Factors that Influence Risk Perception and Consequently Affect Preventive Preparedness and Response/Mitigation Behaviour In Case Of Flood/Landslide Emergency.



Specifically, through a series of self-report questionnaires contained in the web survey, for floods and landslides separately (see Table 4.1 in D3.2), we considered the following variables:

- ***Knowledge*** (e.g., knowledge of previous local floods or landslides, knowledge of response behaviors and emergency management in case of floods or landslides, keep informed about flood, landslide, and weather warnings, level of knowledge on how to protect oneself/respond in case of flood/landslide);
- ***Awareness*** (e.g., awareness of living in a flood/landslide risk area, awareness of areas in the city most at risk of flooding or landslides, awareness of the causes of floods/landslides);
- ***Worry*** (e.g., emotional response experienced in the past or anticipated in the future if a flood or landslide were to occur, level of worry in response to a flood or landslide warning for the following day);
- ***Prior direct experience*** (e.g., type of past experience with floods or landslides);
- and ***Personality*** (e.g., neuroticism and conscientiousness). For more details about the procedure and results see D3.2.

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Results for the assessment of floods and landslide risk perception

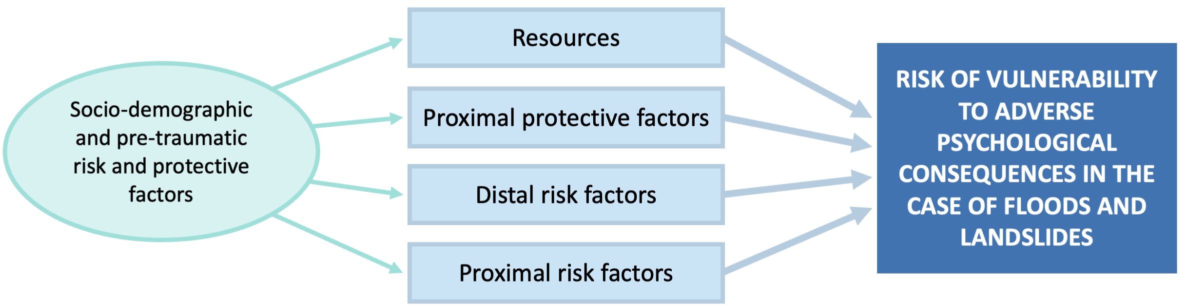
As explained in D3.2,

- the results regarding flood risk perception in the reference convenience sample of 124 subjects, showed that 13 participants (10.5%) had a low risk perception; 76 (61.3%) had a correct risk perception, and finally, 35 (28.2 %) had a high risk perception (Figure 4.3).
- the results regarding landslide risk perception in the reference convenience sample of 124 subjects, showed that 24 participants (19.4%) had a low risk perception; 78 (62.9%) had a correct risk perception, and finally, 22 (17.7%) had a high risk perception (Figure 4.3).

The Assessment of the Risk of Vulnerability to Adverse Psychological Consequences

We also assessed the level of individual risk of developing adverse psychological consequences in the case of floods and landslides through a series of self-report questionnaires contained in the web survey (see Table 4.1 in D3.2). Based on the indications of the literature, to detect individuals at risk of adverse psychological consequences, we considered a series of socio-demographic (i.e., gender, age) and individual and relational pre-traumatic risk and protective factors (i.e., previous traumatic events, social support) in flood and landslide survivors, as explained in D3.2. Subsequently, we categorized each considered variable (for example: gender, age, socio-economic status, previous traumatic events, special needs, psychological well-being, coping strategies, social support) in terms of resources, distal, and proximal risk and protective factors. Then we calculated each subject's total vulnerability score (Figure 4.2). For more details about the procedure and results see D3.2.

