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Gully prevention and control: techniques, failures and effectiveness

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Abstract

Gully erosion is a major environmental problem, posing significant threats to sustainable development. However, insights on techniques to prevent and control gully erosion is scattered and incomplete, especially regarding failure rates and effectiveness. This review aims at addressing these issues and contribute to more successful gully prevention and control strategies by synthesizing the data from earlier studies. Preventing gully formation can be done through land use change, applying soil and water conservation techniques or by targeted measures in concentrated flow zones. The latter include measures that increase topsoil resistance and vegetation barriers. Vegetation barriers made of plant residues have the advantage of being immediately effective in protecting against erosion, but have a short life expectancy as compared to barriers made of living vegetation. Once deeply incised, the development of gullies may be controlled by diverting runoff away from the channel, but this comes at the risk of relocating the problem. Additional measures such as headcut filling, channel reshaping and headcut armouring can also be applied. To control gully channels, multiple studies report on the use of check dams and/or vegetation. Reasons for failures of these techniques depend on runoff and sediment characteristics and cross-sectional stability and micro-environment of the gully. In turn, these are controlled by external forcing factors that can be grouped into (i) geomorphology and topography, (ii) climate and (iii) the bio-physical environment. The impact of gully prevention and control techniques is addressed, especially regarding their effect on headcut retreat and network development, the trapping of sediment by check dams and reduction of catchment sediment yield. Overall, vegetation establishment in gully channels and catchments plays a key role in gully prevention and control. Once stabilized, gullies may turn into rehabilitated sites of lush vegetation

or cropland, making the return on investment to prevent and control gullies high.

Key words

Check dam, Erosion, Failure, Sediment yield, Stabilization, Headcut, Valley-bottom, Vegetation

1. Introduction

Land use and cover change has strongly altered hydrological conditions of land- and soils, resulting in gully development in many regions worldwide. Deforestation, agricultural expansion and intensification, infrastructural development, and urban sprawl have widely resulted in gully development across various topographical, lithological and climatological conditions (Poesen *et al.*, 2003; Castillo and Gómez, 2016) both in historical times (Dotterweich *et al.*, 2003; Stankoviansky, 2003; Vanwallegghem *et al.*, 2006) and at present (Nyssen *et al.*, 2002; Marden *et al.*, 2005; Zheng, 2006; Imwangana *et al.*, 2015). Given that global environmental projections indicate that climatic and coupled hydrological systems will experience important changes over the next decades (Kundzewicz *et al.*, 2014; Li and Fang, 2016), the need for applying more effective gully prevention and control measures becomes increasingly important. To address these challenges, many regions have implemented large-scale land rehabilitation programs (Guyassa *et al.*, 2018; Haregeweyn *et al.* 2015, Hartman *et al.*, 2016; Romero-Diaz *et al.*, 2010). Stabilization methods such as check dams have been applied by rural communities for a long time in order to control gullies (Norton *et al.*, 2002; Wright, Crowley and Crowley, 2008). Throughout the 20th Century, engineered control measures have been increasingly applied following rapid gully

network developments due to unsustainable land usages (Heede, 1978; Haigh, 1984; Sheng and Liao, 1997).

Despite evident successes of gully control schemes, many interventions are only partially successful or controversial (e.g. when its application favours wealthy farmers at the expense of others) (Frankl *et al.*, 2016; Poesen *et al.* 2003, Rey 2004; Sheshnev, 2017; Smit *et al.*, 2017). Furthermore, techniques that work in a certain area may fail in another if environmental settings, particularly pedo-climatic conditions strongly differ (Rebai, Raclot and Ouezdou, 2013; Zimale *et al.*, 2017). Also, when rural communities and their (indigenous) knowledge are weakly integrated in restoration initiatives, this may be a cause for failure (Pawluk, Sandor and Tabor, 1992). Given the high cost for applying gully prevention and control measures (Yitbarek, Belliethathan and Stringer, 2012; Quiñonero-Rubio *et al.*, 2016), a thorough understanding of their impact on gully development and catchment sediment yield is essential. The more effective such measures are, the more likely it is that local communities will also support their implementation and maintenance. This is especially true because complex socio-economic interactions guide the adaptation of techniques and because the cost of interventions should generally be kept as low as possible (Liniger and Critchley, 2007; Jay and Stolte, 2011; Mashi, Yaro and Jenkwe, 2015). Moreover, well-managed gullies may yield a high return on investment as they can be converted into vegetated waterways that provide multiple ecosystem services such as the restoration of perennial flow, production of fodder, fibre and wood, enhanced biodiversity and carbon sequestration (Heede, 1979; Debano and Schmidt, 1990; Rey *et al.* 2019; Roose, 1993; Lira-Caballero *et al.*, 2018; Mongil-Manso *et al.*, 2019).

