LITERATURE REVIEW OF GREY, GREEN AND HYBRID MEASURES FOR SOIL EROSION MITIGATION

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

Therefore, in terms of grey measures, traditional and conventional soil erosion mitigation infrastructure was chosen. Compared to other soil erosion 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, such measures typically provide limited or almost no ecosystem services. Green measures, on the other hand, tend to have prevailing ecosystem functions compared to other soil erosion risk reduction categories and consist primarily of degradable materials. Even though certain technical equipment is usually needed during the implementation stage to build green soil erosion protection measures, subsequently after the set-up procedure these measures tend to have only “green” visual effect. With regard to hybrid measures, soil erosion 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.

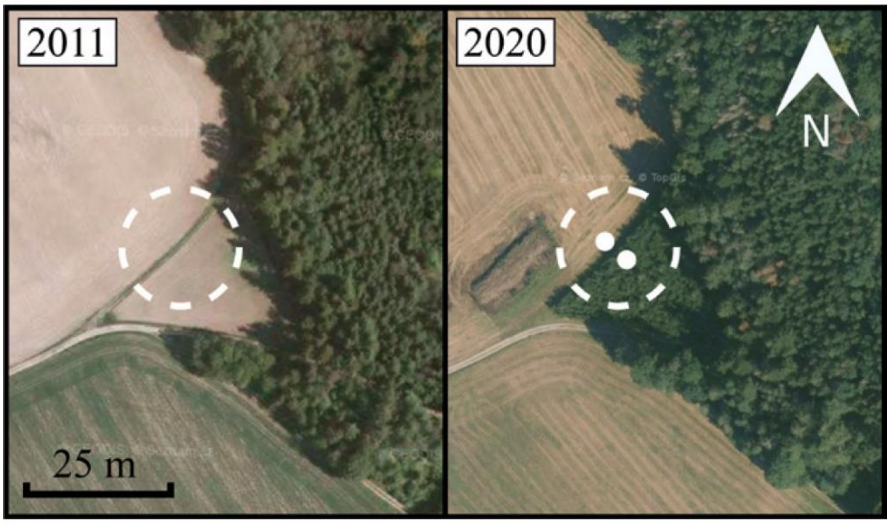
Table 1. *Selected measures for grey, green and hybrid soil erosion mitigation measures.*

Category	**Selected measures**
Grey	check dams, terraces, anti-erosive ditches, small dams, timber crib wall (Kranjska stena), riprap
Green	afforestation, grassing arable land, buffer (vegetated) strips – two types: with and without trees, contour farming, riparian buffer zones
Hybrid	geotextiles, geogrids/geocells, woody dams, water retention polders

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	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.

Soil erosion - green measures

Measure: afforestation	
Real case example where the measure was applied: Czech Republic (Klíč et al., 2023)	 ***Figure 1.*** *Afforestation of arable land in the Czech Republic (Klíč et al., 2023).*
Short summary	Afforestation is a process of converting agricultural lands, marginal lands, or other types of land cover to forests. It is a “management practice that falls into the category of land use change (LUC), as it is a change to a land use type that is less prone to soil erosion and guarantees many positive effects, including improving water quality, new wildlife habitat and wood production” (Ricci, 2020: 3). As a result of the expansion of tree cover in the regions where previously there were no trees, carbon concentration in the air and flood peak discharge can be reduced (Arora and Montenegro, 2011; Johnen et al., 2020). Afforestation is a particularly important and effective anti-erosion measure. However, as this measure cannot be applied to all arable land, it should be supplemented by agrotechnical measures - mulching, stubble sowing, no-till farming, etc., or by grassing. Afforestation is used on soils unsuitable for agricultural production, especially on soils with slopes greater than 17°, or on shallow soils (VÚMOP, 2019).
Feasibility	To implement this measure, first, it is required to find and prepare land where afforestation is going to take place. Following that, necessary tree species are selected and suitable fertilizers depending on the selected vegetation type are picked up. When the trees are planted, they should be maintained during the first years (Climate-ADAPT, 2020). Subsidies are available for afforestation arable land in the Czech Republic (SZIF, 2023): - subsidies for the establishment of forest cover - subsidies for the maintenance of forestry plantations - subsidies to compensate for the cessation of agricultural production
Cost-effectiveness	According to VÚMOP (2019), when evaluating the effectiveness of anti-erosion measures in relation to soil protection, protective grassing or afforestation is certainly the most effective. Furthermore, such areas do not suffer from undesirable erosion shear. Ricci et al. (2020) made an analysis of the farmer return-production cost ratios (FR/PC) for several anti-erosion measures. In steep slope areas (slope > 20 %), afforestation was ranked as the top measure (FR/PC

	= 1.49), assuming that first wood could be cut and sold after 12 years. Johnen et al. (2020) analyzed the effectiveness of the investigated measure on different ecosystem services based on the three different afforestation scenarios. They revealed a positive effect of afforestation on biodiversity, water quality, and carbon concentration. With respect to costs, the same study found that for 1 ha (10,000 m^2) of land around 3,500 trees are needed. Since each tree needs around 1 euro to be planted, the total cost of planting 3,500 trees on 1 ha would be around 3,500 euros. The average price of the cropland that can be used for afforestation, in turn, was found to be around 60,000 euros per ha (Johnen et al., 2020). Sulewski (2018) estimated the cost of afforestation (excluding cost for purchasing land) in Poland on 1,461 EUR/ha (1PLN=0.22 EUR) in 2018, Phillips (2006) on 2,470-4,616 EUR/ha for Ireland.
Flexibility	By reducing soil moisture content, trees help to decrease the likelihood of landslides. Tree roots act as a barrier against soil displacement, strengthening soil layers and attaching the soil to bedrock. In addition, forests can also prevent the fall of rocks and debris, shorten the run-out distance of landslides, and decrease the risks of soil erosion (RECOFTC, 2012). However, Forbes and Broadhead (2013) state that this is only true for shallow landslides. Other benefits of afforestation are strengthening the biodiversity of the landscape areas and improving the ecological balance of the landscape. Stabilization of hydrological and climatic conditions in the landscape, soil protection and water protection. Afforestation also plays a crucial role in flood risk mitigation (see e.g., Johnen et al., 2020 or Bezak et al., 2021).
Maintenance	According to the Climate-ADAPT (2020), during the first year after afforestation the average maintenance cost of tree cover is around 300 euros per ha (10,000 m^2), whereas during the third year the costs can go down to 100 euros per ha. In general, the maintenance process should be carried out during the first 3-5 years. Sulewski (2018) estimated maintenance cost on ca 170 EUR/ha/year (in Poland), according to Kuhlman (2010), average maintenance costs for afforestation are 296 EUR/ha/year.
Climate change	Forests absorb atmospheric CO_2 and thus contribute to climate change mitigation. This is a long-term measure that meets the objectives over the lifetime of the forest cover, i.e., about 60 years. According to the United Nations, afforestation can be considered as one of the most effective measures in relation to climate change mitigation (Arora and Montenegro, 2011). Trees are known to absorb carbon dioxide, which helps to combat the problem of climate change. For example, 0.8 tons of CO_2 per ha (10,000 m^2) of green cover per year can be processed by urban greenery (CNT, 2020b). "Afforestation leads to C accumulation in living biomass, coarse woody debris, and soil organic carbon" Anderson et al., 2010: 175). 1 m2 of temperate forest can store 28.1 kg of C, compared to 1.1 kg/m2 and 12.3 kg/ m2 of C in cropland and temperate grassland (Anderson et al, 2010). However, at the same time, according to Bonan (1997), forests tend to have a lower albedo coefficient, which, in turn, is proportional to the amount of solar radiation being reflected. This implies that croplands are more reflective than trees and, therefore, with the increase in the forest cover over a specific land, the amount of solar radiation absorbed by the trees is also increasing leading to the net climate warming in the regions with higher elevations (Arora and Montenegro, 2011).
Case study example	Afforestation of arable land near the village Chlístov in the Czech Republic (Klíš et al., 2023). Afforestation of arable land near the village Chlístov was realized in 2012. Species composition is 100 % beech. In the same research also two

	other afforested arable land were investigated. First afforested in 1998 with spruce (80 %), larch (10 %), cherry (5 %), pine (3 %) and fir (2 %) and second afforested in 1955 by spruce (99 %) and larch (1 %). The measurement results indicate much better soil properties for the forested soils, as the largest soil fractions (>2 mm and 2-1 mm) remain consistently represented in the sample in the range of 34.18-69.14% and the soil can be assumed to have good infiltration and retention capacity. Better results were investigated in older forests.

