LITERATURE REVIEW OF GREY, GREEN AND HYBRID MEASURES FOR LANDSLIDES MITIGATION

In this section literature review on grey, green and hybrid landslides mitigation measures is presented. Here, such aspects as feasibility, cost-effectiveness, flexibility, maintenance procedure, impact on and mitigation of climate change were considered during the review of the selected measures. In addition, short summary and case study is presented for each measure. However, before going deep into details about each measure, first it is important to mention how these measures were distributed between these three different categories.

Thus, with respect to grey measures, traditional and conventional landslides mitigation infrastructure was chosen. Compared to other landslides risk reduction techniques, grey measures visually represent rigid infrastructure usually made of non-degradable materials, such as concrete or steel, and are known to have prevailing "grey" visual effect. Furthermore, this kind of measures usually provide restricted or almost no ecosystem services. Green measures, on the other hand, tend to have prevailing ecosystem functions compared to other landslides risk reduction categories and are mainly made of degradable materials. Even though certain technical equipment is usually needed during the implementation stage to build green landslides protection measures, subsequently after the set-up procedure these measures tend to have only "green" visual effect. With regard to hybrid measures, landslides mitigation solutions that include functions of both grey and green measures were selected. It should be also mentioned that in this case hybrid measures refer mostly to those solutions that visually look greener and provide ecosystem services; however, they still contain elements of grey infrastructure that help the system to properly perform its functions.

Following that, Table 1 and 2 represent a list of the selected grey, green and hybrid measures and description of the parameters that were investigated during the literature review for each particular measure, respectively.

Table 1. *Selected measures for grey, green and hybrid landslides mitigation measures.*

Category	**Selected measures**
Grey	flexible net barriers, check dams, deep drainage (large diameter wells, horizontal boreholes, etc.), retaining walls (sheet steel retaining walls, gabion walls, piles), modifying the mechanical characteristics of the unstable material (jet grouting, compaction, chemical binders)
Green	afforestation, vegetation planting, live stakes and fascines, biotechnical slope protection (hydroseeding, hydromulching, Euro-Mat, etc.)
Hybrid	retaining walls (woody damstimber crib), earth slope stabilization (terraces or benches, backfilling with lightweight material, excavation), water retention polders, shallow (surface) drainage, surface protection and erosion control (geotextile, substitution with drainage blanket such as biotechnical slope protection using geosynthetic material)

Table 2. *List of descriptors and their explanation.*

Descriptor	**Explanation**
Short summary	Short explanation/description of the selected grey, green or hybrid measure.
Feasibility	How difficult it is to implement the measure in terms of design, implementation procedure, etc. In addition, durability (lifetime) of the measure can be also considered in this section.
Cost-effectiveness	How effective is the measure in terms of flood mitigation and other aspects (if applicable) based on the number of investments (e.g., construction costs).
Flexibility (Other hazards)	Influence of the selected measure on the risk of any other hazard, such as landslides, erosion, sedimentation, groundwater contamination, etc. (if applicable).
Maintenance	Maintenance activities (efforts) needed to keep the structure in the desirable conditions. In addition, maintenance costs can be also considered in this section.

Climate change	Influence of the selected measure on climate change. Here, depending on the selected measure, mitigation or, in contrast, negative impact on climate change can be considered.
Case study example	Description of a case study where the selected measure was implemented or where its implementation was tested.

Landslides - green measures

Measure: afforestation	
Real case example where the measure was applied:	In Switzerland, protective forests have been used traditionally to reduce risk of avalanches, landslides, and rockfalls. https://link.springer.com/article/10.1007/s10346-005-0018-8 Grain for Green afforestation program in China Great Loess Plateau is a renowned example where large-scale afforestation efforts have been successful in reducing landslides and erosion. https://link.springer.com/article/10.1007/s11069-020-04491-x Nepal's Annapurna Conservation Area: The Annapurna Conservation Area Project (ACAP) involves afforestation initiatives that have as a side effect stabilized steep slopes and reduced landslides. https://ntnc.org.np/project/annapurna-conservation-area-project-acap https://www.sciencedirect.com/science/article/pii/S2211464517300568 Not all initiatives and programmes are aimed at landslide mitigation, but it is a frequently mentioned side effect of these programmes
Short summary	Afforestation is a proactive landslide mitigation measure (Papathoma-Köhle and Glade) that involves planting trees and restoring natural forest cover in landslide-prone areas. Vergari et al. (2017) reports that more than 20% of European forests directly protect soil, improve water quality or provide other ecosystem services. It is a nature-based solution that leverages the stabilizing effects of vegetation, primarily tree roots, enhances soil cohesion, reduces surface runoff, and mitigates erosion, thus making slopes more resistant to landslides.
Feasibility	Afforestation is generally feasible in landslide-prone regions, but depends on factors such as available land, climate conditions, tree species suitability, and community involvement. Detailed site assessments are crucial to determine feasibility. Land tenure issues and conflicting land use priorities can hinder afforestation efforts. Long-term commitment and community involvement are essential but may face challenges.
Cost-effectiveness	Afforestation can be cost-effective compared to traditional engineering solutions as the initial costs of planting trees and restoration may be lower than building and maintaining engineered structures. There are also multiple long-term benefits of improved slope stability, reduced erosion, and enhanced ecosystem services that make it a cost-effective strategy. The key effects of forests on landslide mitigation acoridng to review by Vergari et al. (2017) is through (a) interception and evaporation (6-45% reduction of annual rainfall according to Carlyle-Moses and Gosh 2011), (b) suction and transpiration educing soil moisture, (c) infiltration and subsurface flows (supporting soil pore formation), (d) soil reinforcement, (e) buttressing and arching, and (f) surcharge (rather limited effect). The effect is different for various types of landslides. Afforestation is particularly effective in reducing shallow landslides on relatively gentle slopes, soil creep by reinforcing the upper layers of the soil, and rainfall-induced landslides where canopy decreases rainfall erosivity and roots may decrease pore water pressure induced by infiltered rainfall water. Afforestation may also decrease erosion-induced landslides by stabilizing upper soil layers by roots.

	On the other hand, afforestation is limited at highly inclined slopes and it also has a limited effect on deep landslides or deep-seated landslides induced by lithological and tectonic properties.
Flexibility	Afforestation also has a positive impact on soil erosion and on reducing peak discharges through rainfall interception process.
Maintenance	Successful afforestation requires ongoing maintenance, including invasive species management, tree care, and monitoring. Regular inspections and forest management are essential to ensure the health and stability of the forested areas. The maintenance also depends on whether there are more functions assigned to specific forest stands.
Climate change	Afforestation contributes to climate change mitigation by sequestering carbon dioxide through tree growth and enhancing carbon storage in soils. It also supports climate adaptation by reducing the impacts of extreme weather events, such as heavy rainfall by decreasing rainfall erosivity.
Case study example	https://link.springer.com/article/10.1007/s11069-020-04491-x https://www.sciencedirect.com/science/article/pii/S2211464517300568 https://link.springer.com/article/10.1007/s10346-005-0018-8

Measure: Vegetation planting	
Case study example	In the UK, native grasses and ground cover plants are used to stabilize slopes along highways and railways, reducing the risk of shallow landslides during heavy rainfall events. Japanese knotweed and other native vegetation are employed in combination with bioengineering techniques to reinforce slopes and control landslides in mountainous regions.
Short summary	Vegetation measures in landslide risk reduction refer to the use of various types of native or adapted plants, ground covers, and shrubs to stabilize slopes, reinforce soil, and mitigate the risk of landslides (Stokes et al. 2014). Unlike large-scale afforestation, vegetation measures focus on smaller-scale interventions aimed at enhancing local slope stability without necessarily converting the area into a forested landscape.
Case study example	https://link.springer.com/chapter/10.1007/978-3-642-22087-6_5 https://www.e3s-conferences.org/articles/e3sconf/pdf/2018/40/e3sconf_iccee2018_06003.pdf https://link.springer.com/article/10.1007/s10064-020-01783-1
Feasibility	Vegetation measures are generally feasible in various regions, especially those with moderate slopes and suitable soils. They are adaptable to diverse landscapes and can be tailored to specific site conditions.
Cost-effectiveness	Vegetation measures are typically cost-effective compared to large-scale afforestation or extensive engineering solutions. Costs are lower due to reduced material requirements and the use of locally available vegetation. Vegetation measures can be highly effective in mitigating particularly shallow landslides and surface erosion, where plants bind soil particles together, increase soil cohesion and shear strength. Plant can also mitigate slow and gradual mass movements like soil creep, rainfall-induced landslides, where heavy precipitation can saturate the soil and increase pore water pressure, and erosion-induced landslides due to interception of rainfall. Prompt re-vegetation through planting can stabilize the soil, minimizing the risk of post-wildfire landslides. The effectivity of planting is limited on extremely steep slopes or in areas with frequent disturbances. In such cases, additional mitigation measures or a combination of nature-based solutions and engineering approaches may be necessary. Also, some studies report limited effects of grasslands on landslide mitigation compared to forested sites. According to Shu et al. (2017), landslide density in a Spanish case study was 2.0 landslides/km2 in grasslands compared to 0.4 landslides/km2 in forested areas.