Figure 4.2: Factors that Influence the Risk of Vulnerability to Adverse Psychological Consequences in the case of Floods and Landslides



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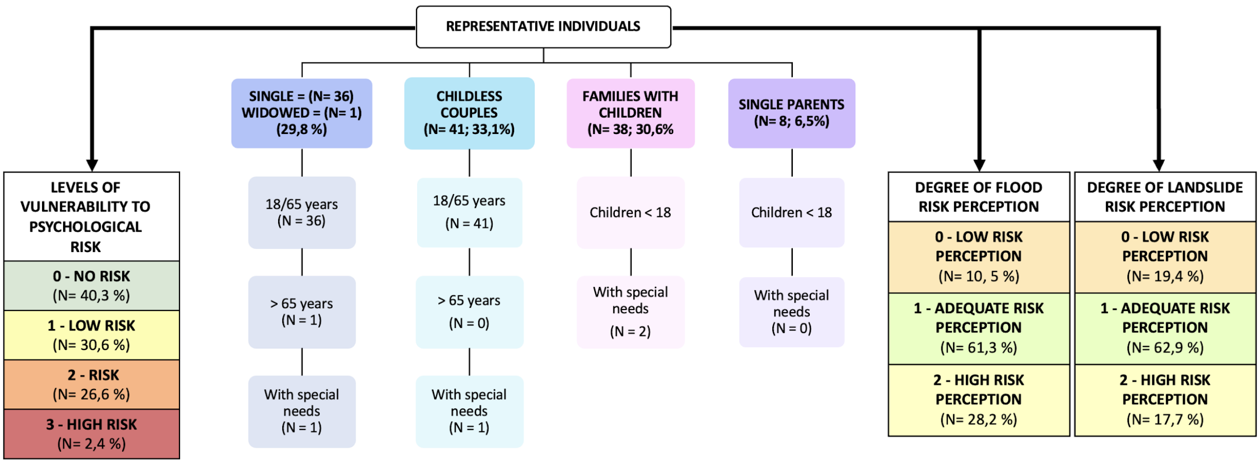
Results for the Assessment of the Risk of Vulnerability to Adverse Psychological Consequences

As explained in D3.2, the results on the reference convenience sample of 124 subjects indicated that 50 participants (40.3 %) showed no risk of adverse psychological consequences; 38 (30.6%) showed a low risk of adverse psychological consequences; 33 (26.6 %) showed a risk of adverse psychological consequences, and finally 3 (2.4 %) showed a high risk of adverse psychological consequences (Figure 4.3)

Figure 4.3: Results about the Sample's Vulnerability to Psychological Adverse Consequences, and the Sample's Quality of Floods/Landslides Risk Perception



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4.3. Guidelines of intervention based on risk perception and vulnerability to psychological risk

Exploring the quality of risk perception and the risk of psychological vulnerability could be **an essential starting point for implementing operational guidelines** to promote an effective emergency management system.

This emergency system could consist of **4 cyclic phases** (APA,n.d.; Bird, 2016; Syra & Murray, 2021), namely:

1. **Adequate preventive preparation** in the population oriented to promote and support a correct risk perception of flood and landslide in terms of acquiring a set of knowledge and skills on how to act before, during, and after an emergency;
2. **Effective risk communication** is activated concomitantly with the alert or the beginning of the emergency, guiding an effective and active response of the population consistent with the extent of the imminent risk
3. **Active and timely response** of the people supported by adequate risk perception based on appropriate protective response and mitigation behaviors consistent with the actual extent of the risk
4. **Post-event recovery** aims to promote an aware and continuous risk culture. This is achieved by revising/updating emergency plans and protective response and mitigation behaviors, activating psychological support services for the affected population, and identifying survivors at risk of psychological vulnerability.

An effective application of these four cyclical phases, which integrates both the consideration of the quality of risk perception and the psychological vulnerability of individuals in the event of floods and landslides, could significantly contribute to improving the emergency management system of such events (see Figure 4.4).