Studies devoted to understand processes and factors of gully erosion in various human-environmental settings have, therefore, multiplied and recently resulted in

several review papers (Castillo and Gómez, 2016; Poesen *et al.*, 2003, 2006, 2011; Torri and Poesen, 2014; Vanmaercke *et al.*, 2016). Concomitantly, several studies on gully prevention and control have also been conducted, but their results remain scattered and incomplete. This is especially so with respect to reported failures of such measures. A comprehensive review on reported failures and successes would benefit scientists, land managers and policy makers aiming to address gully erosion in the most effective and efficient way.

Therefore, the objective of this paper is to present state-of-the-art knowledge of gully prevention and control techniques. Reasons of failure will be discussed and for gully control techniques, they will be synthesised according to factors controlling gully erosion. The reported impact of techniques will be discussed by considering headcut retreat and gully development, channel aggradation and morphology, and catchment sediment yield. Section 2 explains how information was collected from literature and Section 3 provides an overview of currently applied gully prevention and control techniques. Section 4 focusses on gully prevention techniques (land use and soil and water conservation, topsoil resistance, vegetation barriers) and, especially, their effectiveness towards controlling ephemeral gully development in cropland. To note, the term 'ephemeral' is used to define gullies which are shallow enough to be erased by tillage, only to reform again in the same location by additional runoff events (Frankl *et al.*, 2018). This is opposed to 'permanent' gullies, i.e. channels too deep to easily erase with ordinary farm tillage equipment, typically ranging from 0.5 to as much as 25–30 m depth. They often develop from bank gullies, the latter being headcuts that incise earth banks (embankments, agricultural terraces, river banks, gully banks, sunken lane banks or lynchets, Poesen *et al.*, 2003). Although 'permanent' gullies can be persistent features of the landscape for years, decades or even centuries

(Vanwalleggem *et al.*, 2006; Frankl *et al.*, 2011), it is important to note that even 'permanent' gullies can be erased. Another criterion to classify gullies is based on their location in the landscape: i.e. valley-side gullies, valley-bottom gullies, bank gullies, edge-to-field gullies and urban gullies (Poesen *et al.*, 2003). Section 5 considers gully control techniques (in particular check dams and vegetation), failures rates and causes of failure. It also discusses the impact of control measures on headcut retreat, network development, channel aggradation and morphology, as well as catchment sediment yield.

2. Identifying and selecting relevant literature

We conducted a literature review on gully prevention and control techniques. The main source of information were English publications from the SCOPUS database (<https://www.scopus.com/>). A bibliography was created by querying SCOPUS for publications that mention 'Gully' & 'Erosion' or 'Gully' & 'Check Dam' in their title or key words. Variations in spelling (gulley), plural (gullies), gullying and translations (ravine, arroyo, lavaka, donga, wadi (Castillo and Gómez, 2016), were also added to the search query. We limited results to the subject areas of Earth and Planetary Sciences, Environmental Science, Agricultural and Biological Sciences, and Engineering. Citation information, abstract and key words of the resulting records were exported in *.csv format. Other relevant papers or reports that do not appear in SCOPUS, but which were known to the authors of this paper were also added to the bibliography. The resulting bibliography was reduced by searching for 'Control', 'Stabili(z)(s)ation', 'Rehabilitation', 'Reclamation', 'Prevention' in the titles, key words and abstracts. By scrutinizing all remaining abstracts, we further reduced our bibliography to a selection of 190 relevant papers and reports that focussed on prevention and control of gullies.