Maintenance	Maintaining vegetation measures involves regular monitoring, weeding, and the replacement of any damaged or dead plants. Adequate watering during establishment is crucial to ensure plant survival. Maintenance basically depends on agricultural use and management practices (Tasser et al. 2003) that may significantly affect plant properties and their stabilizing effect on soil.
Climate change	Vegetation measures contribute to climate change mitigation by sequestering carbon dioxide through plant growth and improving overall ecosystem health. They also support climate adaptation by reducing extreme hydrological events and erosion.
Other hazards	Vegetation measures can be integrated with other nature-based solutions and engineered measures in order to reduce sediment runoff. Invasive plant species can outcompete desired vegetation, potentially leading to ecological imbalances. Also, some plant species are considered invasive thus inducing other biogenic hazards, but it was also reported as a cause for increased bank erosion (Colleran et al. 2020).

Measure: Live stakes and fascines	
Case study	Live stakes have been effectively used in the US to mitigate erosion and reduce landslide risk in wildfire-affected areas or to protect road infrastructure. Native species like willow and dogwood are commonly employed to stabilize slopes. https://www.wsdot.wa.gov/publications/fulltext/Roadside/SoilBioEngAlternative.pdf In regions such as Nepal and Bhutan, live stakes from indigenous species like alder and willow are used to reinforce slopes and reduce landslides along roads and trails in steep terrains. https://link.springer.com/article/10.1007/s00267-012-0003-7 Detailed review and empirical study from Thailand is reported in thesis by Tadsuwan (2017): http://ethesisarchive.library.tu.ac.th/thesis/2017/TU_2017_5922040455_8719_7216.pdf
Short summary	Live stakes, also known as live fascines, are a nature-based hazard mitigation measure (Richet et al. 2017) involving the planting of live woody cuttings or branches, typically from shrubs or trees, into slopes or areas prone to erosion and landslides. These live stakes take root and grow, reinforcing the soil structure and stabilizing the slope, reducing the risk of shallow landslides.
Case study example	https://www.wsdot.wa.gov/publications/fulltext/Roadside/SoilBioEngAlternative.pdf. https://link.springer.com/article/10.1007/s00267-012-0003-7.
Feasibility	Live stakes are generally feasible in areas with suitable soil and climatic conditions. They are adaptable to a wide range of landscapes. Use of native species is recommended.
Cost-effectiveness	Live stakes are often a cost-effective option for landslide mitigation because of their lower material costs and minimal equipment requirements. They are particularly effective in mitigating certain types of landslides, mainly those associated with surface erosion and shallow landslides. Live stakes, once established, develop robust root systems that stabilize the soil, increase soil cohesion, and enhance shear strength. They are also effective for erosion-induced landslides, and post-wildfire landslides as they help to reestablish vegetation. They can also be used for soil creep reduction. Specific use has been found for bank stabilization along rivers and water streams that could otherwise develop to landslides in adjacent areas. As with other measures, their effectiveness may be limited on extremely steep slopes or in areas with frequent disturbances.
Maintenance	Maintenance for live stakes primarily involves monitoring plant growth, ensuring they establish roots, and replacing any dead or damaged stakes. Adequate watering and protection from browsing animals during establishment are crucial.
Climate change	Live stakes contribute to climate change mitigation by sequestering carbon dioxide through plant growth. Additionally, they support climate adaptation by reducing soil erosion, which can worsen landslides during extreme weather events, and by providing overall ecosystem benefits.

Other hazards	Live stakes can be integrated with other erosion control measures, such as silt fences and check dams, to enhance slope stability and reduce sediment runoff. Improved vegetation cover enhances biodiversity and provides habitat for wildlife. The root systems of live stakes help regulate water flow, reducing the risk of flash floods in some cases. The effects of live stakes can be reduced at steep slopes and by invasive species or disease outbreaks. Successful implementation relies on community engagement and ongoing maintenance.

Measure: Hydroseeding	
Case study	Hydroseeding has been extensively employed in the United States to mitigate landslides in hilly and wildfire-affected regions. After wildfires, hydroseeding helps establish vegetation quickly to prevent post-fire landslides. New Zealand has implemented hydroseeding in areas prone to erosion and landslides, particularly in steep terrains and along highways, to reinforce slope stability.
Short summary	Hydroseeding is a slope stabilization technique used in landslide mitigation (Chen et al. 2014) and erosion control (Montoro et al. 2000) that involves spraying a mixture of water, seeds, mulch, and often soil stabilizers onto erodible or landslide-prone slopes. This mixture, known as a hydroseed slurry, promotes vegetation growth, enhances soil stability, reduces surface erosion, and minimizes landslide risk.
Case study example	https://tme1.com/blog/when-hydroseeding-isnt-enough-stabilizing-steep-slopes-landslide-prone-terrain/. https://onlinelibrary.wiley.com/doi/abs/10.1002/1099-145X(200007/08)11:4%3C315::AID-LDR394%3E3.0.CO;2-4.
Feasibility	Hydroseeding is generally feasible in areas with appropriate access and water supply. Site-specific assessments should consider factors like soil conditions, slope gradient, and seed selection to determine feasibility. Effect of hydroseeding on steep slopes is rather limited (https://tme1.com).
Cost-effectiveness	Hydroseeding can be cost-effective compared to traditional engineering solutions. Its cost-effectiveness stems from reduced material and labor costs, quicker implementation, and the long-term benefits of stabilized slopes and reduced erosion. Hydroseeding is an effective landslide mitigation measure for shallow landslides by increasing soil cohesion and shear strength, erosion-induced landslides by creating a protective vegetative cover on the slope. post-wildfire landslides by rapidly establishing vegetation, and soil erosion control. Hydroseeding may have limitations in addressing deep-seated landslides or landslides driven by factors such as groundwater

	seepage, geological faults, or intense rainfall infiltration into deeper soil layers.
Maintenance	Maintaining hydroseeded areas requires periodic monitoring and potential reseeding. Regular inspection and management of invasive species are essential to ensure the continued effectiveness of the mitigation measure. Emeka et al. (2021) report a study from Malaysia analysing various effects of four seed species. Selection of the appropriate seed for specific conditions is essential. Xiao et al. (2017) reports experimental study that highlights the role of specific composition of mixture used for slope stabilisation.
Climate change	Hydroseeding contributes to climate change mitigation by sequestering carbon dioxide through plant growth and improving soil carbon storage. It supports climate adaptation by reducing soil erosion and by generally increasing water retention.
Other hazards	Hydroseeding can complement other erosion control measures, such as silt fences and check dams, by stabilizing slopes and reducing sediment runoff into water bodies. Improved vegetation cover enhances biodiversity and provides wildlife habitat. Hydroseeding can be integrated with flood risk reduction measures, as stabilized slopes are less prone to erosion during heavy rainfall. Limitations include availability of appropriate seeds and soil stabilizers, and steep or inaccessible terrain.