Guidelines will be proposed to improve emergency management system through the:

Promotion of effective preventive preparation and risk communication that support an adequate knowledge and awareness of risks and consequent functional and protective response in the event of a flood/landslide emergency

Promotion of early identification of the subjects most vulnerable to adverse psychological consequences in the event of floods/landslides in the post-event recovery phase

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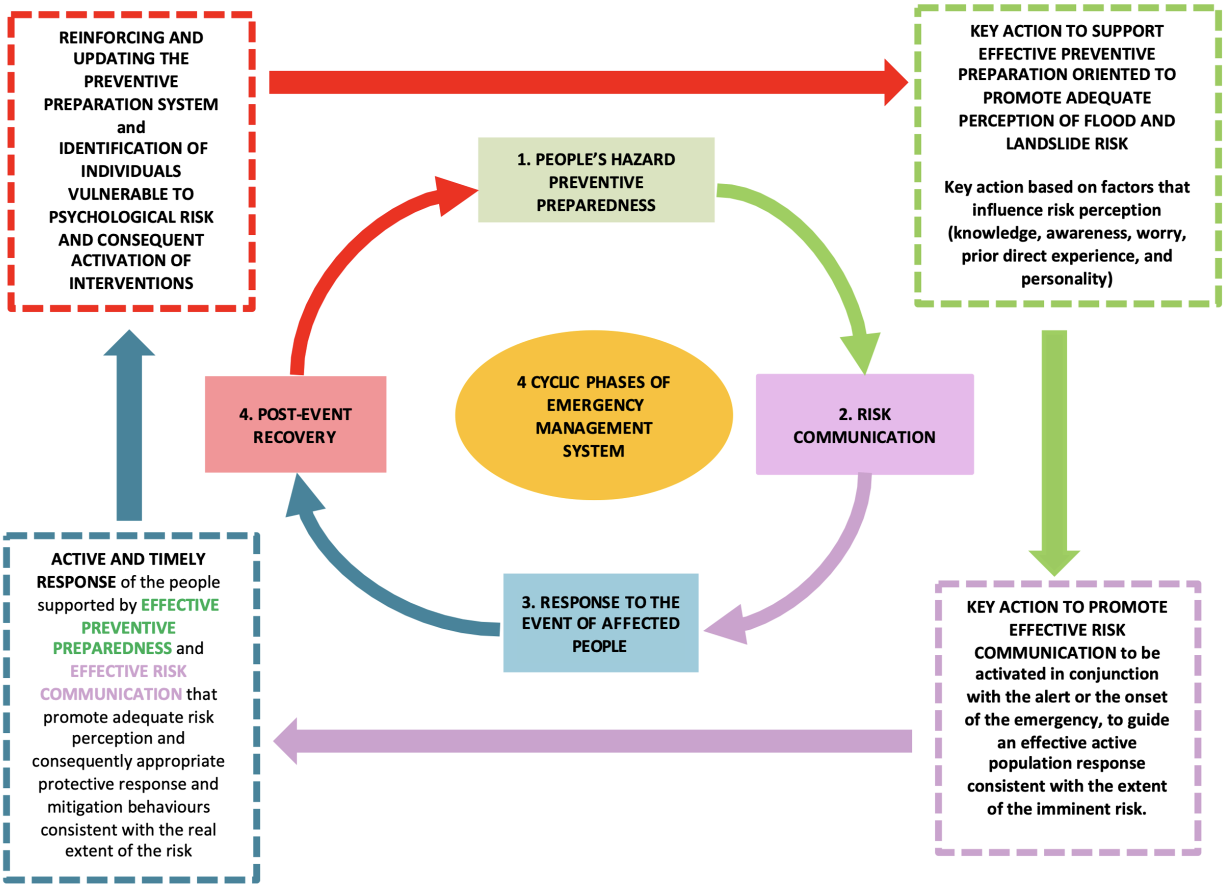
Figure 4.4: Phases of the Guidelines to support an effective emergency management system through the promotion of effective preventive preparation and risk communication and consideration of psychological vulnerability in the case of floods and landslides