Measure: Grassing arable land	
Case study example	https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.interreg-danube.eu%2Fmedia%2Fdownload%2F29123&psig=AOvVaw1V0xKxH9KiSa4UfYsqFd1r&ust=1694716032321000&source=images&cd=vfe&opi=89978449&ved=2ahUKEwiHz4qqm6iBAxUHi_0HHSqTCKEQr4kDegQIARBR  ***Figure 2.*** *Example of grassing arable land, adopopted after::* https://www.researchgate.net/publication/279230806_Long-term_Land_Use_and_Land_Cover_Changes_Affected_by_the_Conservation_Reserve_Program_in_the_Minnesota_River_Valley#fullTextFileContent
Short summary	Conversion of arable land to grassland (pasture) is a measure suitable to control serious erosion, where the soil loss exceeds 10 t ha^{-1} yr^{-1}. According to Franz et al. (2018), vegetation is the most common natural element used to control erosion; it protects the soil and absorbs water. It also prevents wind erosion. Grassland also increases surface roughness and slows surface runoff rates (MZE 2017).
Case study example	Case study – experimental study of soil erosion in bare soil and grassland (Apollonio et al. 2021): The soil erosion reduction results are clear and promising - a consistent decrease of the eroded material (up to 300 times) was observed compared to the investigated vegetation cover (for 70 cm height) with respect to the bare soil condition. According to the experiment results, a vegetation height of 70 already represents a configuration of maximum efficiency for the reduction of the kinetic energy of rain.
Feasibility	The implementation is easy; it consists of sowing grass seed instead of the previous crop. In some cases, the change in land use may also require adaptations in machinery and buildings at the farm level because of changes in the agricultural enterprise (Posthumus et al. 2013).

Cost-effectiveness	The vegetation can reduce the soil erosion rate by 90% (Franz et al., 2018). A series of laboratory flume simulation experiments have shown that vegetation could reduce the mean velocity by 31–65% (Pan & Shangguan, 2006). Researchers also found that the average runoff and sediment reductions were 51.02% and 32.22% for soil with vegetation respectively (Bai et al., 2019). Another research conducted by Frielinghaus (2002) states that: if soil without green plant cover has 100% soil loss, 20-30% of plant cover reduces the soil loss to 25%, while 30-50% of green cover reduces it to 8% and more than 70% (which is the case of grassland) to less than 2%. The costs of grassing arable land are calculated as a loss of agricultural production. Kuhlman et al. (2010) calculated the costs of changing arable land to grassland to be 155 euro per ha. A study by Nix (2009) shows that the annual loss in gross margin caused by changed land use to grassland was 281, 607, and 369 pounds per ha in case of change from winter wheat, potato, and sugar beet respectively. The cost of grass seeds was £50 per ha (Cuttle et al., 2006). The total overall cost of covering 5% of arable land by grassland was calculated by Posthumus et al. (2013) to be £253. The benefit-cost ratio for the 5-year period was calculated by Posthumus et al. (2013) to be between 0.35 and 0.75. The cost of maintenance for hay production is ca. 113 Euro/ha and the profit can be between 208 Euro (in case of low production) to ca 860 Euro per ha.
Maintenance	According to Czech agronomic norms, the costs of managing and harvesting 1ha of grassland include spring dragging 15 Euro/ha, mowing 28 Euro/ha, raking 17 Euro/ha, collection and baling of hay 53 Euro/ha which together makes 113 Euro/ha (www.agronormativy.cz). In England (in 2009) the annual costs (assuming one cut per year) were ca £25 per ha (Nix, 2009).
Climate change	Grasslands are considered to have the potential to play a key role in greenhouse gas mitigation. They are a particularly important store of carbon, and they are continuing to sequester carbon with considerable potential to increase this further. However, grassland agriculture also contributes to GHG emissions, particularly methane and nitrous oxide, and the management of grassland affects net carbon balances and carbon sequestration (Hopkins and Del Prado 2007). Climate change also poses a risk to grasslands; in Europe, some climate scenarios project their decrease (Gibson & Newman 2019). Grassland adaptation to climate change will be variable, with increases or decreases in productivity and increases or decreases in soil carbon stores (O'Mara 2012). Projected scenarios indicate that increased temperatures and CO_2 concentrations have the potential to increase herbage growth and favor legumes more than grasses, but changes in seasonal precipitation would reduce these benefits, particularly in areas with low summer rainfall. Further implications for grasslands

	may arise from the increased frequency of droughts, storms, and other extreme events (Hopkins and Del Prado 2007).
Other hazards	Next to reducing water and wind erosion, grasslands increase surface roughness and slow surface runoff rates and thus reduce the risks of floods. Grasslands can also play the role of sedimentation and trapping belts located directly on land blocks or their parts (Novotný et al. 2017).

Measure: Buffer (vegetated) strips – two types: with and without trees	
Case study	 ***Figure 3.*** *Example of buffer vegetated strips, adopted after:* http://nwrm.eu/measure/buffer-strips-and-hedges https://extension.missouri.edu/publications/g1653 https://se.copernicus.org/articles/8/217/2017/se-8-217-2017.pdf
Short summary	Strips of (mostly) perennial vegetation (their width varies between 1 and 25 m, Van Dijk et al. 1996)) are set out along contour lines and divide the area of arable land. They are used to increase infiltration, slow down runoff and increase sediment deposition (Uusi-Kämppä, 2005), filtration of sediment and the removal of nutrients from the runoff (Van Dijk et al. 1996). The strip vegetation can be herbal (grass, bio-stripes with herbs) or in a form of hedgerows/shelterbelts, planted with wood and bushes species. Grass strips (GS) consist of bands of either planted or indigenous vegetation situated downslope of cropland or animal production facilities to reduce the export of nutrients, sediment, and other pollutants from agricultural areas. Strips can also be part of the crop rotation cycle (Van Dijk et al. 1996), as strip of crop less endangered by erosion (VÚV TGM, 2018). Grass protects the surface against drag by the water flow and rain splash, thus strongly reducing the entrainment of particles. The hydraulic conditions favour the deposition of soil particles transported with runoff coming from upslope fields (Van Dijk et al. 1996).
Case study example	Grassed strips were implemented in agricultural land in Hustopeče in Czech Republic. After implementation, the value LS of RUSLE was decreased (see Karasek et al. 2022).
Feasibility	It can be quickly implemented (within 1-3 years). This measure implies increased costs of cultivation with a link to the acquisition of selected types of agricultural machinery. As part of this type of measure, there is a constant increase in economic costs for land users (VÚV TGM, 2018). The effect is achieved quickly in the case of grassed and herbal strips, in the case of woody vegetation it can be longer.
Cost-effectiveness	The investment costs of (grassed) buffer stripes were estimated by Posthumus et al. (2015) to be 32 pounds/ha for stripes 6m wide.

	Kuhlman et al. (2010) estimates costs of in-field buffers to be 125 Euro/ha/year. They can be remarkably effective in reducing erosion (Van Dijck et al. 1996) and in run-off filtration (Bissonnais et al. 2004). The effect of filtration of sediment from the run-off by grass strips is influenced by several factors: width of the grass strip; the sediment concentration in runoff entering the strip; the flow velocity of the runoff (also depending on slope angle); grass density and height; and the degree of submergence of the grass (Van Dijk et al. 1996). The effectiveness in reducing soil loss was high in most studies, soil loss from the field was reduced by 76% and 98% downstream of the 6-m grass strip and by 81% downstream of 3-m grass strip (Bissonnais et al. 2004). A similar effect was evidenced by Maetens et al. (2012) who (based on plot experiments) found the effectiveness of buffer stripes to be 80% (namely the ratio of the field with this measure and the field without this measure was calculated as 0.2). Van Dijk et al. (1996) measured reduction of sediment discharge between 60-90% for strips 4-5 m and 90-99% for strips of 10m. The lower soil loss reduction of shelterbelts or hedgerows was estimated by Collins et al. (2009), only between 5 – 20% and of in-field buffer stripes between 5 – 50% and Posthumus et al. (2015) estimated soil loss reduction of shelterbelts to be only 10% and of in-field buffer stripes to be 25%. The cost-benefit ratio in the 5-year period was estimated to be between 0.84 to 3.75 (in-field buffer stripes) and 0.02 to 0.25 (shelterbelts) (Posthumus et al., 2015). The latter is so low due to the longer time of tree establishment which makes the measure less effective in the first years. This measure can be recommended for slopes that are not extreme (less than 25%).
Maintenance	The maintenance includes regular cutting in the first 12–24 months to reduce weeds. In the case of grassed stripes also an annual cut. The costs of maintaining can be ca. £1.50/ha/year (Posthumus et al. 2015), depending on the density and width of stripes and on the share of grassland (cutting grass costs £25/ha/year considering one cut/year, Nix, 2009).
Climate change	Grasslands are considered to have the potential to play a key role in greenhouse gas mitigation. They can store carbon and contribute to sequestering carbon (Hopkins and Del Prado 2007); however, the effect of narrow and sparsely placed strips is of course much smaller than grassing the entire plot. On the other hand, grasslands can be endangered by climate change (Gibson & Newman 2019). Grassland adaptation to climate change will be variable, with increases or decreases in productivity and increases or decreases in soil carbon stores (O'Mara 2012).
Other hazards	Next to reducing water and wind erosion (in the case of wooden strips), they increase surface roughness and slow surface runoff rates and thus reduce the risks of floods. Grasslands can also play the role of sedimentation and trapping belts located directly on land blocks or their parts (Novotný et al. 2017, Maetens et al. 2012).