Landslides - hybrid measures

Measure: woody dams	
Real case example where the measure was applied:	Woody dams have been utilized globally as effective landslide mitigation measures. Notable examples include their use in the Italian Alps, Japan, Spain or United States. Dolomites, Italy: woody dams, often constructed using logs, branches, and debris, are placed in areas susceptible to debris flows and landslides. These structures are designed to slow down surface water runoff and trap debris, reducing the potential for shallow landslides during heavy rainfall or snowmelt events. Japan: Japan experiences frequent heavy rainfall and is prone to landslides, especially in forested areas. Woody dams are used to reduce the risk of landslides. These dams help in stabilizing the slopes and controlling surface water flow, thereby decreasing the likelihood of landslides. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004EO150001 Spain: woody/log dams are used in some areas of Spain to mitigate erosion and shallow landslides after wildfires. https://www.sciencedirect.com/science/article/pii/S001670611400336X United States: particularly in regions susceptible to wildfires, woody dams are employed as a post-fire and erosion mitigation strategy. Wildfires can increase the risk of debris flows and landslides due to the loss of vegetation and altered soil properties. https://pubs.geoscienceworld.org/aeg/eeg/article-abstract/xxvi/1/109/137372/Long-Term-Landslide-Hazard-Mitigation-Programs
Short summary	Woody dams, also known as check dams or log dams, are nature-based solutions employed for shallow landslide and erosion risk reduction. These structures are composed of logs, branches, and other woody debris strategically placed in a sloping terrain to mitigate landslide hazards. Their primary purpose is to slow down surface water runoff, control erosion, and stabilize soil and rock slopes, thereby reducing the potential for landslides.
Feasibility	Woody dams are generally considered feasible, especially in forested and hilly terrains with sufficient availability of native woody material. They require a supply of woody debris, which is usually available in such areas. Their feasibility can be influenced by local regulations and land use planning, as well as the availability of skilled labour for construction. UNISDR (2013) shows that log dams can be used in combination with reforestation efforts to mitigate landslide hazard.
Cost-effectiveness	The cost-effectiveness of woody dams as a landslide mitigation measure varies depending on the type of landslide and local conditions. They are cost-effective for smaller and shallow landslides and are particularly beneficial in areas where traditional engineering solutions may be impractical or too expensive. Also, they may help as a sediment trap upstream and erosion control measure, therefore indirectly helping to mitigate the preconditions for landslides. For larger, deep and structurally preconditioned deep-seated gravitational slope deformations, the cost-effectiveness may decrease considerably, and additional measures may be required.
Flexibility	Woody dams can have positive interactions with other natural hazard mitigation measures. For example, they can also help reduce flood risk and provide benefits

	for water quality. Similarly, they have a synergic effect for erosion control in non-vegetated (mostly post-fire) environments. Margiorou et al. (2022) showed their effect and stability in the long-term at a site affected by wild fire 20 years ago. However, it's essential to consider the potential downstream impacts, as increased sediment retention may lead to riverbed elevation and related flood risks. This may be resolved by hybrid check dams (Schwindt et al. 2018).
Maintenance	Regular maintenance is essential to ensure the continued effectiveness of woody dams. This includes removing debris buildup, ensuring proper water flow, and replacing deteriorating wood. Maintenance costs are generally lower compared to more complex engineering solutions, but they require labour force regularly controlling and maintaining the dams.
Climate change	Woody dams contribute positively to climate change adaptation by reducing the risk of distributed shallow landslides, which can be exacerbated by increased rainfall and changing precipitation patterns. They also help in retaining moisture in soil, which can aid in forest regeneration and carbon sequestration, contributing to climate resilience.
Case study example	https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004EO150001 https://www.sciencedirect.com/science/article/pii/S001670611400336X https://pubs.geoscienceworld.org/aeg/eeg/article-abstract/xxvi/1/109/137372/Long-Term-Landslide-Hazard-Mitigation-Programs

Measure: terraces	
Real case example where the measure was applied	Terraces have been employed globally as an effective measure to reduce landslide hazards with notable applications in the Himalayas, Andes, and Southeast Asia or Mediterranean, but they are also well-known from agricultural regions of Central Europe. Nepal: The hilly terrain of Nepal is characterized by extensive terrace farming. Terraces, known as "Dhan" or "Ropai," are commonly used for agriculture in the region. These terraces not only enable farmers to cultivate crops on steep slopes but also play a role in stabilizing hillsides and preventing soil erosion, which helps reduce landslide risk. https://link.springer.com/article/10.1007/s10064-005-0025-y India: In the Indian Himalayan region, some states employ extensive terrace farming techniques on the rugged slopes. These terraces support the cultivation of crops such as rice, wheat, and maize. Andes: In the high-altitude Andes of Peru or Bolivia, the terrace farming techniques known as "andenes” were historically used. These andenes are stone-built terraces used for agricultural purposes. They prevent soil erosion, control water runoff, and stabilize steep slopes. https://digitalcommons.usf.edu/cgi/viewcontent.cgi?article=1049&context=geologia
Short summary	Terraces, often referred to as bench terraces or contour terraces, are useful solutions used for landslide risk reduction. These structures involve the creation of horizontal or gently sloping platforms on hilly or mountainous terrain to control surface water runoff, minimize erosion, and stabilize slopes, ultimately mitigating the risk of landslides.
Feasibility	The feasibility of terraces varies depending on the terrain and local influencing factors. In areas with steep slopes and a history of landslides, terraces are often a viable option. Factors such as soil type, vegetation, and land use planning play a crucial role in determining their feasibility. Local regulations and community engagement can also affect their implementation.
Cost-effectiveness	The cost-effectiveness of terraces as a landslide mitigation measure is favourable for a wide range of landslide types. They are particularly cost-effective for shallow landslides, debris flows, and slow-moving landslides. Terraces can often be built with locally available materials, reducing construction costs, and are less expensive than more complex engineering solutions. On the other hand, it was also noted by that poorly constructed agricultural terraces may be prone to landsliding (Galve et al. 2014; Ažman 2015; Wen et al. 2021) and with an increasing extent of terraces, more land can be affected by landslides and suffer from additional impacts.
Flexibility	Terraces may interact positively with other natural hazard mitigation measures. For instance, they can help reduce flood risk by controlling surface water runoff and improving water infiltration. It is necessary to consider potential downstream effects, such as sedimentation in rivers or changes in water quality, and coordinate with other hazard management strategies.
Maintenance	Terraces require regular maintenance to remain effective. This includes ensuring that drainage systems remain functional, repairing damaged terraces, and managing vegetation. Proper maintenance is critical for their long-term performance and can be cost-effective when compared to landslide repair or

	rehabilitation. Also, planning and design (dry r we constructions) of terraces play a crucial role in their stability.
Climate change	Terraces contribute to climate change adaptation by reducing soil erosion, retaining moisture in the soil, and promoting the growth of vegetation. These features enhance soil stability and resilience against extreme weather events, including heavy rainfall and increased precipitation, which can trigger landslides.
Case study example	https://ui.adsabs.harvard.edu/abs/2015EGUGA..17.9680A/abstract https://digitalcommons.usf.edu/cgi/viewcontent.cgi?article=1049&context=geologia https://link.springer.com/article/10.1007/s10064-005-0025-y https://www.mdpi.com/2073-445X/11/7/963

Measure: water retention polders	
Some examples of application:	While water retention polders are mostly built for flood risk reduction, they may also be employed in lowland areas for bank erosion and landslide control, and for retaining water and reducing landslide hazard in mountainous areas. The Low-Land Countries of Europe: water retention polders, known locally as "waterbergingen," are used in the Netherlands or Belgium. These polders are strategically located in landslide-prone regions, such as the hilly areas of Limburg, to temporarily store excess rainwater, preventing slope saturation and landslides. https://thinkhazard.org/en/report/2163-netherlands-limburg/LS China: poldering is a traditionally management approach in lowland regions of China, but they may also be used to reduce the hazard of oversaturated flows and rapid shallow landslides in both mountainous and lowland areas. https://www.xjtlu.edu.cn/en/news/2023/02/why-is-the-polder-landscape-an-important-water-heritage-of-china https://www.adrc.asia/publications/TDRM2003Dec/11_MR.%20HONGTAO%20WAN%20_FINAL_.pdf Andes: water retention polders are employed in areas with a history of debris flows and landslides. These structures store excess water from heavy rainfall events and are integral components of local disaster risk reduction plans. https://www.fao.org/3/i2232e/i2232e.pdf
Short summary	Water retention polders are hybrid solutions primarily designed to mitigate flood hazard and hazard of debris, mud, and other oversaturated flows, but they can also help in landslide hazard mitigation by controlling water levels in susceptible areas. These engineered depressions or reservoirs temporarily retain excess rainfall and surface runoff, reducing the saturation of slopes and thereby minimizing landslide occurrence.
Case study example	https://www.fao.org/3/i2232e/i2232e.pdf. https://www.xjtlu.edu.cn/en/news/2023/02/why-is-the-polder-landscape-an-important-water-heritage-of-china.
Feasibility	The feasibility of water retention polders as a landslide mitigation measure depends on the local topography, hydrology, and available land. They are particularly suited for areas with seasonal or periodic landslide risk predisposed by heavy rainfall (typhoon, monsoon, and other events), and where it's possible to create depressions for water storage. Aside topography, feasibility assessments should consider factors like land ownership, land use, and the availability of suitable sites, since polders require certain minimum area of land to be effective.
Cost-effectiveness	Water retention polders are generally cost-effective for a wide range of landslide types. They are especially beneficial for shallow landslides, debris flows, and areas with recurrent rainfall-induced landslides. While initial construction costs can vary, the long-term cost-effectiveness is favourable compared to the expenses associated with landslide damage and recovery. Water retention ponds can be strategically placed in areas prone to shallow landslides to intercept and store excess rainfall or runoff, reducing water infiltration into the slope and preventing the development of critical pore water pressures that trigger landslides. With similar mechanisms, water retention ponds may also provide hazard mitigation measure for mudflows and debris flows. At shoreline settings, the polders combined with other measures (e.g., fascines) may help to reduce riverbank and coastal erosion landslides. Wate retention polders may retain water above the cut slopes found in transportation infrastructure, thus providing support during heavy rainfall events inducing cut slope landslides. Finally, they may be used to