GUIDELINES TO SUPPORT AN EFFECTIVE EMERGENCY MANAGEMENT SYSTEM THROUGH THE PROMOTION OF EFFECTIVE PREVENTIVE PREPARATION AND RISK COMMUNICATION, AND CONSIDERATION OF PSYCHOLOGICAL VULNERABILITY IN THE CASE OF FLOODS AND LANDSLIDES

1: KEY ACTION TO PROMOTE PEOPLE'S HAZARD PREVENTIVE PREPAREDNESS

Preventive preparedness for landslides and floods consists of acquiring knowledge and skills on how to act before, during, and after an emergency. This could increase personal safety and self-efficacy, reducing the risk of increased exposure and psychophysical vulnerability in case of real danger. At this phase, knowledge, awareness, worry, previous direct experiences, and personality could significantly influence the overall risk perception prior to landslide/flood events (Biernacki et al., 2009; Lechowska, 2018; Siegrist & Arval, 2020). Therefore, key actions will be proposed by considering the quality of each risk perception factor.

KNOWLEDGE AND AWARENESS KEY ACTION IN THE CASE OF FLOODS AND LANDSLIDES	
LOW KNOWLEDGE and LOW AWARENESS: **KEY ACTION FOR INTERVENTION** **AIM:** to improve knowledge and awareness of the real risks of floods and landslides in one's local area, in order to promote better self-efficacy in protective responses to be adopted in case of emergency.	**KEY ACTION TO SUPPORT LOW KNOWLEDGE** 1- Promote sensitization campaigns, trainings in workplaces/schools, or distribute posters or other official materials to support: a) knowledge of territorial vulnerability with respect to previous landslide/flood events (see also key action for prior experience for further discussion) b) knowledge of how the warning system and emergency plans of the municipality of residence and the services/institutions responsible for the warning/intervention processes work c) knowledge of effective protective response and mitigation behaviors before, during, and after landslide/flood events and subsequent establishment of a personal/family emergency plan. 2- Keep informed of local flood, landslide, and weather warnings by relying solely on official channels to identify potential imminent hazards in advance, not expose yourself to risks, and adopt timely protective behaviors in case of emergency. **KEY ACTION TO SUPPORT LOW AWARENESS** Promote sensitization campaigns, trainings in workplaces or schools, or posters or other official materials to support: a) awareness of the causes of floods and landslides and the impacts they can have at the personal and community levels. b) awareness of the real local hydrogeological risk in terms of mapping areas at risk/safe c) awareness of the risk of exposure of one's residence to hydrogeological risk.

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KNOWLEDGE AND AWARENESS KEY ACTION IN THE CASE OF FLOODS AND LANDSLIDES

KEY ACTION TO MAINTAIN A CORRECT KNOWLEDGE AND AWARENESS

KEY ACTION FOR INTERVENTION

AIM:
to maintain through ongoing education an up-to-date knowledge and awareness of local flood and landslide hazards and the effective protective behaviors to adopt in case of an emergency

KEY ACTION TO MAINTAIN A CORRECT KNOWLEDGE

1- Periodically organize refresh courses or distribute posters or other updated official materials to support ongoing education with respect to:

a) the knowledge of territorial vulnerability to previous landslide/flood events (see also key action for prior experience for further discussion)
b) the knowledge of the functioning of the local warning system and emergency plans and the services/institutions responsible in the warning/intervention processes
c) knowledge of effective protective response and mitigation behaviors before, during, and after landslide/flood events and subsequent updating of personal/family emergency plan

2- Keep informed of local flood, landslide, and weather warnings by relying solely on official channels to identify potential imminent hazards in advance, not expose themselves to risks, and adopt timely protective behaviors in the event of an emergency

KEY ACTION TO MAINTAIN A CORRECT AWARENESS

Periodically organize refreshment courses or distribute posters or other updated official materials to support ongoing education with respect to:

a) awareness of the causes of floods and landslides and the impacts they can have on personal and community levels
b) awareness of the local real hydrogeological risk in terms of mapping of risk/safe areas
c) awareness of the risk of exposure of one's residence to hydrogeological risk