3. Overview of gully prevention and control techniques

Since the mid-20th Century, approaches to prevent and control gully erosion have been presented in technical recommendations (FAO, 2020) and field guides (Sabir, Lichaa El-Khoury and Salman, 2020). By collecting evidence-based studies from all over the world, the Database on Sustainable Land Management Practices (WOCAT, 2020) considers over thirty approaches of gully control, as applied in different human-environmental settings. An overview of the different techniques discussed in this paper is given in **Error! Reference source not found..**

4. Gully prevention

4.1. Techniques and their characteristics

4.1.1. Land use and soil and water conservation

Gullies are typically formed as a result of high runoff rates being produced on land. Through its impact on peak runoff, land use strongly controls the topographic threshold conditions for gully head development (Torri and Poesen, 2014). For example, a conversion of forest or pasture (rangeland) to cropland can result in significant reductions of the resistance of hillslopes to gully initiation. As a result, the prevention of gully erosion mainly depends on reducing peak runoff rates. This can be achieved by land use change (Maetens *et al.*, 2012) or through the application of soil and water conservation measures (Liniger and Critchley, 2007; Maetens, Poesen and Vanmaercke, 2012). A detailed discussion of the land use and soil and water conservation techniques and their effect on runoff production goes beyond the scope of this paper, and is comprehensively discussed in other works, such as for Africa (Wolka, Mulder and Biazin, 2018), China (Chen *et al.*, 2020) or Europe (Maetens *et*

al., 2012; Maetens, Poesen and Vanmaercke, 2012).

4.1.2. Topsoil resistance

Gully development can also be prevented by improving the resistance of topsoils to incision. This mainly applies to locations where gullies are recurrent in concentrated flow zones (i.e. ephemeral gullies). The following measures have been reported for cropland.

A. No tillage. No tillage plots, having compact and cohesive topsoils in valley bottoms better resist flow shear stresses exerted by concentrated flow than plots with conventional ploughing. Ploughing results in loose, less cohesive and hence, more erodible topsoils that are typically more prone to gullyng (Poesen *et al.*, 2003; Knapen *et al.*, 2007).

B. Topsoil compaction. Building on the same principle that more cohesive topsoils have a larger resistance to incision by concentrated flow, Ouvry (1989) compacted mechanically concentrated flow zones after drilling in Northern France and observed that this treatment significantly reduced ephemeral gully development. Along the same lines, Poesen *et al.* (2003) concluded that knowledge of the thickness and properties of compact soil sublayers in concentrated flow zones is crucial and that any tillage operation (subsoiling) in these zones leading to a loosening of these layers should be avoided in order to prevent deep incisions by concentrated flow.

C. Grassed waterways. Grassed waterways are a commonly applied as a gully prevention approach in concentrated flow zones (Chow, Rees and Daigle, 1999; Fiener and Auerswald, 2003; Evrard *et al.*, 2008). They are broad shallow channels, often located within large fields, with the primary purpose of

evacuating surface runoff from cropland without causing gully erosion along the thalweg. To do this as effectively as possible, selected fast-growing grasses are sown in the waterway. Once established, the grass should be frequently mowed to reduce hydraulic roughness. Otherwise, the tall grass can induce sediment deposition that might damage the sward, and subsequently, gullies may develop (Fiener and Auerswald, 2003). Whereas grassed waterways are a common ephemeral gully erosion prevention practice in North America and increasingly in northern Europe, it is rarely adopted by farmers cultivating relatively small field plots or in semi-arid parts of the world where it is difficult to establish and maintain a good vegetation cover (Prosser and Slade, 1994; Poesen *et al.*, 2003).

Overall, vegetation plays a crucial role in valley bottoms when it comes to preventing incision by concentrated flow, triggering sediment deposition and reduce the sediment connectivity of catchments (Poesen *et al.*, 2003; Mekonnen *et al.*, 2017; Frankl *et al.*, 2019). Although the increased resistance to entrenchment by concentrated flow due to the presence of vegetation has been mainly attributed to aboveground biomass and its effect on overland flow energy dissipation, an increasing number of studies have also demonstrated the significant role of plant roots in reinforcing topsoils, thereby increasing cohesion (for a review, see: Vannoppen *et al.*, 2015). Clearly, the suitability of various vegetation types as well as both the effects of the above and belowground biomass needs to be considered in gully prevention plans (De Baets *et al.* 2009).

D. Double drilling. Gyssels *et al* (2007) observed that double drilling (i.e. increasing the crops density) in concentrated flow zones reduced ephemeral

gully erosion rates by 25%. The effect of double drilling on channel development was particularly clear in the early growth stages of the wheat seedlings. This was mainly attributed to the associated higher root densities and, therefore, larger topsoil cohesion as compared to conventionally (single) drilled topsoils. As an alternative to grassed waterways, double drilling can be a measure avoiding potential losses in cropland productivity.