Measure: Contour farming	
Case study	 ***Figure 4.*** *Example of contoour farming, adopted after:* https://www.plymouthswcd.com/contour-farming https://livinghistoryfarm.org/farming-in-the-1930s/crops/contour-plowing/ https://wicci.wisc.edu/2021-assessment-report/land/wisconsin-agriculture-stressed-by-climate-change/ Source: https://www.plymouthswcd.com/contour-farming
Short summary	Contour cultivation is tillage operations parallel the contour (Quinton and Catt, 2004). It reduces runoff by increasing surface roughness perpendicular to the slope. The increased surface roughness reduces the velocity of any flowing water, providing more time for infiltration and reducing erosion rates (Stevens et al. 2009). By plowing along the contours or with a small deviation from the contours with rotary plows that turn the soil against the slope, it is possible to make a significant contribution to protecting the soil from erosion (Novotný et al. 2017). As a direct effect, there is a reduction in fertilizer loss and an increase in crop yields. Liu et al. (2013) pointed out that the major effect is obtained in the slope ranges between 3% and 8% since in steep slope areas there could be a high risk of tractor overturning (Abubakar et al., 2010). It promotes higher yield by reducing the loss of fertile soil and by keeping more moisture in soils. For this reason, contour farming has been considered part of the structural practices useful to decrease sheet and rill erosion (Santhi et al., 2014). In Italy, contour farming is one of the standard land management practices in hilly areas which has been used since the beginning of 1900 in the Apennine and Sub-Apennine areas (Bazzoffi et al., 2011).
Feasibility	The change to operating across the contour has not been explicitly costed. Additional time spent in the field because of a reduced work rate will increase the operational costs per hectare associated with crop establishment, and, potentially, fertilizer application and spraying of agrochemicals. Many farmers are reluctant to adopt contour cultivation because of the difficulties with cultivation and spraying operations (Stevens et al. 2009). There can also be problems with the stability of machinery working across the slope (Quinton & Catt, 2004). Somewhere, contour farming doesn´t require much of additional costs while in different conditions it may require the need of special machinery. However, in extreme

	slopes above 15-21 % the grassing of the field may be more advisable. In some cases, also the shape of the field can make contour farming difficult in case it has a shape of an elongated rectangle with a short side along the contour. In most cases, contour farming requires only more frequent turning on the headlands (Macho 2018).
Cost-effectiveness	There are no investment costs necessary unless there is a need for special machinery (in very steep areas). Thus, it is cheap measure; there can be some increased annual cost of contour ploughing which was estimated by Posthumus et al. (2013) to be £32 ha^{-1} $year^{-1}$ (it assumes that the costs for preharvest field operations will increase by 10% and the costs for harvesting can increase by 25%). The reduction of erosion was estimated by Stevens et al. (2009) as the range between 9–98% and an average of 72%. Dorren and Rey (2004) estimated it up to 50%. Ricci et al. 2020 reported erosion reduction (after contour farming adoption) that reached 22 %; from 5.95 to 4.61 t ha^{-1}). Maetens et al. (2012) compared literature sources about soil loss in several agricultural lands across various countries (Algeria, Croatia, Finland, Germany, Hungary, Marocco, Portugal, Spain, Turkey, and UK) and calculated the Mean annual soil loss ratio (soil loss with contour ploughing / soil loss with conventional practice) was found to be 0.5. The potential yield increase in cereals can be 16% compared to standard ploughing (Quinton & Catt, 2004). The benefit-cost ratio was calculated by Posthumus et al. (2013) as 2.67. Some farmers consider this practice as time-consuming because of the creation of additional rows in corners and at the end of the field (Ricci et al. 2020).
Maintenance	Since this measure consists just in changing the way of farming, there are no maintenance costs associated with it. Therefore, only increased processing costs of field operations and harvest can be expected which were estimated to be £32 ha^{-1} $year^{-1}$ (Posthumus et al. 2013).
Climate change	As this measure reduces run-off and concentrated run-off (Stevens et al. 2009), it can mitigate some phenomena associated with climate change, especially extreme precipitation. The increased infiltration increases the water supply in the soil and can improve the cooling effect of vegetation, mitigating high summer temperatures.
Other hazards	This measure can be used to slow down surface runoff and reduce its volume. At the same time, it prevents concentrated runoff. It can decrease the risk of floods. Agrotechnical measures also have a slightly positive effect on the hydro morphology of watercourses: they prevent the introduction of fine soil particles and inorganic sediments into watercourses (Ricci et al. 2020).

<table>
<tr><th colspan="2">Measure: riparian buffer zones</th></tr>
<tr><td>Some examples of application:</td><td>
Figure 5. Riparian zone restoration on the Maly Potucek Stream, Czechia (https://www.zahrada-olomouc.cz/krajinne-a-ekologicke-realizace/).
Other example of application:
http://hydropro.cz/portfolios/revitalizace-sedlickeho-rybnika/
https://www.nativeplantsolutions.ca/what-we-do/riparian-zone-restoration/</td></tr>
<tr><td>Short summary</td><td>Riparian zones represent an important ecosystem providing a range of functions and services important to humans—for example, biodiversity support, a reduction in erosion risk, or the transport of pollutants from the surrounding landscape to watercourses. At the same time, it is an environment that has been often subjected to significant pressure during the agricultural cultivation of the landscape or the development of industrial and residential activities of human society (Jakubínský et al. 2023). A vegetated buffer, barrier, or filter strip is a parcel of land designated to separate land used for agriculture from valued aquatic or terrestrial habitats. Riparian vegetation has the capacity to deliver a disproportionately high amount of ecosystem services relative to their extent in the landscape (e.g., Sweeney and Newbold 2014) because of their ecotone characteristics and the ecological functions of RV (Capon et al. 2013).</td></tr>
<tr><td>Case study example</td><td>Many case studies can be found on this type of measure - a selection of some case studies is available here: http://nwrm.eu/measure/buffer-strips-and-hedges</td></tr>
<tr><td>Feasibility</td><td>This measure is quite demanding, as it is a linear measure along watercourses where many landowners must agree to possible interventions. If the measure is implemented only within the riverbed, it is not effective enough, as evidenced by several studies. For example, according to Yuan et al. (2009), grass buffers as narrow as 3 m can remove significant amounts of sediments from agricultural runoff with a maximum benefit</td></tr>
</table>