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WORRY KEY ACTION IN CASE OF FLOODS AND LANDSLIDES

KEY ACTION IN CASE OF LOW AND HIGH WORRY

KEY ACTION FOR INTERVENTION

AIM IN CASE OF LOW WORRY:
Contrast the underestimation of dangers given by low worry that could lead to the enactment of risky and reckless behaviors or delay in adopting protective behaviors

AIM IN CASE OF HIGH WORRY:
Promote the correct perception of risks in order to contrast the experience of intense and dysfunctional emotional reactions that could foster hasty, counterproductive and potentially harmful and dangerous choices that hinder the ability to rationally assess the situation and make effective decisions.

KEY ACTION TO PROMOTE ADEQUATE WORRY

Foster sensitization campaigns in workplaces/schools or distribute posters or other official materials to:

1- Promote the importance of relying only on official channels to receive news and updates on risky situations and following the directions of authorities in case of emergency. Correct information is the first tool for prevention.
2- Promote adequate knowledge and awareness of flood and landslide hazards through the previous key actions to foster a realistic perception of the probability/gravity/impacts of potential floods and landslides contextualized at the territorial level
3- Explain the importance of mental health following floods and landslides
4- Promote knowledge of the functioning of the warning and intervention system to foster a realistic and conscious perception with respect to what to expect in the phases leading up to and following an emergency

ATTENTION TO WORRY:

The effects of worry in some cases can lead, paradoxically, to emotional numbness. This occurs after repeated exposure to emotionally intense situations, such as living in risky areas. Furthermore, the risk of overexposure to threatening situations is particularly high given the current media environment, in which people are confronted every day with a high number and variety of intense emotional experiences (Shome et al., 2009).

KEY ACTION TO INCREASE HISTORICAL MEMORY OF FLOODS AND LANDSLIDE AND ANALYZE PRIOR PERSONAL EXPERIENCE

KEY ACTION TO INCREASE HISTORICAL MEMORY OF FLOODS AND LANDSLIDE AND ANALYZE THE PRIOR PERSONAL EXPERIENCE

↓

KEY ACTION TO INTERVENTION

AIM:
To promote knowledge of local/territorial vulnerability related to previous landslide/flood events

AIM:
To promote the analysis of one's past personal experiences.

Risk perception tends to be low in areas where hazards are rare. Conversely, risk perception tends to be higher in cases of direct experience of the event.

KEY ACTION TO PROMOTE ADEQUATE HISTORICAL MEMORY OF LOCAL/TERRITORIAL VULNERABILITY TO FLOODS AND LANDSLIDE

Promote sensitization campaigns or distribute posters or other official materials that reconstruct the local and territorial history of landslide and flood events by promoting a comprehensive view of past vulnerability and potential future risks, enhancing historical memory as a prevention tool. This process has a twofold purpose:

a) to improve the perception of risk and counter the illusory perception of invulnerability that might occur in areas that have not experienced recent events by making people aware of the real possibility of such events happening again.

b) to strengthen attention to the early signs of risk in vulnerable areas by promoting knowledge of protective preventive response and mitigation behaviors and knowledge of warning/intervention systems.

KEY ACTION TO PROMOTE ANALYSIS OF ONE'S PAST PERSONAL EXPERIENCES

Promote reflection on any personal experiences related to previous landslide/flood events,

- comparing the current risk and situation with those experienced in the past,
- and analyzing the effectiveness of responses adopted during past events,

in order to improve one's protective response and mitigation behaviors in case of future emergencies.

INFLUENCE OF PERSONALITY IN RISK PERCEPTION AND DISASTER RESILIENCE

Personality traits are relatively stable patterns of thoughts, feelings, and behaviours (Kandler, Bleidorn, & Wright, 2015).. The Big Five trait taxonomy is a model that includes five dimensions of personality (Bekirkan et al., 2024; McCrae & Costa, 1997; Novikova, 2013; Widiger & Oltmanns, 2017).