4.1.3. Vegetation barriers

Vegetation barriers are narrow strips of plants or plant residues that are increasingly being used as measures to reduce the connectivity of catchments in terms of water and sediment fluxes (Boardman *et al.*, 2019) (**Error! Reference source not found.**). They can mostly be found at plot edges where they do not to hinder farming activities too much. Their principal function is to reduce sediment export from cropland and thus mitigate negative off-site effects of erosion (e.g., muddy floods, pollution of rivers). Being implemented in concentrated flow zones where ephemeral gullying is recurrent, they also prevent their development. This can be achieved as the barriers slow down and spread out surface runoff, and thus reduce peak runoff, force the deposition of eroded sediment and improve infiltration (Richet, Ouvry and Saunier, 2017). The selection of plants or residues depends on their local availability and suitability. Properties that determine their effectiveness are the density and the morphological traits of the plants used (stem and leaves) (Kervroëdan *et al.*, 2018).

Barriers of plant residues can be made of wood chips, bundles of brushwood, bales straw/coconut, etc (**Error! Reference source not found., Error! Reference source not found.**). They have the advantage that their dense structures makes them immediately effective in protecting against erosion and that they can be rapidly applied when soil

surfaces are temporally exposed (Haan, Barfield and Hayes, 1994).

Barriers of live vegetation can be grown from grasses, live fascines or hedgerows (Error! Reference source not found., Error! Reference source not found.). In addition to erosion control, they are especially valuable for the creation of habitats and the strengthening of ecological connectivity. When densely grown, they will retain their functionality over long periods (Ouvry *et al.*, 2012). Their survival is, however, often threatened by poor management. This is especially the case in cropland where they compete with crops for water, light and nutrients or where their growth can hinder farm operations and shelter perceived pests. Farmers may, therefore, trim shrubs too much to allow rejuvenation and cause (often intentionally) the vegetation to die. Flessner (1997) noted a survival rate of only 54% for willow stakes after 1.5 years.

Suitable native plants species for different environments across the globe have been proposed, taking into account their effectiveness for gully erosion control as well as other benefits (ecosystem services). Important selection criteria include the resistance to possible herbicide usage, a limited risk to house pathogens harmful to crops and being adapted to local pedoclimatic conditions (NRCS, 2010). Therefore, especially native plants species are advised. Willow (*Salix alba* L.) is commonly used for live fascines in the moist-temperate climate of NW Europe (Frankl *et al.*, 2018). Other widely promoted species include stiff grasses or shrub hedges species like switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus sinensis* Andress), vetiver (*Vetiveria zizanoides* (L.) Nash), eastern gamagrass (*Tripsacum dactyloides* L.), or rows of seabuckthorn shrubs (*Hippophae rhamnoides* L.) (Dewald *et al.*, 1996; Ritchie, Kemper and Englert, 1997; Angima *et al.*, 2002; Rachman *et al.*, 2004; Ibanez *et al.*, 2014; Cao *et al.*, 2015).

4.2. Effectiveness of vegetation barriers to prevent gully development

The effectiveness of vegetation barriers to control erosion by concentrated overland flow mainly depends on their hydraulic roughness, which impacts flow velocity and in turn soil detachment rate, sediment transport capacity and runoff infiltration (Vander Linden, 2011). The effects of (narrow) vegetation filter strips applied along contours to control overland flow and soil loss by sheet and rill erosion are well studied (Gumiere *et al.*, 2011; Maetens *et al.* 2012b). However, fewer data are available for vegetation barriers installed in concentrated flow zones (Dabney *et al.*, 2004; Vander Linden, 2011; Richet, Ouvry and Saunier, 2017; Kervroëdan *et al.*, 2018). Available results show that newly implemented fascines from plant residues can be very effective in altering flows of water and sediment (Richet, Ouvry and Saunier, 2017), but the effectiveness of older structures is often much lower. In the long term, densely grown hedgerows may therefore be more beneficial (

).

In a study by Frankl *et al.* (2018), the implementation of vegetation barriers in N-France did not have a significant effect on limiting ephemeral gully erosion. A major concern was that gaps could develop in the vegetation barriers, due to the deterioration of the vegetation barrier over time, soil piping or animal burrowing. In addition, a clear water effect caused incision just below the vegetation barriers that functioned well. These gaps created preferential flow paths that strongly reduced the effectiveness of structures made of fascines (

). Considering the volumes of sediment trapped behind vegetation barriers, the same study showed that out of 269 barriers, 47% functioned as a sediment trap. However, in S-Belgium, only 7% of the vegetation barriers were reported to function as a sediment trap (Degré and Bielders, 2016).