	achieved with widths of 6 m or more. The Natural Resources Conservation Service (NRCS) recommended a minimum grass buffer width of 8–10 m to protect water quality (USDA–NRCS, 1997), this should be sufficient for sediment trapping and for the performance of other functions and services. There are also a variety of social and economic factors that can curb the adoption of riparian buffers, including: a lack of incentive programmes, poorly defined goals, or lack of maintenance.
Cost-effectiveness	According to Gene et al. (2019), studies have investigated the cost-benefit relationship associated with the installation of buffers (Santhi et al., 2003; Yuan et al., 2009). Establishment of buffers often involves removing an area of the field out of production, which translates into lost revenue for the farmer. However, vegetated buffers may also benefit the farmer through incentive programs and/or a cost reduction associated with reduced erosion and nutrient losses. Most studies have concluded that vegetated buffers represent a net benefit, although the size of the benefit varies (benefit: cost ratios ranged from 1.2 to 4.1) (Santhi et al., 2003). The total cost of riparian buffer strips includes the costs of planning, the costs of planting (trees, shrubs, local vegetation), the costs of land and/or revenue lost from replacing farm/grazing areas, and the cost of maintenance works. These costs are hugely dependent on the location and size of the buffer strip, yet they are shown to be balanced with the long-term benefits.
Maintenance	The expected lifetime is over 25 years if the measures are well established in the first years of implementation, with most maintenance in the first 5-10 years. 10-15 years could be needed to develop a fully mature riparian buffer which includes trees and shading benefits and a biodiversity corridor. However, within 1 year, shrubs and local vegetation could be planted which already begin to display their first positive effects in terms of reduced erosion, and pollutant filtration. Monitoring and upkeep of the area should be carefully managed especially during the first 5 years, scaling down management efforts between 5-10 years after the buffer establishment, once it becomes more mature and less vulnerable to local environmental pressures (Climate-ADAPT, 2023). According to the European Commission (2006) there was a maintenance cost of 75 to 150 €/ha for a 3m buffer strip.
Climate change	Riparian ecosystems are naturally resilient, provide linear habitat connectivity, link aquatic and terrestrial ecosystems, and create thermal refugia for wildlife: all characteristics that can contribute to ecological adaptation to climate change. Because riparian systems and the projected impacts of climate change are highly variable geographically, there is a pressing need to develop a place-based understanding of climate change threats to riparian ecosystems. Restoration practitioners should consider how they can modify practices to enhance the resilience of riparian ecosystems to climate change. Such modifications may include accelerating the restoration of private lands, participating in water management decisions, and putting the emerging field of restoration genetics into practice. Since climate change is projected to affect water resources for many urban and agricultural uses (Tanaka et al. 2016, Alcamo et

	al. 2007, Milly et al. 2008), the social and political pressures to modify riparian systems for water storage, transport, and extraction may increase. The ecological stresses of climate change on dammed rivers are projected to be greater than on undammed rivers (Palmer et al. 2008). If societies choose to respond to climate change by building taller levees, deeper wells, and larger dams, riparian ecosystems will be put at greater risk. Restoration practitioners and ecologists must engage with decisionmakers about water management. This engagement will need to include providing information on how changes in water use will influence the outcome of riparian restoration efforts.
Other hazards	Riparian buffer strips are an adaptation option able to: -prevent flooding: riparian buffers give room for natural dynamics of a river, such as rising and falling water levels, and allow for the slowing down of streamflow and creation of meandering flow paths. This reduces the channel erosion potential of rivers and thus the potential of downstream flooding. -mitigate drought: through improving groundwater recharge by increasing soil permeability and increased contact time of water with soils, or through shading effects provided by trees and shrubs that improve micro-climatic conditions. -ensure cooling: the shading effect of riparian buffers helps to create a microclimate that serves to cool over-shadowed water bodies, increasing air humidity and stabilizing temperatures.

Soil erosion - hybrid measures

Measure: geotextiles (Jute nets, coir blanket)	
Real case example where the measure was applied: Czech Republic (Geomat, 2023b, Geomat 2023c)	  ***Figure 6.*** *Use of coir blankets for erosion protection of a slope in the village of Olomučany (Czech Republic) and the use of jute nets as erosion protection of slopes during road reconstruction in Žacléř (Zech Republic).*
Short summary	"Geotextiles are nets or mats which protect the soil and reduce the detachment and transport capacity of rainfall and overland flow (…) Geotextiles are normally made of permeable materials which can be either biological (biodegradable) or synthetic" (Alvarez-Mozos 2014). Biodegradable geotextiles are also used as a temporary soil loss protection measure on sites, where vegetation cover was planted, but is still not reached maturity (Kalibová et al., 2016) since vegetation cover, such as turfgrass sods, are the best erosion control measures on sloping hillsides (Krenitsky et al., 1998; Kalibová et al. 2016) According to the measurements made by Álvarez-Mozos et al. (2014) or Kalibová et al. (2016), geotextiles (jute nets and coir blankets) significantly contribute to lower soil loss (sediment concentrations measured in these treatments were lower than the control). However, as Álvarez-Mozos et al. (2014) or Paz et al. (2018) found out, on high steep slopes sites (>45°) geotextiles can lead to in higher runoff rates (2–3 times larger than on control sites), but for less steep slopes (<27°) geotextiles can reduce run-off (Kalibová et al., 2016). Although some studies (e.g., Chen et al. 2011) highlight the risk of erosion on steep slopes, where geotextiles were implemented (runoff can scour under the mats flushing soil out) in the experiment of Álvarez-Mozos et al. (2014) this has not been confirmed.
Feasibility	Geosynthetics in general (geotextiles, geomats, geocells etc.) are applied for erosion control to the surfaces of slopes to encourage the growth of new vegetation and provide anchorage to the root structures. According to Wu et al. đ(2020). Due to the characteristics of high strength, low cost, and easy to use, geotextiles are widely used in geotechnical engineering such as soft foundation reinforcement, slope protection, and drainage system". The lifetime of jute nets is about 12-24 months. They are used on (milder and shorter) slopes intended to be grassed, where the grass can engage and protect the slope surface in a short time. Coir blankets are also used on steeper and longer slopes. Their lifetime is 7-9 years and are used on slopes planted with shrubs, where the period of vegetation involvement is longer, or on slopes threatened by flowing water. Geomats is a 3D anti-erosion/vegetation mattress that provides permanent erosion protection for slopes and stability of the soil.

	The open structure allows good permeability for water and air while permanently stabilizing the topsoil. (Greenmax, 2023). Compared to other anti-erosion measures, this is a simple and inexpensive solution.
Cost-effectiveness	Posthumus et al. (2014) calculated the investment costs of geotextiles £ 256/ha (= € 298). In general, "the cost of synthetic geotextiles is significantly higher than that of biological materials" (According to Álvarez-Mozos et al., 2014: 169)
Flexibility	Since soil erosion is closely related to landslides, geosynthetic are also used for landslide mitigation to provide tensile strength and added stiffness to the soil (Damians et al., 2023).
Maintenance	Maintenance costs are £ 1.25/ha (= € 1.45), which are spent for mowing (once a year). Some geotextiles (made from biological materials) will degrade after several years and they need to be replaced periodically (Posthumus et al., 2014).
Climate change	Geotextiles used as soil erosion control measure have only limited impact on climate change mitigation. Only if the geotextiles are covered with plants, can one speak about (little) carbon sequestration. In comparison to geocells, geotextiles are less dense covered by vegetation due to the small openings of the material - for it the roots, it is difficult to penetrate the geotextile (Paz et al., 2018).
Case study example	Revitalization and strengthening of the surface of the steep slope using anti-erosion coconut netting (coir blanket) anchored with steel staples and planting of trees and shrubs in the village of Olomučany in the Czech Republic (Geomat, 2023b). In the village of Olomučany they needed to revitalize and strengthen the surface of the slope. After agreement, planting shrubs and trees suitable for the site was proposed as a solution. Anti-erosion 700g coir blanket and 200g non-woven geotextile were used as erosion protection until the vegetation reach maturity. Jute nets as erosion protection of slopes during road reconstruction in Žacléř, Czech Republic (Geomat, 2023c). A jute erosion control net was added to the slopes of the reconstructed earth embankment, which will decompose over time. But before that happens, it will provide slope protection and support for the growing grass.