1) **OPENNESS** (open-mindedness, curiosity and interest in many areas)
2) **CONSCIENTIOUSNESS** (task-oriented, self-discipline, and organized)
3) **EXTRAVERSION** (assertive and sociability)
4) **AGREEABLENESS** (cooperative and friendly)
5) **NEUROTICISM-EMOTIONAL INSTABILITY** (the vulnerability to unpleasant emotions such as anger, irritability, anxiety, guilt, and depression. It provides a vulnerability for a wide array of different forms of psychopathology, including PTSD, anxiety, mood, substance, somatic symptom, and eating disorders)

Personality traits seem to influence
RISK PERCEPTION AND DISASTER RESILIENCE

Understanding the relationship between personality traits, risk perception, and disaster resilience can provide valuable insights into how individuals perceive and respond to the risk of hazard and cope and manage stress during and after the emergencies.

INFLUENCE OF PERSONALITY ON RISK PERCEPTION AND DISASTER RESILIENCE

Some studies have shown that **NEUROTICISM** and **CONSCIENTIOUSNESS** seem to **increase risk perception** (Siegrist & Arvai, 2020).

In addition, personality traits seem to influence resilience in response to stressful and traumatic events like disasters (Bekirkan et al., 2024). Specifically:

- **EMOTIONAL STABILITY,**
- **EXTRAVERSION,**
- **AGREEABLENESS,**
- **CONSCIENTIOUSNESS,**
- **and OPENNESS**

have a **significant POSITIVE EFFECT ON INDIVIDUAL DISASTER RESILIENCE,** which can help people to cope with stress more effectively, face the circumstances and adjust to new conditions. (Bekirkan et al., 2024). Conversely, **NEUROTICISM** have a **significant negative impact and DECREASES INDIVIDUAL DISASTER RESILIENCE**.

KEY ACTION in CASE OF NEUROTICISM

Offering support to individuals with higher levels of neuroticism can help them develop positive coping strategies and resilience, increasing their preparedness for the stresses associated with disaster response and improving outcomes during emergency situations (Bekirkan et al., 2024).

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2. KEY ACTION TO PROMOTE EFFECTIVE RISK COMMUNICATION

Flood and landslide risk communication is a process through which information is conveyed regarding the nature of the hazard, the general level of exposure, and protective response and mitigation behaviors to be adopted (in conjunction with the warning or onset of an emergency). Risk communication must be effective, with the dissemination of clear, timely, consistent, and up-to-date information to encourage the adoption by the population of appropriate measures in line with the extent of the risk. In fact, ineffective risk communication can lead to distortions in hazard perception (APA, n.d.), causing:

- an underestimation of the risk may lead to minimising the seriousness of the situation, delaying the adoption of protective measures, and the implementation of risky, reckless, or passive behaviour;
- an overestimation of risk can generate alarmism, panic, and impulsive choices, putting people at risk and compromising the effectiveness of rescue and emergency management operations.

KEY ACTION TO PROMOTE EFFECTIVE RISK COMMUNICATION	
KEY ACTION TO PROMOTE EFFECTIVE RISK COMMUNICATION ↓ 🎯 **AIM:** To provide effective risk communication, activated in conjunction with the alert or the onset of an emergency. The information provided must be timely, up-to-date, clear, and accessible in order to promote a realistic perception of risk and guide an active and effective public response, consistent with the level of imminent risk	**KEY ACTION TO PROMOTE EFFECTIVE RISK COMMUNICATION** Construction of a multichannel strategy characterised by: 1. Clarity of communication and local contextualisation and updating: Use clear, direct, and accessible language that is not overly technical and difficult to understand. Messages should also provide up-to-date information on the actual local situation and practical instructions on what to do, where to go,o and who to contact in case of need/emergency 2. Pay attention to the effects of worry, which can lead to emotional numbing following repeated exposure to an emotionally intense/threatening situation (see section Key action for Worry). 3. Consistency and non-contradiction between the communications of the various services/bodies responsible for the alert and intervention processes