5. Gully control

5.1. Techniques and their characteristics

5.1.1. Runoff diversion

In the case of deep gullies, controlling further incision may be achieved by diverting runoff away from the headcut into a diversion or retention channel (Sheng and Liao, 1997). Flow diversion is controversial as this may cause the formation of new gullies further away (Smit *et al.*, 2017; Ben Slimane *et al.*, 2018; Martins *et al.*, 2019). However, when the runoff is diverted into a rehabilitating forest and on slopes where the risk of initiating gullies or landslides is limited, such diversions may, in addition to gully erosion control, result in several beneficial effects. These include groundwater recharge, sediment and nutrients deposition and improvement of vegetation growth (Descheemaeker *et al.* 2009, Guyassa *et al.*, 2019). These benefits are especially pertinent in semi-arid areas.

5.1.2. Gully reshaping

A way of controlling gullies is by (partly) filling them up and reshaping their banks into stable slopes. The latter may be uniformly dipping slopes for small gullies or terrace steps for large gullies. The aim is to cease the erosion processes (such as plunge pool erosion, piping and gully wall collapse) that cause headcuts and banks to retreat (Poesen, Torri and Van Walleggem, 2011). Reshaping and filling alone is, however, rarely effective. If no accompanying measures are taken, a new gully will soon incise the reshaped channel (Poesen, 1989). Therefore, filling and reshaping is usually accompanied with a protective ground cover made of a geomembrane (Poesen, 1989), synthetic or biological geotextile (Fullen *et al.*, 2011), stone rip-rap or vegetation (Ndona and Truong, 2006; de Brito Galvão *et al.*, 2011; Ayele *et al.*, 2018).

5.1.3. Check dams

Check dams are transverse structures installed in channels to control gully erosion. They can be built from various materials, including woven wire, (brush)wood, earth, loose rock, gabion (wire net structures, filled with rocks), polyethylene bags filled with soil or stone masonry, live vegetation or other materials that are locally available (such as trash, tires or even old cars). Since the 19th Century, check dams have been widely implemented in mountain torrents and rivers to stabilize degrading channels, retain sediment and regulate sediment transport (Piton *et al.*, 2017). Hydraulically, their aim is to reduce flow velocities and control runoff evacuation. As the stream power decreases, sedimentation behind check dams occurs. This transforms the long, uniform and steep length profile of the gully bed into successive, nearly horizontal steps (Ayres and Scoates, 1939; Heede, 1966; Hudson, 1987). As such, channel depth decreases, which can in turn strongly limit the expansion of gully networks through seepage erosion, plunge pool erosion, slumping or piping acting on the gully wall. Furthermore, filled gullies provide lateral support to adjacent slopes which reduces the chances of landsliding (Nyssen *et al.*, 2003). In addition, vegetation growth and survival conditions improve in the vicinity of filled check dams because of their localized effect on rising groundwater tables, the availability of nutrients and fine sediments (Frankl *et al.*, 2016; Lucas-Borja *et al.*, 2018). The application of check dams in gullies is, therefore, often done jointly with other catchment-wide soil and water conservation measures or reforestation (Heede, 1979). Furthermore, as they are mostly conceived as temporary structures that stop channel erosion, trap sediment and facilitate the growth of a permanent vegetation cover. Once these structures collapse or rot away, the established woody vegetation would control erosion (Heede,

1979; Böll *et al.*, 2009).