Measure: geogrids/geocells, geomats	
Real case example where the measure was applied: Czech Republic (Geomat 2023c)	 ***Figure 7***. *Protection of the slopes of the settling basin of the sugar factory in Dobrovice (Czech Republic) with geocells.*
Short summary	Geomats and geocells are used to hold topsoil in place, thus preventing slippage; Damians et al., 2023). According to Álvarez-Mozos et al. (2014): "Geogrids has 3D transverse structures which is supposed to provide enhanced soil holding ability (…) They have a higher tensile strength than the biological products geotextiles" (jute nets and coir blankets). The most suitable material for geogrids/geocells is high density polyethylene (HDPE) in terms of strength, durability, ease of handling and costs. Geocells are used for stabilization, improving foundation conditions, reinforcement and as an anti-erosion element, e.g., for retaining soil particles, roots or small plants during excavation and construction work and especially on stressed banks of reservoirs and streams. While greening provides a cost-effective solution to gentle slopes, geocells provide an economical solution to difficult erosion conditions. The fill material is protected by the cell itself and therefore protected against displacement. If the geocell system is placed at the bottom or sides of riverbeds and road embankments, it will protect the slope against damage from water erosion (Geomat, 2023a). According to Paz (2016:3): "Due to its 3D structure, it offers additional confinement to the soil. The confinement system reduces the lateral movement of soil particles" Geomat is defined as a three-dimensional permeable structure made of polymer fibers and/or other elements mechanically, thermally, chemically or otherwise bonded together. These products are intended for the erosion protection of slopes. They protect slopes and banks that are stressed by wind, rain, flowing water or waves. Geomats are mostly made of HDPE, but they can also be made of natural materials (Geomat, 2023a). Geogrids/geocells are more effective in protecting soil loss on steep slopes than coir or jute products. However, "the placement of the geogrid is vital; when buried, the soil loss rates observed were much larger than when surface laid" (Álvarez-Mozos et al., 2014: 177). Usually, geogrids are covered by well-developed vegetation canopy which further improves its soil erosion control function.
Feasibility	Installation of geomats and geocells as an anti-erosion measure is less complicated and less expensive than many other measures (dams, gabion walls, retention polders etc.). Before the installation of the geomats, slope area must be thoroughly cleared of all boulders, tree stumps and other remnants of larger vegetation. The slope must be levelled, especially the various depressions and hollows. The geomat strip must then be leveled on the slope, carefully pressed flat against the slope surface

	and anchored with a sufficient number of anchor pins. After the installation, it is necessary to spread good quality soil, preferably fertilized topsoil, over the entire area of the geomat. The soil is then sown with grass seeds and watered regularly, at least for the first 2 weeks (Geomall, 2023). The anti-erosion function of plastic geomats and geocells is not limited.
Cost-effectiveness	No detailed information could be found about cost-effectiveness.
Flexibility	Geogrids/geocells/geomats are also often used for landslides mitigations. As Damians et al. (2023: 198) refer, they "have been extensively used for the construction of Reinforced Soil Structures (RSSs), and in many landslide stabilization projects, for slopes as high as 60 m"
Maintenance	Geomats and geogrids require no maintenance when sufficiently filled with soil. All that is needed is to take care of the vegetation (grass cutting).
Climate change	Geocells and geomats have only limited impact on climate change mitigation. Only if they are covered with plants can it help to carbon sequestration. However, the climate change mitigation function of this kind of measure is very low (compared to afforestation or other similar measures).
Case study example	Protection of the slopes of the settling basin of the sugar factory in Dobrovice (Czech Republic) with geocells (Geomat, 20023d). The sugar factory's operator needed effective erosion protection of the slopes of the newly built settling basin, which will be periodically flooded with waste sludge from sugar production. When designing a suitable solution for the consolidation of the slope surface, the designer proposed geocells backfilled with aggregate of 32/63 mm fraction. Due to the periodic flooding of the slope, geocells with perforated walls were chosen. Geocells was also the cheapest solution, meeting the designer's requirements.

Measure: Woody dams	
Some examples of application:	 ***Figure 8****. Woody dam on the Smrček stream, Czechia (source: https://orvysocina.lesycr.cz/realizovane-vodni-stavby/hrazeni-bystrin-smrcek/).*
Short summary	Woody dams are made of natural woody materials, laid in streams and ditches (Eden Rivers Trust, 2023). These may also be known as 'leaky barriers' or 'leaky debris dams'. They are constructed in-stream to slow the flow of a river by creating a permeable space that allows water through but reduces the amount of water in the stream during high flows, such as during a storm. These structures can also encourage bank spillovers which delays downstream peak flows. Whilst maintaining banks and removing obstructions from rivers is sometimes essential to reducing flood risk, other times there will be certain areas in the channel were leaving obstructions such as fallen trees or adding leaky woody dams could have multiple benefits (UK Environment Agency 2021). With a particular spatial arrangement of wood pieces, these dams are structurally distinct from natural in-stream wood accumulations (Lo et al. 2022).
Case study example	St. Helens Sankey Valley NFM, UK – The aim of the Natural Flood Management project in Sankey Valley was to use hybrid woody dams to attenuate the flow of floodwater into downstream Blackbrook and improve the habitat. The project was run in partnership by Natural Environment Research Council, St. Helen's Council, the Environment Agency and the University of Liverpool. Four hybrid woody dams built to retain rapid flood flows in Stanley Brook tributary before arriving in downstream Blackbrook. Construction of a fourth dam took place by the Environment Agency, giving an overall cost of £2,000 for the four dams (https://thefloodhub.co.uk/wp-content/uploads/2018/09/Leaky-Woody-Dams-Natural-Flood-Management.pdf).
Feasibility	There is a little evidence for natural flood management measures such as Runoff Attenuation Features (RAFs), which include leaky barriers, having an impact at larger (> 10 km^2) catchment scales and for extreme events (> 100 year return period) (Grace, 2020). Installing woody dams depends on the characteristics of a

	watercourse and, just as importantly, its surrounding catchment (Avery, 2012). For example, the watercourse gradient, catchment soil type, elevation, and land use are examples of catchment parameters that must be assessed before the implementation. If the watercourse gradient is too steep, interventions such as leaky barriers may not be appropriate as scour may be exacerbated within the streambed (Thomas & Nisbet, 2012).
Cost-effectiveness	According to Eden Rivers Trust. (2023) the cost of installation and maintenance is low. Leaky (woody) dams do need to be cleared of debris and sediment occasionally so that water can still flow through the gaps. This reduces the likelihood of water flowing over the top of the barrier. For example, leaky barriers in Belford catchment, UK were~£100–1000, although costs depend on its design, material availability, access, and inflation. Wilkinson et al. (2019) state that the woody dams are spatially quite small measures (500–2,000 m^3) which only hold water for a short period of time (12–24 hrs). All these features are inexpensive, costing between £1,000 and £10,000 each (Quinn et al., 2022).
Maintenance	Hardwood leaky barriers are estimated to require reinstallation every 25 years (Fennell et al., 2023), otherwise, it can be assumed that most woody dams only have very low maintenance requirements, which can also be carried out using local wood stocks.
Climate change	Woody dams can help mitigate some of the impacts of climate change, manifested by more frequent occurrence of hydrological extremes (especially flash floods), as they are usually placed on hillslopes or in ephemeral headwater streams to increase hydraulic roughness and store small volumes of water temporarily during storm events to slow its delivery to the river (Grabowski et al., 2019).
Other hazards	Woody dams, which are often deliberately built to be permeable, allow low flows to pass under or through but hold back high flows, providing temporary water storage analogous to beaver dams. It is hoped that a diverse collection of such features deployed in a catchment may hold back enough floodwater (in-channel or on the floodplain) to mitigate flood risk downstream (Hankin et al., 2020). Woody dams also have a wide range of environmental benefits such as diversification of habitats thus increasing biodiversity, climate regulation through increased carbon storage and improvements to air and water quality (Fennell et al., 2023). If in suitable locations, increased infiltration to recharge groundwater may improve catchment resilience to drought (Norbury et al., 2021).

Measure: Water retention polders	
Some examples of application:	 ***Figure 9****. Water retention polder Žichlínek, Czechia (Source: SINDLAR Group, 2008).*
Short summary	A polder is a low-lying tract of land enclosed by embankments (barriers) known as dikes that forms an artificial hydrological entity, meaning it has no connection with outside water other than through manually operated devices. Its re-naturalization is enhancing polders with sub-natural characteristics, allowing better water storage in watercourses inside the polder, and increased biodiversity (NWRM, 2015).
Case study example	A comparative analysis of polders located in two purposively chosen Central European River basins in Poland and Hungary was performed. For both regions and Europe, flood risk and flood damage are predicted to increase in the next decade due to the highly dynamic nature of climate change (IPCC, 2021). Because of the constantly increasing flood risk in both river basins, attempts are being made to find and implement innovative flood-protective measures. In both regions, polders play a key role in FRM. Although the background conditions for both regions appear to be similar, the processes adopted by the two countries to achieve the same goal, i.e., implementation of polders for flood risk reduction, were different and brought about different outcomes. Details of this case study can be found at: https://onlinelibrary.wiley.com/doi/full/10.1111/jfr3.12897.
Feasibility	The time to implement adaptation measures for polders varies greatly depending on the structure typology, the strengthening measure and whether an EIA must be performed. Implementation times are in the rough range of 5-25 years. As building a polder requires access to diverse plots, land acquisition is clearly a challenging task for the responsible water authorities (Albrecht & Hartmann, 2021). However, the establishment of polder areas leads to a decrease in available land for arable fields and grasslands (Karrasch et al., 2016).
Cost-effectiveness	Cost estimates for adapting dikes and levees differ depending on the type of structure and reinforcing method. Some indicative costs are reported in a review study given by Aerts (2018). The benefits of implementing different flood adaptation measures are usually expressed as reduced flood risk or reduced damage. Investments in polders may be economically attractive for reducing flood risk in large parts of the world, but not everywhere. Therefore, alternative solutions should always be evaluated, and it should be noted that measures that give more room to the river often provide several co-benefits for ecosystems (Climate-ADAPT, 2016).