	control and manage excess water from rain or other sources at mining sites and tailings dams.
Maintenance	Regular maintenance is essential to ensure the continued effectiveness of water retention polders. Maintenance activities include dredging to remove sediment buildup, inspecting and maintaining outlet structures, and ensuring proper vegetation management. Properly maintained polders help to preserve their functionality.
Climate change	Water retention polders contribute significantly to climate change adaptation by reducing landslide risks in the face of increasing precipitation and extreme weather events. By controlling water flow and reducing slope saturation, these structures enhance resilience against climate-related landslide hazards. These effects are mostly obvious for flood hazard control and biodiversity conservation, however.
Other hazards	Water retention polders can have positive interactions with other natural hazard mitigation measures, mostly with flood control and water resource management. They help in managing water flow, which can reduce the risk of both landslides and floods. Similarly to log/check dams and slope terracing, the plans and designs for water retention polders should clearly consider potential downstream effects for sediment budget and interactions at the floodplain and catchment scale.

<table>
<tr><th colspan="2">Measure: biotehnical slope protection using geosynthetic material</th></tr>
<tr><td>Some examples of application:</td><td>
Figure 1. Example of biotechnical slope protection in Slovenia (Reference: Tomaž Cej, Rejda d.o.o.).</td></tr>
<tr><td>Short summary</td><td>Biotechnical/ Bioengineering method stabilizes soil slopes surface by the intertwining of roots, which maximizes seepage of runoff into soil by intercepting rainfall, and retarding the runoff velocity (Ahn et al., 2002).
The landslide prevention using geosynthetics can be implemented in various ways (Damians et al., 2023):
using geotextiles and geomembranes to perform barrier function and/or filter function, which prevents the effects of water seepage;
using high strength geosynthetics to reinforce the soil, thus making stable even for very steep slopes;
using geomats and geocells for hold topsoil in place, thus preventing slippage;
using geocomposite drains to allow excess rainwater to disperse safely, without washing the soil away;
applying geosynthetics for erosion control to the surfaces of slopes to encourage the growth of new vegetation and provide anchorage to the root structures, thereby increasing their erosion resistance under significant hydraulic stresses, further stabilizing slopes through natural means.</td></tr>
<tr><td>Case study example</td><td>In Slovenia, biotechnical slope protection system using geosynthetic material is not a very common method used for landslide protection. It is rather used as a complementary measure in combination with other measures for erosion control and slope stabilization of artificial slopes.</td></tr>
<tr><td>Feasibility</td><td>The geosynthetics are anchored in a trench 150 mm deep and 150 mm wide on the top of the slope and then unrolled along the slope without being stretched. A permanent seeding should be applied before placing the blankets (transportation.alberta.ca).
Based on (https://www.larimit.com/mitigation_measures/1021/) implementation of this measure has the following advantages and disadvantages
Advantages:
erosion control also in disturbed areas where vegetation is slow to establish;</td></tr>
</table>

	• synthetic mats can be used as reinforcement to add tensile strength to a soil matrix; • suitable also along steep slopes (> 3:1 H:V) or slope channels with high water flow Disadvantages: • not suitable for very steep rocky sites; • some synthetic materials can produce air/water pollution and, if used for stream bank stabilization this is a threat to aquatic species; • some geotextiles are tightly woven, making difficult for grass seed to root into the underlying soil or strangling the plants during their growth; • the slopes must be uniform and relatively smooth before installation to ensure complete contact with the soil. The associated labour cost may be high.
Cost-effectiveness	The systems is multifunctional and relativley inexpensive and does not require elaborate equipment for installation. The maintainance of biotehnical slope protection are not demending and expansive since the system is self-repering (Ahn et al., 2002). According to Damians et al., 2023 geosynthetics bring significant social, technical and functional benefits in comparison with other foundation-stabilization methods such as drainage, excavation, and replacement with certain granular materials or chemical stabilization. Compared with traditional drainage methods (i.e., sand and gravel), a key advantage is that geosynthetics-based solutions significantly reduce the required thickness of aggregate layers compared with conventional solutions.
Maintenance	Geosynthetic material is either biodegradable (e.g. natural fibers) or non-biodegradable (polyester, polypropylene or polyethylene). As technology has advanced, the concept and function of non-biodegradable geotextiles and other geosynthetics has become the preferred choice. With technological advances, the concept and function of non-biodegradable geotextiles and other geosynthetics have become the preferred choice. Repeated field studies have investigated the life cycle of geosynthetics has been observed under UV, chemical, and biological conditions. Due to their composition of polymers (e.g., polyester, polypropylene, or polyethylene), geotextiles have become a practical, easy-to-maintain product used in geotechnical applications. The maintenance of geosynthetics has proven that geosynthetic materials have a long life cycle, especially those that are not biodegradable. (Reference: https://bluestonesupply.com/pages/geosynthetics-how-do-they-prevent-landslides)
Climate change	The use of geosynthetics has become an essential material for reaching environmental sustainability. Geosynthetics are durable polymers that provide high performance, and they often contribute to making infrastructures more sustainable in many aspects (Damians et al., 2023).
Other hazards	The functions and applications of biotehnical slope protection include reinforcement, separation, drainage, filtration and protection, which all favour landslide mitigation (Fang et al., 2023).

	It is one of the mitigation methods used for erosion control and for preventing the slope from being vulnarable to slope mass movements (for example: shallow landslide, small size rock falls).

<table>
<tr><th colspan="2">Measure: shallow surface drainage (combination of drainage ribs and trenches)</th></tr>
<tr><td>Some examples of application:</td><td>
Figure 2. Stone drainage ribs have a dual function: (1) first as a drainage system on a slope and (2) then as a supporting structure. (Reference: Engineering geology Facebook).</td></tr>
<tr><td>Short summary</td><td>Surface drainage is principal measure in landslide remediation. Its main purpose is to collect and control direct surface water (Mihalić Arbanas & Arbanas, 2015).
Drainage increases the stability of the soil and reduces the weight of the sliding mass. Drainage can be either surface or subsurface. Surface drainage measures require minimal design and costs and have substantial stability benefits. They are recommended on any potential or existing slide (Highland and Bobrowsky, 2008). Surface drainage can be implemented as ditches, channels or pipes.</td></tr>
<tr><td>Case study example</td><td>Surface drainage rarely stands alone, it usually complements other engineering structural measures such as retaining walls, subsurface drainage, etc.
In Slovenia, surface drainage is also used as an emergency measure for slope instability due to rainfall. It is efficient and easy to implement. It can become problematic if surface drainage is not properly implemented and maintained or remains abandoned. In this case, this intervention in the slope can have an opposite effect and lead to additional water resorting in the sliding surface. Some examples of surface drainage are presented below:

Figure 3. Surface ditches implemented in the upper part of landslide Betel (Jesenice, Slovenia) (Archive GeoZS).</td></tr>
</table>

	 ***Figure 4**. Example of inappropriate implementation and maintenance of drainage system caused that surface water flows uncontrolled along the landslide and across the road (spring Urbas, landslide Urbas, Jesenice)..*
Feasibility	Surface drainage measures require minimal design and costs and have substantial stability benefits. They are recommended on any potential or existing slide. Although surface drainage is low-cost and simple to implement measures, it is crucial to implement with careful consideration, including preliminary investigations and design plans.
Cost-effectiveness	In comparison with other remediation measures implementation of surface drainage generally have the lowest cost and the highest efficacy measures (Mihalić Arbanas & Arbanas, 2015).
Maintenance	Maintenance of surface drainage systems is crucial to ensure they function and effectiveness. To perform proper maintenance, consider the following steps: Regular inspections, regular cleaning and unclogging, repairs, Maintenance is simple, inexpensive, and usually does not require sophisticated equipment.
Climate change	The implementation of surface drainage has no direct contribution to climate change. Due to climate change, an increase in the frequency and intensity of precipitation events is expected, and thus an increase in slope instabilities. Consequently, surface drainage will play an important role in landslide prevention and remediation.
Other hazards	Surface drainage measures generally have a positive effect on slope stability, especially erosion control and flooding.