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KEY ACTION TO PROMOTE EFFECTIVE RISK COMMUNICATION	
KEY ACTION TO PROMOTE EFFECTIVE RISK COMMUNICATION **AIM:** Promote correct emotional and behavioural activation counteracting: 1- dysfunctional emotional reactions and unnecessary alarmism (high risk perception) 2- underestimation and delays in implementing protective behaviour	**KEY ACTION FOR THE CONSTRUCTION OF A RISK COMMUNICATION STRATEGY AIMED AT REGULATING HIGH RISK PERCEPTION** 1. avoid vague and ambiguous information or information that leaves space for unfounded alarmism or catastrophic interpretations. 2. offer clear, up-to-date, operational, reassuring instructions, and calibrated to the real extent of risk and practice. 3. use positive examples to reinforce the sense of personal self-efficacy by showing cases in which the adoption of correct behaviour has prevented damage or saved lives 4. enhance the importance of preparedness by communicating that being informed and knowing how to respond is already a form of protection. 5. emphasise the importance of implementing protective response and mitigation behaviours calibrated to the real extent of the risk and following the instructions provided by the services/agencies. The aim is to counteract the implementation of unnecessary, hasty, and counterproductive protective responses and mitigation behaviours given by high and dysfunctional emotional reactions (panic, anxiety, fear ...) that may hinder effective response to the emergency and increase individual vulnerability. 6. include in the messages an acknowledgement of dysfunctional emotions (e.g. fear, anxiety) accompanied by services/bodies to which one can turn for support and indications on possible emotional management strategies **KEY ACTION FOR THE CONSTRUCTION OF A RISK COMMUNICATION STRATEGY AIMED AT REGULATING LOW RISK PERCEPTION** 1. Considering the indications for the regulation of a high risk perception, communicate up-to-date data with respect to the real severity/entity of the risk in order to counteract the denial/minimisation of dangers and delay in the implementation of protective response and mitigation behaviours 2. highlight the possible consequences of not activating protective responses and mitigation behaviours 3. involve direct testimonies of people who have experienced similar events, to stimulate identification and attention.

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3. PEOPLE'S RESPONSE TO EVENT

People's hazard preventive preparedness and **risk communication** influence the quality of the population's risk perception and consequently quality of responses to flood and landslide emergencies (Figure 5.

Indeed, preventive preparedness and risk communication anticipate the emergency on a temporal level and could influence decision-making and behavioral processes, determine people's ability to recognize and understand the hazard, correctly assess its severity/extent, and implement appropriate protective response and mitigation behaviors.

Thanks to effective preparedness and risk communication, a trained and informed population could better perceive the real risk and implement timely, effective, and coordinated response behaviors consistent with the real risk, fostering greater self-efficacy and personal safety (e.g., preventive evacuation, adherence to emergency plans, and adoption of self-protective measures).

Conversely, inadequate preventive preparation or ineffective risk communication can lead to inadequate risk perception and delayed response, underestimation of risk, resistance to evacuation, or unnecessary, rushed, and counterproductive protective response and mitigation behaviors leading to increased personal exposure and vulnerability to hazards.

Figure 4.5: Influence of Hazard Preventive Preparedness and Risk Communication on the Quality of the Population's Risk Perception and Consequently Responses to Flood and Landslide Emergencies

4. POST-EVENT RECOVERY

In the post-event recovery phase, it is important to implement a reinforcement and update of the preventive preparedness system, increasing the resilience and protection of the population through:

1. A review of the emergency plans after the event to correct any logistical or communication weaknesses encountered in order to make the plans more adherent to reality and effective in case of new emergencies.
2. Analyzing the emerging issues and introducing new preventive and protective responses and mitigation measures will improve future response capacity.
3. Post-event communication campaigns to promote a risk-aware and continuous culture.
4. Activating psychological support services for the affected population and **early identification of vulnerable people at psychological risk** (see section The Assessment of the Risk of Adverse Psychological Consequences and deliverables D3.2)