Maintenance	Polders need regular maintenance and strengthening to ensure their protection capacities and to meet safety requirements. One of the most common failure mechanisms of polders is breaching in case water overtops them. Polders can be built in a way that allows for overtopping (e.g., by strengthening the inner wall or broadening and reinforcing the surface). Such polders prevent the uncontrolled catastrophic breaks associated with devastating flooding of the hinterland. Damage can still occur due to the water that overtops the structures, but they are much smaller compared to a polder break (Climate-ADAPT, 2016). The expected lifetime of adapted dikes and levees is usually more than 30 years. It should be noted though, that maintenance plays a key role and that maintenance requirements change over time due to the aging of the structures and changes in river discharges.
Climate change	The dynamic nature of climate change, together with intensive floodplain development, have resulted in flood damage of an enormous scale. This has fueled discussions on the implementation of innovative flood-protective measures capable of coping with constantly changing environmental, social, formal, and economic conditions. Depending on context, polders can be seen as an innovation, especially when compared to hydraulic engineering solutions in FRM. They also bring benefits to the environment by protecting natural ecosystems, as well as to people by decreasing flood risk and ensuring safety (Warachowska et al., 2023).
Other hazards	The implementation of polders has several ecosystem services benefits that are intertwined with the reduction of some risks - a quality overview of the ecosystem services provided by polders can be found here: http://nwrm.eu/sites/default/files/nwrm_ressources/n14_-_re-naturalization_of_polder_areas.pdf The polders aimed at increasing two regulating and maintenance services. The water storage capacity creates a buffer for regulating natural hazards and the retained freshwater in the polders might be used during dry summer periods for irrigation (Karrasch et al., 2017).

Soil erosion - gray measures

Measure: Check dams	
Some examples of application:	 *Figure 10. Check dam in Slovenia.*
Short summary	Check dams provide protection against erosion in the torrential streams and provide stabilization against erosive processes in the mountains. Besides protection against erosion, they also provide flood control for the downstream areas. Usually, they are built in a cascading system, considering the geomorphological properties of the stream. Their purposes vary: sediment retention, slope consolidation, slowing down the activity of landslides, reducing the slope of the banks, reducing the longitudinal slope of the stream. They can be built from cut stone, masonry or concrete, wood, and stones. Check dams are commonly used on alpine streams. Can be also considered as a combined measure – check dams provide for (lateral) hillslope consolidation and slope inclination decrease, enabling growing conditions for the vegetation cover, as presented in Piton, et. al., (2016). Generally, check dams can be used as a buffer for the erosion processes in the mountain valleys and to control sediment transport in the lower areas of the stream.
Case study example	https://theses.hal.science/tel-01420209 Piton, G., Carladous, S., Recking, A., Tacnet, J. M., Liébault, F., Kuss, D., … Marco, O., Why do we build check dams in Alpine streams? An historical perspective from the French experience, Earth Surface Processes and Landforms, 42(1), 91–108, https://doi.org/10.1002/esp.3967, 2016.
Feasibility	A necessary measure in mountain streams with a significant sediment production and transport capacity.
Cost-effectiveness	For construction local material is used. The cost increases due to the location of the dams – they are often in remote areas.
Maintenance	Retention check dams require emptying of the sediment trapped behind the dam, the frequency depends on the sediment production capacity of the stream. Concrete and cut stone structures are more robust toward abrasion, while wood and stone structures will be more susceptible to abrasion due to the flow of water. Regular maintenance should consist of regular visual inspections – frequency depends on the erosion processes specific for each site. Their maintenance is considered expensive – located in remote areas at high altitude, steep valleys. This is why often old structures are just being abandoned and instead a new dam is constructed.
Climate change	They are a climate change mitigation measure. By construction of the check dams we can mitigate the increased erosion due to the increased frequency of extreme hydrological events.
Other hazards	It can also be used for landslides risk reduction

Measure: Terraces	
Some examples of application:	 ***Figure 11**. Example of terraces in Ourika catchment, adopted after:* https://www.mdpi.com/2673-4834/2/4/44 https://www.sciencedirect.com/science/article/pii/S2213305414000113 https://www.sciencedirect.com/science/article/pii/S2095633921000228 http://www.adottaunterrazzamento.org/ Widomski (2011)
Short summary	Terraces have been used as the oldest and most popular management practice for soil and water conservation all over the world (Zuazo et al., 2005). They are constructed as earthen structures or they can be supported by stone, eventually concrete walls. Their purpose is to reduce the slope steepness and divide the slope into short gently sloping sections (FAO 2000). They reduce the runoff velocity and soil loss, increase the soil moisture content through improved infiltration and reduce evaporation. They can also be created to divert runoff to a prepared or safe area. We can distinguish retention terraces, designed to accumulate and infiltrate runoff (broad-based terraces), and graded or diversion terraces (back-sloping) designed to intercept or divert runoff into protected waterways (FAO 2000). Within Europe, terraces are more common in Southern Europe (Stanchi et al. 2012), mainly in Spain, Italy, France, Portugal, and Hungary (basically for vineyard cultivation, Widomski 2011), while in Central Europe, terraces come into consideration only in rare cases; in the Czech Republic, they are used in the most erosion-endangered areas with steep slopes of more than 20% (Novotný et al. 2017).
Case study example	Djuma et al. (2017) modelled soil erosion in Cyprus with PESERA and found that hillslopes with well-maintained terraces produce erosion rates 10 times lower than the same hillslope without terraces which means a reduction of soil by 91%.

	https://iucn.org/sites/default/files/2023-05/practice_g.terraces_final.pdf https://air.unimi.it/retrieve/handle/2434/602037/1638448/Camera_et_al_2018_postprint_terrace_effectiveness_soil_erosion.pdf
Feasibility	Building terraces is expensive and demanding. Terraces with technical stabilization (stone or concrete supporting walls) take up less space but are significantly more demanding financially and technically, terraces with an earth slope require more space, but are technically and financially easier. They are preferably designed on deep soils (the wider the terrace platform and the higher the grade, the stronger the soil profile must be) (Novotný et al. 2017). Sandy and coarse soil is not suitable for terracing (IWRM, 2016).
Cost-effectiveness	Terracing is one of the most expensive practices (Ramos et al., 2007, IWRM, 2016) which is used only in agricultural land with very steep slopes (Napoli et al. 2020) ranging from 16% to 40% (IWRM, 2016), FAO (2000) recommends them for slope steeper than 20%with. They are effective on soils with high erodibility factor (IWRM, 2016) and should be proposed to control serious erosion (>10 t ha^{-1} yr^{-1}) (Kuhlman et al. 2010). According to Dumbrovský et al. (2014), the acquisition costs of $1m^3$ of terrace volume was 10,72 Euros and maintenance costs varied between 0.37 and 0.6 Euros/$1m^3$ of terrace volume. In America, Kling et al. (2007) estimated costs of establishment of 1m of terrace length to vary between 3.97 to 14.92 dollars. The density of terraces can be between 3,000 to 6,000 m/ha, according to the slope (Stanchi et al. 2012); calculating with the mean price and mean density, the costs would be 42,502 dollars/ha. The yearly maintenance costs according to Kuhlman et al. (2010) is 200 euros/ha/year. The efficiency of a terrace system is influenced by Local conditions and their dimensions, form, and stability (Dorren and Rey 2004) and increases by applying additional conservation practices (i.e., contour ploughing, strip cropping, high vegetation cover). Results obtained in Paraná (IAPAR, 1984) showed that terracing makes it possible to reduce soil losses by half, independently of the used cultivation system. Chow et al. (1999) observed dramatic decreases in soil loss of potato filed, from an average of 20 tonnes per hectare to less than one tonne per hectare (which means soil loss reduction by more than 95%) by terracing sloping fields in combination with constructing grassed waterways and contour planting. Bai et al. (2019) showed that terracing reduces soil erosion even by up to 99%. Schuman et al. (1973) found that runoff on a slope with level terraces was 8 times as low as on a comparable slope with contour planted crops. The in-situ measurements from Japan showed a reduction of soil loss from by approx. 88.2% (in case of soil terraces) and 92.4% (in case of stone wall terraces) (Nakoa 2000). Bevan and Connelly (2011 found that terraces in Greece decreased mean soil erosion rates by 56% compared to areas without terraces. Based on literature data from 14 plots in Europe and in some non-european Mediterranean areas, Maetens et al. (2012) found that