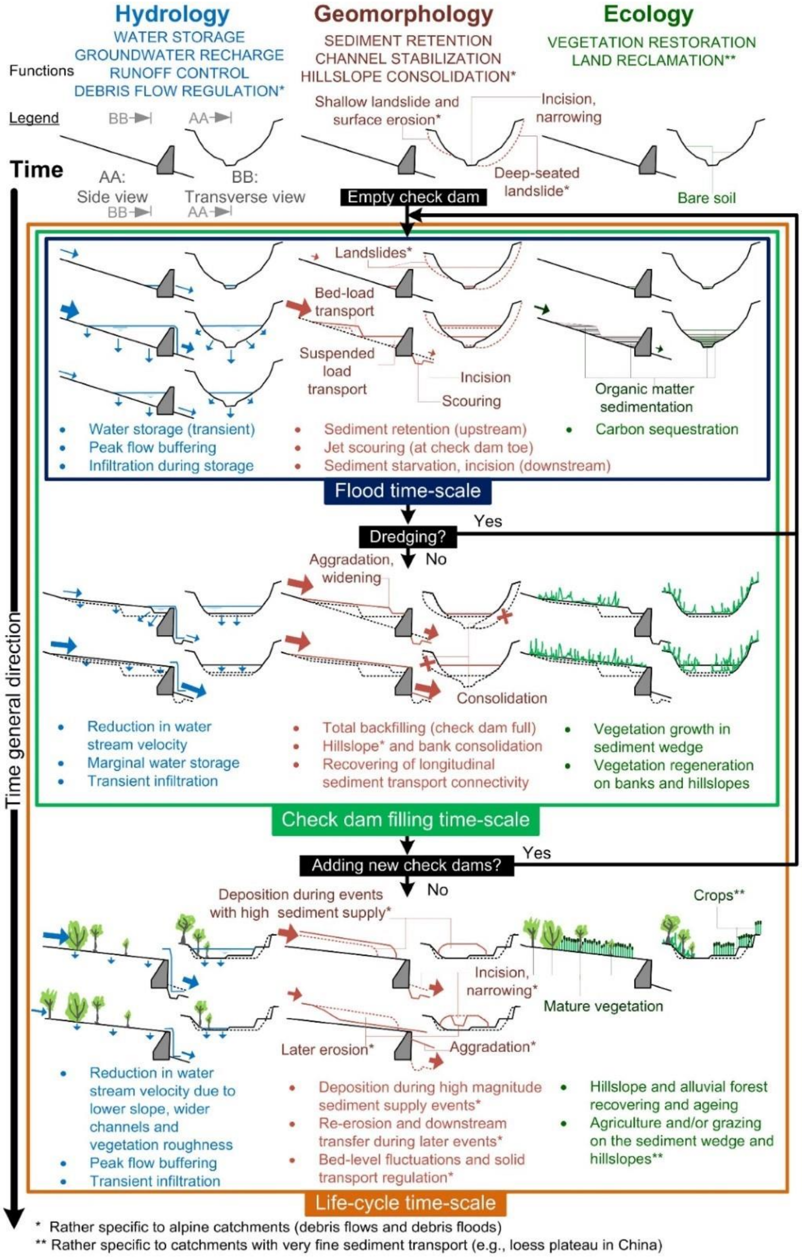
Landslides - gray measures

Measure: flexible net barriers	
Some examples of application:	 ***Figure 5****. Flexible net barrier in Lukenjski graben torrent in Slovenia (Jošt Sodnik).*
Short summary	Flexible barriers serve as effective protection against landslides, particularly against debris flow or rockfall. This type of mitigation measure has a large deformation, which makes it suitable to absorb dynamic impact loads (Volkwein et al., 2011). A typical flexible rockfall protection system consists of a steel net attached longitudinally to so-called support ropes (Volkwein et al., 2011). The advantages of flexible barriers are that they are relatively easy to install in steep, natural terrain, are visually less conspicuous and have less environmental impact compared to reinforced concrete barriers (Choi and Cheung, 2013)
Case study example	Whilst flexible barriers have been in use for over twenty years as a protective measure against boulder falls and rock falls, the application of flexible barriers for resisting the impact of natural terrain landslide debris is a relatively new concept Choi and Cheung (2013). Flexible steel net barriers are commonly used in mountainous regions to mitigate geological hazards such as rockfalls and debris flows (Wendeler et al. 2006). Choi and Cheung (2013) presents a set of mitigation measures that were applied in the Hong Kong.
Feasibility	It is important to select the appropriate mitigation measure based on the specific environmental conditions and water flow characteristics of the area of concern. Rigid check dams are well suited for areas where stable, long-term control is required, while flexible barriers are more adaptable to changing conditions and are preferable in areas with frequent events that require rapid response and maintenance. Flexible net barriers are very convenient for remote and hard to access areas.
Cost-effectiveness	According to Volkwein et al. (2015), flexible net barriers serve as a cost-effective mitigation measure. Compared to rigid mitigation measures (Hu et al., 2020; Su et al., 2021), flexible barriers are easy and economical to be installed, maintained and replaced, especially in mountainous regions. However, the cost-effectiveness of this mitigation measures depends on several factors, such as purpose (rockfall, debris flow, torrential flood, etc.), barrier design (capacity, energy load, etc.), location (mountains, urban area, hard-to-reach access areas, etc.), installation, maintenance, and local conditions (UV exposure, temperature fluctuations, etc.).
Maintenance	Flexible barriers are designed to withstand both dynamic and static impact loads. They require constant maintenance to ensure optimal performance, including regular cleaning to remove vegetation and minor events. After any significant impact event, it is essential to perform inspections and maintenance. It is important to note that flexible barriers can be deformed during an impact event (Vicari et al., 2021).

Climate change	The advantages of flexible barriers are that they are relatively easy to install on steep natural terrain, less visually obtrusive and have less environmental impact compared with reinforced concrete barriers (Choi and Cheung, 2013).
Other hazards	With flexible net barriers you can protect area from multiple slope mass movements processes such as rockfall, debris flow, torrential flood and/or their combination.

Measure: check dams	
Some examples of application:	 ***Figure 6***. *Check dams in sequences (Koroška Bela, Jesenice, Slovenia)*.
Short summary	Check dams are small dams for sediment storage constructed in the channels of steep gullies to stabilize the channel bed. They are commonly used to control the frequency and volume of channelized debris flows (Highland and Bobrowsky, 2008). Check dams are transverse engineering structures of varying size and height that are constructed of various materials such as concrete blocks, loose rocks, rocks in gabion baskets, or wood (Lucas-Barja et al., 2021). Check dams are the most important control measure because they reduce the flow velocity of water and limit erosion, trap sediments, stabilize the banks of ravines, and control landslides on hillslopes (Castillo et al., 2014, Mekonnen et al., 2015; Quiñonero-Rubio et al., 2016).
Case study example	A literature review showed that a lot of studies represent different study cases were check dams were implemented as a landslide structural mitigation measure. The latest: Baggio and d'Agostion, 2022 analyzed the erosion and deposition in a debris-flow event with check dam collapses in the Rotian channel (E Italian Alps). One of the latest studies of check dams was presented by Zhou et al., 2023. It shows the the assessment analysis of check dams and afforestation in mitigating debris flows based on study case located in Loagan Gully in China. In Slovenia check dam with 14,000 m3 retention volume was implemented Brezovški and Lukenjski graben torrents below the Krvavec ski area (Bezak et al., 2020).