Indeed, floods and landslides can significantly affect the mental health of communities, increasing the risk of developing Post-traumatic Stress Disorder (PTSD), depression, and anxiety symptomatology (Kumar, 2023; Walinski et al., 2023; Kabunga, 2022; Parel & Balamurugan, 2021; Fernandez et al., 2015). The literature highlights a series of risk and protective factors that can influence mental health, amplifying or reducing the risk of psychological vulnerability (Asnakew et al., 2019; Bei et al., 2010; Dai et al., 2017; Mason, Andrews & Upton, 2010; Shabani et al., 2024). These factors include ***Socio-demographic factors*** (e.g., gender, marital status, education level, income); ***Pre-traumatic factors*** that concern both personal and family background (e.g., history of individual or family special needs, prior traumatic events), individual functioning (e.g., coping strategies), and relational variables (e.g., social support of family and friends); ***Peri-traumatic factors*** (during or in the immediate aftermath of the traumatic experience; e.g., trauma severity); and finally, ***Post-traumatic factors*** (in the period after traumatic experiences, e.g., social support, coping strategies) (Asnakew et al., 2019; Bei et al., 2010; Dai et al., 2017; Mason, Andrews & Upton, 2010; Shabani et al., 2024). In addition, certain groups of the population, such as children, elderly, and subjects with special needs (e.g., previous disabilities, chronic diseases, and mental illness), could be more exposed to risk of physical and psychological vulnerability due to natural disaster (Cianconi et al., 2020; Sharpe & Davidson, 2022; White et al., 2023; Medved et al., 2022; Maltais, 2019; Han, 2017; Walker et al., 2015; Aldrich & Benson, 2008; Peek, 2008; Miller & Arquilla, 2008). Specifically,

- children may be more vulnerable due to their inability/difficulty to understand the risks and difficulty in coping independently with an emergency situation resulting from their dependence on adults. In addition, severe natural disasters could result in the separation, injury or death of parents or family members and the displacement of children to rescue shelters (Peek, 2008);
- elderly people may show resistance to leaving their homes, be less likely to consider evacuation notices and be more likely to remain alone in their homes during

emergencies (Maltais, 2019). In addition, if they have mobility problems, they could experience difficulties in escaping from risky places (Maltais, 2019);

- people with disabilities may have a greater difficulty or inability to take protective measures and react and evacuate quickly (especially those with serious conditions or who require special care or equipment), recognize warning signs or understand threats, the state of emergency and the instructions given (Han, 2017);
- for people with chronic diseases, before being taken into care by the competent services, during the emergency phase there may be temporary suspensions in therapeutic regimens that could contribute to exacerbating and worsening symptomatology (Maltais, 2019; Aldrich & Benson, 2008; Miller & Arquilla, 2008);
- people with severe mental illness may use dysfunctional coping strategies or have insufficient social resources to help them cope with post-event stressors (Medved et al., 2022).

The factors that can influence vulnerability to psychological risk and identify the most at-risk subjects are crucial. In the psychological section of SAFE-LAND, we have considered socio-demographic and pre-traumatic factors to propose an early identification of the subjects most vulnerable to psychological risk, also before the occurrence of a flood or a landslide (see Section *The Assessment of the Risk of Vulnerability to Adverse Psychological Consequences* and deliverables D3.2). In particular, a series of individual and relational variables (distal and proximal risk factors) could amplify vulnerability to psychological risk or protect psychological well-being (proximal resources and protective factors). These factors could constitute a sort of risk or protective humus that leads individuals to show different levels of vulnerability to psychological consequences even before a flood or landslide event occurs. Understanding and evaluating these pre-existing factors could provide essential indications on an individual's vulnerability to psychological risk, which could worsen and become chronic after the emergency, especially in the presence of serious peri- and post-traumatic factors (for example, getting injured, losing relatives, damage to the house, etc.). Therefore, identifying individuals' vulnerabilities and strengthening and supporting adaptive resources and protective functioning at the individual and relational levels could constitute effective preventive interventions.

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