	terraces were reducing erosion in average by 75% compared to plots without terraces.
Maintenance	Regular inspections of the terraces, especially after significant storm events, are suggested to improve their performance (William, 1997). Terraces can be easily eroded, and they require a lot of maintenance and repair (Dorren & Rey, 2004). Numerous studies have shown that to prevent water erosion processes and to improve slope stability, terraces require constant maintenance (Gallart et al., 1994). The yearly maintenance cost according to Kuhlman et al. (2010) is 200 euros/ha/year. Numerous studies have indicated a decline in soil quality and an increased risk of soil erosion following the abandonment of agricultural terraces which could lead to deterioration of the terrace as a whole and to gully formation leading to increased erosion (Deng et al. 2021; Lasanta et al. 2019). Modern terraces sometimes require specific modifications to allow mechanization (Ramos et al., 2007), such as levelling and construction of linked benches on steep slopes. Mechanization is sometimes the only way to make terraced agriculture economically profitable (Cots-Folch et al., 2006).
Climate change	By modifying the relief of mountainous and hilly regions, agricultural terraces provide several environmental benefits that could mitigate the risk of climate change. They increase the soil moisture content through improved infiltration and reduce evaporation (FAO 2000), improve rainfall absorbency, reduce run-off, help to accumulate biomass and thus smooth extreme summer temperatures (Deng et al. 2021). However, the climate change brings changes in precipitation pattern, increasing the extreme events. The concomitance of land abandonment and precipitation change is increasing the land degradation risk in terraced land (Vergari et al., 2013).
Other hazards	Terraces also contribute to increasing the soil moisture content through improved infiltration and reducing peak discharge rates of rivers. Due to increased infiltration and reduced run-off, they can partly contribute to flood mitigation. Terraced areas also improve slope stability. They play a key role in gully erosion control, due to the slope gradient reduction (Martinez-Casanovas and Ramos 2006) and represent protection against mass movements or landslides (IUCN, 2023) but poorly maintained terraces can, on the contrary, promote landslides. Terraces abandoned for a short time result in the most hazardous land use class. These findings of a study from Italy reveal that land abandonment and agricultural mismanagement especially intensify shallow landslide magnitude (Brandolini et al., 2018).

Measure: Anti-erosive ditches	
Some examples of application:	 ***Figure 12**. Example of anti-erosive ditch, adopted after:* https://www.fao.org/3/au297e/au297e.pdf https://farmwildlife.info/how-to-do-it-5/field-boundaries/ditches/ Catch anti-erosive ditch in cadastral area of Lhotka near Zlín (source: VÚV TGM) Novotný et al. 2017
Short summary	An anti-erosive ditch/channel is a drainage channel constructed to prevent runoff water from upper hill to enter a field or to catch runoff water on a field where it can either infiltrate or may be diverted. It is a linear feature placed where it is necessary to interrupt the sloping field. It is oriented parallelly with contours, eventually it has very gentle slope (1%). It can be combined with other anti-erosive measures (grass stripe, road, stripe cultures, bio-corridor, etc.). Above the ditch or channel, it is recommended to establish grassed stripe at least 5-6m wide to catch the soil particles (Novotný et al. 2017, Kuypers, Mollema & Topper, 2005). We can distinguish ditches and channels. They differ in size, shape and depth; the channels are 0.6-1.2 m deep and have steeper slopes (1:1.5–1:2), thus they are not crossable by agricultural machinery while ditches are shallow and have gentle slopes (1:5 to 1:10), are mostly grassed and thus they are crossable by field machinery (Novotný et al. 2017). Channels can be divided into catching channels, which are placed above the crop field and divert the water coming from other areas placed above, and collecting channels, which are placed directly on the crop field to interrupt the length of their slope. The distance of them is calculated based on the erosion formula (USLE) or by simulation model (SMODERP). The draining channel is a recipient of both previously described channel types. This is wider and has a slightly steeper slope and thus is often stabilized by pavement or stones but can be also grassed (Novotný et al. 2017). In Mediterranean areas, temporary ditches are also used. These are narrow and shallow and are crossable by mechanization, but it is necessary to renew them as they disappear after several years (Francaviglia & Neri, 2020, Bazoffi et al. 2011).

Feasibility	The measure requires preparation in the form of the acquisition of agricultural land, resolution of property rights and processing of project documentation. Preparation and implementation take about 7 (or more) years, the effect is visible within three years (VÚV TGM 2018). The correct calculation of the capacity and distance of ditches or channels is necessary so that the water can be safely drained and soaked (Bazoffi et al. 2011). It is also necessary to plan the drainage of water to the final recipient. The implementation itself is financially demanding (VÚV TGM, 2018).
Cost-effectiveness	The use of these measures is suitable in case of inefficiency or impossibility of implementing fewer demanding types of measures (organizational and agrotechnical) or it can be used for the purpose of dividing the arable land into smaller parts, eventually to protecting people and their property (VÚV TGM, 2018). It is costly; the average cost for a ditch with grassed profile (without other planted vegetation) is ca. 1500 CZK/bm. Posthumus et al. (2015) estimate the costs of swales as 212 pounds/ha (if 30% of farmland drains into the swale). They estimated the benefit-cost ratio in 5-year period to be between 0.23 and 2.78. The correct size and distance of the drainage channels are important with respect to their ability to intercept the water coming from the area between two drainage channels, reducing the speed and permitting the sedimentation of the eroded material. These considerations make it imperative that water management with level ditches must be carried out up to standards, otherwise, it will worsen the situation and can even accelerate soil erosion (Bazoffi et al., 2011). The effectiveness also depends on the slope of the field, the study from Tuscany, Italy revealed that these measures are more efficient on slopes lower than 9%, in the case of the steeper slope, these measures couldn´t control erosion to an acceptable level (Napoli et al., 2020). In the study of Macho (2018), the erosion expressed as a value of average soil loss (G) was reduced by 30% after the implementation of one anti-erosive ditch into the field of the slope length cca. 200m. In the study carried out in Italy (in 16 regions), results pointed out that temporary ditches were significantly effective in reducing soil erosion by 67% (Francaviglia & Neri, 2020); their results showed that, on average, the presence of ditches significantly decreased erosion by 22.6 Mg ha^{-1} yr^{-1} compared to erosion without temporary ditches (10.3 vs 32.9 Mg $ha^{-1}yr^{-1}$). Another study showed the effect of small temporarily made ditches at distances less than 80m; their data showed that in corn fields they reduced soil erosion by 94% and runoff by 32% (Bazoffi et al., 2011). However, anti-erosive ditches are less effective in soil loss reduction than terraces, which reduced soil loss 4.7-12.3 times better (Napoli et al., 2020).
Maintenance	Regarding maintenance, it is necessary to clean ditches regularly and keep them clear including all objects on them to keep the channelling capacity of the drainage ditches (Kuypers, Mollema & Topper, 2005). The grassed stripe above the ditch or channel should

	be mowed regularly to keep the ideal roughness of its surface (Novotný et al. ,2017). The maintenance including mowing and dredging was 1 Euro/1m length/year in 2018 in France (Patault et al., 2021). According to Posthumus et al. (2015) the lifetime of Swale is ca. 15 years. They think that maintenance costs are negligible.
Climate change	The climate change brings also higher share of extreme precipitation events and therefore, these measures have mitigating effect decreasing the erosion resulting from it. Increased water infiltration contributes to a better supply of water in the soil and thus also to higher evapotranspiration and the cooling function of the vegetation (crop) grown on the plot.
Other hazards	Similarly, as terraces, anti-erosive ditches and channels influence (next to erosion) other hazards in the area; they increase water infiltration and decrease risk of floods.