<table>
<tr><td>Feasibility</td><td>Check dams are often built in a sequence of staircase to reduce bed erosion, sediment transport, flow velocity and bank destabilisation (Zeng et al., 2009). Even if check dams are designed with geomorphologic conditions in mind after analysing past events, they may not be representative of future events (Hübl et al., 2005).</td></tr>
<tr><td>Cost-effectiveness</td><td>Check dams serve a variety of purposes and are considered a cost-effective and long-term mitigation measure. Retaining dams serve a variety of purposes and are considered a cost-effective, long-term mitigation measure. In addition to landslide control, they are also used for torrent control, water supply enhancement, agricultural land development, and watershed restoration. The design of specific check dams and their cost-effectiveness vary depending on the environmental context.
The review of check dams effectivness is detailed represented in the Lucas Barja et al., 2023:



</td></tr>
</table>

Maintenance	They require extensive maintenance following high velocity flows. In particular, it is recommended that at a minimum, check dams be inspected weekly, prior to forecasted rain events, daily during extended rain events, and after the conclusion of rain events. Replace missing rock, bags, rolls, etc. Replace bags or rolls that have degraded or have become damaged (California Stormwater BMP Handbook Construction, 2009). However, if such structures are collapsed or partially damaged due to extreme events, poor maintenance, and/or their improper localization, the released torrent sediments from these structures can exacerbate the hydrological impact of the flood and sediment-related disasters in downstream areas, resulting in a catastrophic phenomenon similar to the failure of a landslide dam (Wang, 2013; Zhang et al., 2019; Motagh and Akhami, 2023).
Climate change	Changes in vegetation and an increase in extreme precipitation events are expected in the future, and with them the occurrence of slope mass movements associated with intense precipitation events. According to Luan et al. (2022), the check dams will play an important role in climate change adaptation. Zhou et al. (2023) also presented a combination of check dams and afforestation as the most important control measure.
Other hazards	Depending on the structure and shape of a check dam, its objectives and functions can differ (Zhou et al., 2023). Dams are known to be effective in protecting downstream regions from floods by regulating water discharge in the upstream section of the river. A less common use of check dams is to control runout and shallow landslides in the source area of debris flows(Highland and Bobrowsky, 2008).

Measure: deep drainage (Subsurface darinage)	
Some examples of application:	 ***Figure 7****. Drainage wells (landslide Slano Blato, Slovenia).*
Short summary	Drainage is a principal measure used in the remediation of landslides (Hutchinson, 1977). The purpose of deep drainage is to reduce seepage force by lowering pore pressures. Deep drainage could be made of: drainage wells (Pulko et al., 2012), horizontal drains (Cook et al, 2012), drainage tunnels (Yan et al., 2019), etc. Deep drainage is often combination of measures like drainage wells with horizontal drains (Cotecchia, 2020), or drainage wells and support cessions (Pulko et al., 2012). Most often drainage system work by gravity, but sometimes pumps are used to remove water from wells. Horizontal Drains: Horizontal drains are most commonly used deep drainage and are typically used when the excavation of drainage trench is challenging due to depth or stability concerns during the excavation. These drains consist of series of horizontal boreholes fitted with perforated (plastic) pipe, typically with diameter of 120 to 150 mm, in parallel of fan configuration. Typical installation angle is set at 2 to 5 ° above the horizontal plane to facilitate the gravitational flow of water. Installation of filer layer is problematic at best, so geosynthetic filters could be wrapped around drainage pipe. Drainage Wells and small diameter vertical drains: Deep wells are used for draining unstable slopes when the required depths make the construction of drainage trenches economically unfeasible. In certain cases, smaller drainage wells are positioned so closely that they overlap and create an interconnected drainage system resembling a drainage trench. A horizontal drain is drilled to connect drainage well and to remove water from the wells, or pumps are utilized to extract the water from them, when horizontal drain is not feasible. Drainage tunnels, galleries:

	Drainage tunnels are used when construction of drainage wells is economically not feasible. Often, they are used for remediation of large deep-seated landslides in highway and hydroelectric projects. Drainage tunnels are often combined with drainage boreholes (vertical or sub-horizontal).
Case study example	Thera are a lot of case studies for different deep drainage applications: Shrestha et al., 2008, studied ground flow in Nuta-Yone landslide in Japan and reasons for different effect of horizontal drains and to find potentially better locations for the future landslide remediation measures. Pulko et al., 2012 presented use of drainage wells for remediation of two Slovenian deep-seated landslide (Slano blato and Macesnik). Yan et al., 2019 presented the effectiveness of drainage tunnel for stabilisation of Donglingxing landslide near Sanbanxi Hydropower Station reservoir in China.
Feasibility	Deep drainage is only possible where ground investigation detects presence of water and design studies show significant reduction in failure potential. Well construction could be problematic in case of active landslides (Pulko et al., 2012). Drainage galleries are constructed in stable ground and vertical drains are drilled into landslide body. Both horizontal and vertical drains could be sheared in case of large landslide movements, and needed reconstruction.
Cost-effectiveness	Deep drainages are typically cost-effective measure only in case of large deep-seated landslides and thus used almost exclusively used in large projects like motorways and hydro-powerplants.
Maintenance	Using drainage as a long-term solution poses challenges, as it requires regular maintenance to ensure continued functionality (Bromhead, 1992). Often horizontal and vertical drains need to be redrilled due to clogging and/or damage due to landslide movements. Ground water monitoring is required to verify design and prove its functionality. Electric pumps need constant electrical supply and maintenance to work properly.
Climate change	Climate changes is expected to increase a frequency of “extreme” precipitation events. This, in turn, results in decrease in slope stability of natural slopes (Bernardie et al., 2021). Since deep drainage systems are often engineered to only reduce mass movements or to allow reactivation in “extreme” precipitation events, the increase of frequency of such events may reveal inadequacies in the current design.
Other hazards	De-watering could change water flow and dried wells for irrigation or drinking water supply, or it could change water conditions at the surface to the extent it no longer supports a unique plant community (Popescu and Sasahara, 2009). Outflow from drainage system could result in local erosion problem in case it is not properly designed. Ground water could be contaminated and could change surface waters.

Measure: modification of slope geometry	
Some examples of application	 ***Figure 8****. Slope reshaping at landslide Slano Blato (Slovenia). Smoother slopes at front are reshaped, rougher slopes at back are natural slopes after activation of landslide..*
Short summary	Reshaping of landslide body is second most used method for the remediation of landslides (Hutchinson, 1977). By changing slope geometry resistance forces could be increased or driving forces could be decreased. Both actions increase stability of slopes. Driving forces are decreased by reshaping or reducing slope grade. By loading toe of the landslide resistance forces are increased. Commonly loading is made of rock fill (buttress). Note: Some reshaping of slopes is made in case of other support features.
Case study example	Slano Blato landslide.
Feasibility	Reducing slope grade is possible in case hinterland of landslide is relatively flat. Large landfills for excavated material must be prepared. Reducing gradient of slopes for activated landslide during road construction could be problematic due to plot constrains. Rock buttresses are possible in case there is good quality ground at the toe of the landslide.
Cost-effectiveness	Cost effectiveness depend on landside geometry and needs to be compared to other alternative solutions (drainage, retaining walls, etc.).
Maintenance	Initially correction of slope in case erosion happened. Later mowing the grass, cutting shrubs, etc. In some cases, observation of landslide movements in necessary.
Climate change	Climate changes is expected to increase a frequency of “extreme” precipitation events. This, in turn, results in decrease in slope stability of natural slopes (Bernardie et al., 2021). Similarly slope stability of remediated slopes should be decreased as well.
Other hazards	In case of soft rock weathering could reduce rock strength and cause reactivation of landslide. Newly constructed slopes are prone to erosion.

Measure: retaining structures	
Some examples of application:	 ***Figure 9***. *Anchored pile wall on highway Razdrto-Vipava (landslide Rebernice, Slovenia) (photo B. Pulko).*
Short summary	Retaining structures increases resisting forces at the toe of the landslide. There are many options like: gravity retaining walls (masonry, crib-block walls*, gabion walls*, reinforced concrete walls), cantilever or anchored piles walls, soldier walls, caissons or sheet pile walls, etc. Gravity walls support the soil trough weight of structure and with structure stiffness and strength transfer loads from ground behind the structure (O'Rourke and Jones, 1990). They are often inclined into ground to reduce ground action forces and overturning moments. Cantilever walls uses soil weight to reduce overturning moments. Pile or similar walls support ground trough transfer of forces into deeper layers of ground. Piles need themselves to resist bending moments due to ground action. In anchored pile walls some of the soil action is transferred via anchors to the stable ground to reduce bending moments in structures. * described in separate chapters
Case study example	Landslide Rebernice on highway Razdrto-Vipava is Slovenia was stabilized by series of pile wall (Pulko et al., 2005).
Feasibility	Retaining structures are relatively well understood and easy to implement structures. These structures are relatively rigid and cannot accommodate significant landslide movements. Crib-block walls and gabion walls, on the other hand, are more flexible and can withstand more deformations. Anchors need to be constantly monitored to ensure proper function. In case anchor forces are higher than designed, additional anchors need to be installed.
Cost-effectiveness	Cost effectiveness depend on structure size. Gravity walls are most cost effective, but could be constructed to only small hights. Cost of cantilever walls could be problematic due to relatively big excavations and support needed during excavations. Pile walls are most expensive but allows remediation of deep-seated landslides. Soil reinforcement is usually more cost effective then gravity walls (Sahu et al., 2021).
Maintenance	Properly designed retaining structures require minimal maintenance. Some repair work may be necessary due to material degradation, particularly in the

	case of concrete. Weeds, frost, and salts are the primary factors contributing to material degradation. Retaining structures can be built with drainage systems, which must be regularly maintained to ensure their proper functioning. Larger or more critical retaining structures need to undergo monitoring to detect any deformations. In case of anchored pile walls anchor forces needs to be measured and anchor heads needs to be checked regularly for any damage. Damaged anchors need to be replaced.
Climate change	Climate changes is expected to increase a frequency of “extreme” precipitation events. This, in turn, results in decrease in slope stability of natural slopes (Bernardie et al., 2021). Similarly slope stability of remediated slopes should be decreased as well.
Other hazards	Not relevant.

Measure: modifying the mechanical characteristics of ground	
Some examples of application:	 ***Figure 10**. Anchored reinforced concrete frame on highway Razdrto-Vipava (landslide Rebernice, Slovenia) (photo B. Pulko).*
Short summary	Soil reinforcement could be used to increase internal strength of back fill. With geostrip or geogrid geosynthetics a shear forces are transferred to stable soil body. They are manly used to restore the slopes after landslide had occurred. Soil nailing or prestressed anchored reinforced concrete beams are used to in-situ stabilise landslide. A vertical wall could be made using gabions or concrete facing. Soil nailing increases shear resistance of soil/soft rock by installing number of steel bars. Stability of surface is maintained by shotcrete reinforced by steel mash. They are mainly used in temporally excavations as the steel soil nails are not corrosive resistant or areas with potential instabilities. Ground anchors are similar to soil nails, but are prestressed. Instead of steel bars steel wires are used. Commonly there is a “free” section where there is no friction contact with surrounding soil/rock and “bounded” section which is grouted to create good contact with surrounding soil/rock. Commonly concrete frame is used to transfer anchor forces into the soil.
Case study example	Turner and Jensen (2005) give description of soil nailing used to stabilise active landslide on highway in Wyoming USA. Nguyen et al. (2020) give description of ground anchors used to stabilize deep-seated Thong Nhat landslide in Vietnam. Rimoldi et al. (2021) gives example of soil reinforcement used for slope restoration after landslide activation in Asia.
Feasibility	Soil nails and ground anchors are relatively rigid and cannot accommodate significant landslide movements. Recent developments go in specialised design to accommodate larger ground movements (Brezzi et al., 2021). Permanent anchored systems are generally considered to have a service life of 75 to 100 years. They need to be constantly monitored to ensure proper function. In case anchor forces are higher than designed, additional anchors need to be installed. Damage to anchor head might cause corrosion problems. Soil nails have potential corrosion problem.
Cost-effectiveness	Soil reinforcement proved to be more effective in terms of construction time and cost compared to other solutions (Rimoldi et al., 2021). Ground anchors are reliable, but costly measure to stabilise landslides. compared with other countermeasures. Compared with soil nails, ground

	anchors provide larger resistance to sliding and are mainly used for larger landslides.
Maintenance	In case of prestressed ground anchors, forces need to be measured and anchor heads needs to be checked regularly for any damage. Damaged anchors need to be replaced.
Climate change	Climate changes is expected to increase a frequency of “extreme” precipitation events. This, in turn, results in decrease in slope stability of natural slopes (Bernardie et al., 2021). Similarly slope stability of remediated slopes should be decreased as well.
Other hazards	Not relevant.

References

Ahn, T.B., et al. (2002). Stabilization of soil slope using geosynthetic mulching mat. Geotextiles and Geomembranes, https://doi.org/10.1016/S0266-1144(02)00002-X.

Baggio, T., D'Agostino, V. (2022). Simulating the effect of check dam collapse in a debris-flow channel. Science of The Total Environment, 816, 151660. https://doi.org/10.1016/j.scitotenv.2021.151660.

Bezak, N., Jež, J., Sodnik, J., Jemec Auflič, M., Mikoš, M. (2020). An extreme May 2018 debris flood case study in northern Slovenia: analysis, modelling, and mitigation. Landslides, 17, 2373-2383. https://doi.org/10.1007/s10346-019-01325-1.

Bouroullec, I. (2021). Modelling landslide hazards under global changes: the case of a Pyrenean valley, Natural Hazards Earth Systems Science, 21, 147–169.

Brezzi, L., Bisson, A., Pasa, D., & Cola, S. (2021). Innovative passive reinforcements for the gradual stabilization of a landslide according with the observational method. Landslides 18:2143-2158.

Bromhead, E.N. (1992). The stability of slopes. Blackie Academic and Professional, London: 217.

Castillo, V. M., Mosch, W. M., García, C. C., Barberá, G. G., Cano, J. N., López-Bermúdez, F. (2007). Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). Catena, 70(3), 416-427. https://doi.org/10.1016/j.catena.2006.11.009.

Carlyle-Moses, D.E., Gash, J.H.C. (2011) Rainfall interception loss by forest canopies, chapter Forest Hydrology and Biogeochemistry, Ecological Studies, 216, Springer, pp. 407-423.

Chen, Y.C., et al. (2014). Mechanisms of Forest Restoration in Landslide Treatment Areas. Sustainability. https://doi.org/10.3390/su6106766.

Choi, K. Y., Cheung, R. W. (2013). Landslide disaster prevention and mitigation through works in Hong Kong. Journal of Rock Mechanics and Geotechnical Engineering, 5(5), 354-365. https://doi.org/10.1016/j.jrmge.2013.07.007.

Colleran, B., et al. (2020). Invasive Japanese knotweed (Reynoutria japonica Houtt.) and related knotweeds as catalysts for streambank erosion. River Research and Applications. https://doi.org/10.1002/rra.3725.

Cook, D., Santi, P., Higgins, J. (2012). Prediction of piezometric surfaces and drain spacing for horizontal drain design. Landslides 9:547-556.

Cotecchia, F., Petti, R., Milella, D., Lollino, P. (2020). Design of Medium Depth Drainage Trench Systems for the Mitigation of Deep Landsliding. Geosciences 10: 1-24.

Damians, I.P., et al. (2022). Sustainability of Geosynthetics-Based Landslide Stabilization Solutions. Progress in Landslide Research and Technology, Volume 1 Issue 1, https://doi.org/10.1007/978-3-031-16898-7_14.

Emeka, O.J., et al. (2021). Evaluation of the Effect of Hydroseeded Vegetation for Slope Reinforcement. Land, https://doi.org/10.3390/land10100995.

Fang, K. et al. (2023). Centrifuge modelling of landslides and landslide hazard mitigation: A review. Geoscience Frontiers, https://doi.org/10.1016/j.gsf.2022.101493.

Galve, J.P., et al. (2015). Assessment of shallow landslide risk mitigation measures based on land use planning through probabilistic modelling. Landslides, https://doi.org/10.1007/s10346-014-0478-9.

Highland, L. M., Bobrowsky, P. (2008). The Landslide Handbook—A Guide to Understanding Landslides. Reston, Virginia, CO: U.S. Geological Survey (USGS) National Landslide Information Center (NLIC). https://doi.org/10.3133/cir1325.

Hu, H., Zhou, G. G., Song, D., Cui, K. F. E., Huang, Y., Choi, C. E., Chen, H. (2020). Effect of slit size on the impact load against debris-flow mitigation dams. Engineering Geology, 274, 105764. https://doi.org/10.1016/j.enggeo.2020.105764.

Hutchinson, N. (1977). Assessment of the effectiveness of corrective measures in relation to geological conditions and types of slope movement. Bulletin of the International Association of Engineering Geology 16: 131–155.

Hübl, J., Holub, M., Suda, J. (2005, November). Structural mitigation measures. In 3rd Probabilistic Workshop: Technical Systems+ Natural Hazards, edited by: Bergmeister, K., Rickenmann, D., Strauss, A., Wieshofer, S., Curbach, M., and Proske, D., Universität für Bodenkultur, Department für Bautechnik und Naturgefahren (pp. 115-126).

Lucas-Borja, M. E., Piton, G., Yu, Y., Castillo, C., Zema, D. A. (2021). Check dams worldwide: Objectives, functions, effectiveness and undesired effects. Catena, 204, 105390. https://doi.org/10.1016/j.catena.2021.105390.