Measure: small dams	
Some examples of application	 ***Figure 13**. Example of small dam, adopted after:* https://www.thinktrees.org/wp-content/uploads/2019/07/WEBS-Fact-Sheet-7-Small-Dams-Reservoirs.pdf
Short summary	Small dams (earthen, concrete) can reduce downstream peak flow and flooding, they can help to reduce sediment or nutrient transport (for example Nitrogen, Phosphorus). The use of small dams varies; often the aim of the construction is to cover multi-purposes, e.g., dry flood-control dams, back-flood control dams, other uses, such as recreational, water storage, irrigation, conservation of wetlands, habitats. The most common small dam type is embankment where the materials used for the construction include natural soil or/and rock. The second most common type of small dams is gravity dam constructed with concrete or masonry. Can be adapted to local conditions – to provide for small-scale measures, with inclusion of recreational use or incorporating farming needs for example. The decision as to which type of dam to build depends on the foundation conditions in the valley, the availability of construction materials, the accessibility of the site, financiers, and promoters responsible for the project. When a small dam is damming a stream the auxiliary services and structures to provide for fish migration must be designed.
Case study example	https://www.thinktrees.org/wp-content/uploads/2019/07/WEBS-Fact-Sheet-7-Small-Dams-Reservoirs.pdf https://www.emerald.com/insight/content/doi/10.1108/IJCCSM-12-2014-0141/full/pdf https://ascelibrary.org/doi/full/10.1061/%28ASCE%29HE.1943-5584.0001005 https://www.sciencedirect.com/science/article/pii/S2095633921000198
Feasibility	Depending on the site specifics – cost-benefit analysis should be performed, financial and ecological feasibility evaluated.
Cost-effectiveness	It depends on the dam type and site specifics. Local equipment should be used when possible.
Maintenance	Visual inspections, vegetation management (trimming of grass, removal of low vegetation), monitoring of siltation. Management of human and animal presence. Each dam needs to have a maintenance and operational program which must be followed.
Climate change	Buffer for climate change/variability of flow, creation of ponds, wetlands, or other riparian ecosystems.
Other hazards	Reservoirs are susceptible to silt-up. Must be properly constructed and maintained, due to the risk of overtopping. Proper site selection. Proper flood hydrology studies. Susceptible to seepage, especially with design flaws, poor maintenance. Sufficient freeboard must be provided during all hydrological conditions.

Measure: kranjska stena (Timber crib wall) And also other similar types of gabion or crib wall structures, steel bin walls	
Some examples of application:	 ***Figure 14***. *Example of timber crib wall (kranjska stena) in Slovenia.* https://www.gov.si/assets/ministrstva/MK/DEDISCINA/NESNOVNA/RNSD_SI/Rzd-02_00027.pdf
Short summary	This type is structures is used for water regulation, rehabilitation of erosion hotspots, or stabilization of hillslopes. This type of structure can also be used directly in the watercourse in longitudinal and lateral direction. It is especially suitable for regulating torrents and mountain and mountain watercourses. Crib type of support structures can be utilized when a thin unstable top layer of soil needs to be stabilized, while the subsoil layer is stable. Crib wall structures should have a volume of 10-15 percent of the volume of the soil to be stabilized. The fill material must be compacted and drained, and structure drainage must be provided. Gabion walls due to the cobble fill and mesh design are well drained by the design properties. The main advantage of this type of structures is adaptability, and flexible design, able to adapt to local properties and time-effects. In torrents, mountain and hilly watercourses coincide with landscape features, and creates less negative environmental impacts as riparian insurance.
Case study example	Timber crib wall is part of the Register of Living Cultural Heritage of Slovenia and it is widely used in for reguation of alpine streams. https://www.gov.si/assets/ministrstva/MK/DEDISCINA/NESNOVNA/RNSD_SI/Rzd-02_00027.pdf (in Slovenian).
Feasibility	Feasible in erosion prone areas and areas where nature-based solutions are preferred. For the construction it prefers that local materials are used.
Cost-effectiveness	When available, local materials can be used, which makes especially the timber crib walls very cost effective.
Maintenance	Regular inspections are required, since the structure has elastic properties and can adjust to the changes in terrain it is important that with regular maintenance work, we prevent local failures.
Climate change	A measure to stabilize erosion hotspots is to provide slope stabilization.
Other hazards	Proper drainage must be provided otherwise the structure is prone to overturning or sliding failure. Can be used as support for landslides disaster risk reduction.

Measure: riprap	
Some examples of application:	 ***Figure 15**. Vegetated riprap in the Chodovecky stream, Czechia (source: https://www.prostranstvi.cz/Priklady-dobre-praxe/Databaze/Revitalizace-vodnich-toku-ve-meste).*
Short summary	Riprap, also known as “rock armor,” is typically defined as a permanent, erosion-resistant ground cover of large, unsecured, stone applied to river margins, although regularly shaped concrete blocks may also be used. Riprap characteristics vary widely depending on the environment in which it is placed and the nature of the erosion control desired (Reid & Church, 2015). Riprap can impact stream channels by locally reducing sediment and wood input and by coarsening bank material. Reduced inputs of sediment from bank erosion may lead to localized channel incision, resulting in a coarsening of the bed surface gravels and simplification of local morphology as channels degrade (e.g., Arfeuillère et al., 2023).
Case study example	These measures are common - for example, several restorations of smaller urban watercourses took place in Prague, Czechia, in the past, which also included the application of rip-rap measures. More information about these approaches can be found here: http://www.praha-priroda.cz/vodni-plochy-a-potoky/vodni-toky/kosikovsky-potok/revitalizace-a-opravy-na-kosikovskem-potoce/revitalizace-koryta-kosikovskeho-potoka/
Feasibility	According to Reid & Church (2015), it appears that, among many stream managers, riprap has lost favor as the channel stabilization measure of choice as other methods of channel stabilization (such as bioengineering solutions) have become available (Quigley and Harper, 2004), even if these methods are often considered to be less secure in critical sites. Variability in riprap extent and setback, riverine sediment texture, and channel morphology will lead to substantial differences in the specific responses of individual river environments to bank stabilization from riprap placement.
Cost-effectiveness	Riprap is an extremely common material for construction projects and often assumed to be the most cost-effective option for channel armoring. Placement of rock riprap is one of the most cost-effective measures for erosion protection, structural stability, and slope stabilization (Abt et al., 2013). However, in some studies it has been found that the price of riprap measures is very dependent on natural conditions - especially on the distance over which it is necessary to transport the material. A study done by Auburn University found that in the state of Alabama riprap’s unit cost can fluctuate drastically based on the location of a given

	project. In the northern regions of the state riprap's unit cost can be as low as 73% of the state average, whereas in the south the rate can be increased as much as 160% that of the state average (Gerber, 2022). Several studies have indicated that bioengineering is an effective alternative to the use of riprap on stabilized riverbanks, and the approach leads to increased plant diversity and succession, almost resembling those of natural riverbanks (Tisserant et al., 2021).
Maintenance	Since riprap is a natural material composed of stone or boulders and is readily available in many areas, it has been used extensively in erosion protection works. In some areas, riprap is produced by quarrying hard, durable rock. In other areas, riprap is collected from talus or by excavating large river cobbles from alluvial deposits. Riprap, when properly designed and used for erosion protection, has an advantage over rigid structures because it is flexible when under attack by river currents, it can remain functional even if some individual stones may be lost, and it can be repaired easily. Properly constructed riprap can provide long-term protection if inspected and maintained periodically and after flood events (Lagasse et al. 2006).
Climate change	The phenomenon of climate change is projected to have significant impacts on regional hydrological features and especially on the intensity and frequency of occurrence of extreme flood events. Modified weather patterns and in turn modified hydrological flow regimes pose severe threats to the safety of hydraulic structures, such as riprap (Ravindra et al. 2018). According to Kalogeraki & Antoniou (2022) ripraps are also applied around piers on the river bridges as a climate change adaptation measure. Size of the riprap is then determined based on the maximum expected design flood flow at the bridge site over the projection period.
Other hazards	Riprap is useful for supporting the self-purification process of flow and large stone layers at the bottom of the riverbed and can regulate the movement of sediments (Quigley et al., 2004). Riprap placement also tends to sever organic material input from the riparian zone, with loss of shade, wood input, and input of finer organic material (Reid & Church, 2015).

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