Margiorou, S., et al. (2022). Pre/Post-Fire Soil Erosion and Evaluation of Check-Dams Effectiveness in Mediterranean Suburban Catchments Based on Field Measurements and Modeling. Land, https://doi.org/10.3390/land11101705.

Mekonnen, M., Keesstra, S. D., Stroosnijder, L., Baartman, J. E., Maroulis, J. (2015). Soil conservation through sediment trapping: a review. Land degradation & development, 26(6), 544-556. https://doi.org/10.1002/ldr.2308.

Mihalić Arbanas, S., et al. (2015). Landslides: A Guide to Researching Landslide Phenomena and Processes. Handbook of Research on Advancements in Environmental Engineering, 10.4018/978-1-4666-7336-6.

Montoro, J. A., et al. (2000). Three hydro-seeding revegetation techniques for soil erosion control on anthropic steep slopes. Land Degredation & Development, https://doi.org/10.1002/1099-145X(200007/08)11:4<315::AID-LDR394>3.0.CO;2-4.

Motagh, M., Akhani, H. (2023). The cascading failure of check dam systems during the 28 July 2022 Emamzadeh Davood flood in Iran. Natural Hazards, 116(3), 4051-4057. https://doi.org/10.1007/s11069-023-05814-4.

Nguyen, L.C., Tien, P.V., Do, TN. (2020). Deep-seated rainfall-induced landslides on a new expressway: a case study in Vietnam. Landslides 17: 395–407.

Papathoma-Köhle, M., Glade, T. (2013) The role of vegetation cover change for landslide hazard and risk. In: Renaud FG, Sudmeier-Rieux K, Estrella M (eds) The role of ecosystems in disaster risk reduction. UNU-Press, Tokyo, pp 293–320

Popescu, M. E., Sasahara. K. (2009). Engineering Measures for Landslide Disaster Mitigation. In. Landslides Disaster Risk Reduction: 609-631.

Pulko, B., Majes, B., Mikoš, M. (2014). Reinforced concrete shafts for the structural mitigation of large deep-seated landslides: an experience from the Macesnik and the Slano blato landslides (Slovenia). Landslides 11: 81–91.

Pulko, B., Popović, Z., Majes, B. (2005). Stability analysis and rehabilitation measures of landslide Rebernice. In: Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering: 2563-2566.

Quiñonero-Rubio, J. M., Nadeu, E., Boix-Fayos, C., de Vente, J. (2016). Evaluation of the effectiveness of forest restoration and check-dams to reduce catchment sediment yield. Land Degradation & Development, 27(4), 1018-1031. https://doi.org/10.1002/ldr.2331.

Richet, J.B., et al., (2017). The role of vegetative barriers such as fascines and dense shrub hedges in catchment management to reduce runoff and erosion effects: Experimental evidence of efficiency, and conditions of use. Ecological Engineering. https://doi.org/10.1016/j.ecoleng.2016.08.008.

Rimoldi, P., Lelli, M., Pezzano, P., Trovato, F. (2021). Geosynthetic Reinforced Soil Structures for Slope Stabilization and Landslide Rehabilitation in Asia. In: Understanding and Reducing Landslide Disaster Risk. WLF 2020. ICL Contribution to Landslide Disaster Risk Reduction. Springer, Cham. 397-404.

Schiwndt, S., et al. (2018). Sediment traps with guiding channel and hybrid check dams improve controlled sediment retention. Natural Hazards and Earth System Sciences, https://doi.org/10.5194/nhess-18-647-2018.

Sahu, S.R., Shrotriya, D., Kumar, B. (2021) Study of Cost Effectiveness of Reinforced Earth Wall Over Conventional Retaining Wall Considering Different Heights. International Journal of Trend in Scientific Research and Development 5(6): 1166-1169.

Shrestha, H.K., Yatabe, R., Bhandary, N.P. (2008). Groundwater flow modeling for effective implementation of landslide stability enhancement measures. Landslides 5: 281–290.

Shu, H., et al. (2019). Relation between land cover and landslide susceptibility in Val d'Aran, Pyrenees (Spain): Historical aspects, present situation and forward prediction. Science of The Total Environment, https://doi.org/10.1016/j.scitotenv.2019.07.363.

Su, L. J., Xu, X. Q., Geng, X. Y., Liang, S. Q. (2017). An integrated geophysical approach for investigating hydro-geological characteristics of a debris landslide in the Wenchuan earthquake area. Engineering Geology, 219, 52-63. https://doi.org/10.1016/j.enggeo.2016.11.020.

Stokes, A., et al. (2014). Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners. Plan and Soil. https://doi.org/10.1007/s11104-014-2044-6.

Tadsuwan, K. (2017). THE STUDY OF THE EFFECTS OF VEGETATION ON SLOPE STABILIZATION FOR LANDSLIDE PREVENTION IN THAILAND. PhD thesis, available at: http://ethesisarchive.library.tu.ac.th/thesis/2017/TU_2017_5922040455_8719_7216.pdf.

Tasser, E., et al. (2003). Effects of land use in alpine grasslands on the probability of landslides. Basic and Applied Ecology. https://doi.org/10.1078/1439-1791-00153.

Turner, J. P., Wayne, G. J. (2005). Landslide Stabilization Using Soil Nail and Mechanically Stabilized Earth Walls: Case Study. Journal of Geotechnical and Geoenvironmental EngineeringArchive 131(2): 141-150.

Vergari, C. et al. (2017). Root reinforcement dynamics of European coppice woodlands and their effect on shallow landslides: A review. Earth-Science Reviews. https://doi.org/10.1016/j.earscirev.2017.02.002.

Vicari, H., Ng, C. W., Nordal, S., Thakur, V., De Silva, W. R. K., Liu, H., Choi, C. E. (2022). The effects of upstream flexible barrier on the debris flow entrainment and impact dynamics on a terminal barrier. Canadian Geotechnical Journal, 59(6), 1007-1019. https://doi.org/10.1139/cgj-2021-0119.

Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., et al. (2011). Rockfall characterisation and structural protection–a review. Natural Hazards and Earth System Sciences, 11(9), 2617-2651.

Volkwein, A., Wendeler, C., Stieglitz, L., Lauber, G. (2015). New approach for flexible debris flow barriers. In IABSE symposium report (Vol. 105, No. 48, pp. 1-7). International Association for Bridge and Structural Engineering.

UNISDR. (2013). Forests and Landslides: The role of trees and forests in the prevention of landslides and rehabilitation of landslide-affected areas in Asia. Available at: https://www.unisdr.org/preventionweb/files/53056_i3245e.pdf.

Xiao, H., et al. (2017). Experimental study on the soil mixture to promote vegetation for slope protection and landslide prevention. Landslides, https://doi.org/10.1007/s10346-015-0634-x.

Wen, Y., et al. (2021). Experimental Study on Landslides in Terraced Fields in the Chinese Loessial Region under Extreme Rainfall. Water, https://doi.org/10.3390/w13030270.

Wang, G. L. (2013). Lessons learned from protective measures associated with the 2010 Zhouqu debris flow disaster in China. Natural Hazards, 69, 1835-1847. https://doi.org/10.1007/s11069-013-0772-1.

Wendeler, C., Volkwein, A., McArdell, B. W., & Bartelt, P. (2019). Load model for designing flexible steel barriers for debris flow mitigation. Canadian Geotechnical Journal, 56(6), 893-910. https://doi.org/10.1139/cgj-2016-0157.

Yan, L., Xu, W., Wang, H., Wang., R., Meng, Q., Yu, J., Xie, W.-C. (2019). Drainage controls on the Donglingxing landslide (China) induced by rainfall and fluctuation in reservoir water levels. Landslides 16: 1583–1593.

Zeng, Q. L., Yue, Z. Q., Yang, Z. F., & Zhang, X. J. (2009). A case study of long-term field performance of check-dams in mitigation of soil erosion in Jiangjia stream, China. Environmental Geology, 58, 897-911. https://doi.org/10.1007/s00254-008-1570-z.

Zhang, F., Yan, B., Feng, X., Lan, H., Kang, C., Lin, X., et al. (2019). A rapid loess mudflow triggered by the check dam failure in a bulldoze mountain area, Lanzhou, China. Landslides, 16, 1981-1992. https://doi.org/10.1007/s10346-019-01219-2.

Zhou, G., Lyu, L., Xu, M., Ma, C., Wang, Y., Wang, Y., et al. (2023). Assessment of check dams and afforestation in mitigating debris flows based on dendrogeomorphic reconstructions, field surveys and semi-empirical models. Catena, 232, 107434. https://doi.org/10.1016/j.catena.2023.107434.