5.1.4. Vegetation

A key strategy to control gullies is revegetation. Detailed investigations of plant morphologies have allowed to identify favourable traits to reduce the vulnerability of soils to water erosion and shallow mass movements (Gyssels and Poesen, 2003; De Baets *et al.*, 2007; Vannoppen *et al.*, 2017). Overall, selecting species for gully erosion control are based on (i) the erosion reducing and sediment trapping capacity of plants based on above-ground (e.g. stem diameter, density and stiffness, basal branching, specific leaf area and density) as well as below-ground traits (e.g. root density, added cohesion, root network type, rooting depth) and (ii) the ability of plants to grow, survive and reproduce on gully floors and banks (depending on characteristics like the reproduction rate, establishment, drought resistance and tolerance, growth rate, etc.) (De Baets *et al.*, 2009; Farhadi *et al.*, 2018). As pointed out by Shellberg and Brooks (2013), gully banks and floors can be harsh and nutrient-poor environments, where the hydrology and soil chemical conditions may hamper vegetation growth. Given that soil conditions vary considerably between regions, several authors identified suitable species for particular environments, such as the Mediterranean (De Baets *et al.*, 2009; Burylo, Hudek and Rey, 2011; Burylo, Dutoit and Rey, 2014; Farhadi *et al.*, 2018) and Ethiopian highlands (Reubens *et al.*, 2009, 2011; Talema *et al.*, 2017; Zegeye, Langendoen, *et al.*, 2018).

Several studies demonstrated the potential of vegetation to stabilize gullies, using various stiff grass and shrub species (**Error! Reference source not found.**). In the Southern French Alps, the conditions for plant establishment, survival and trapping

efficiency have been extensively studied in experimental catchments (Rey, 2003, 2004, 2009; Rey, Isselin-Nondedeu and Bétécarrats, 2005; Burylo, Rey and Delcros, 2007; Erktan and Rey, 2013; Erktan *et al.*, 2013, 2015; Rey and Burylo, 2014; Rey and Labonne, 2015). Key is to establish a dense cover on the gully floor, so that basal flow velocity is reduced (Erktan *et al.*, 2013). Homogeneous covers (in the form of a brush or mat layer) with limited morphological diversity are more advantageous. As summarized by Erktan and Rey (2013), the morphological traits that define the sediment trapping efficiency of vegetation barriers vary with flow intensity. Canopy completeness is more important to trap sediment at low flow intensities, while resistance to flow (basal branching, stem density) becomes more important at high flow intensities.

5.2. Failure rates and factors controlling the failure or success

The failure or success of gully control measures depend on two main factors, (i) runoff and sediment characteristics of the gully system and (ii) the cross-sectional stability and micro-environment of the gully (**Error! Reference source not found.**). The former determines the flow energy that gully control measures have to withstand and can influence the life-expectancy of the applied measures. The latter sets the boundaries to the type of measures that could be applied without imminent risk of failure. Gully stabilization, therefore, requires a tailored approach. Both factors interact and are driven by a number of external forcing factors, which can be grouped into three main categories: (i) geomorphology and topography, (ii) climate (iii) and bio-physical environment (**Error! Reference source not found.**).

Understanding patterns and processes of gullying and their geomorphic context can be important to understand success and failure (Heede, 1970), but is generally

overlooked. Deep gullies (cf. permanent gullies) usually develop according to a 'cut-and-fill' cycle. Such cycle has shown to be a recurrent phenomenon in many regions, taking typically 50-100 years to be completed (Lanckriet *et al.*, 2015; Larsen *et al.*, 2013; Nachtergaele *et al.*, 2002; Porter and An, 2005; Vanwalleghem *et al.* 2005b). Similar mechanisms have been reported for 'erosion cells' in central Australia (Pickup, 1985).

The geomorphic 'cut' phase is characterised by a rapid network development and channel degradation. It is driven by the initially steep longitudinal gradient of the gully floor at the headcut, which is geomorphologically unstable (Imeson and Kwaad, 1980; Olley and Wasson, 2003; Sidorchuk, 2006; Marden, Herzig and Arnold, 2011). Gullies that are in a 'cut' phase are more likely to experience high flow shear stresses and unstable channel cross-sections. This results in conditions unfavourable for vegetation establishment. Controlling gullies in a 'cut' phase is a difficult task that may only be successful when using 'hard' engineering approaches (e.g. check dams **Error! Reference source not found.**), often at high maintenance costs.

As the longitudinal profile develops a more gentle slope (through headcut retreat and channel knickpoint migration), channel degradation slows down, and the gully evolves towards a geomorphic 'fill' phase. Aggradation of the gully bed and stabilization of banks then become the dominant processes. When channel cross-sections are stabilizing, gullies develop micro-environments suitable for vegetation establishment. During a 'fill' phase, effective measures are often easier to implement (Frankl, Poesen, Haile, *et al.*, 2013) and 'soft' engineering approaches (using vegetation, **Error! Reference source not found.**) can suffice to fix both channel bottom and banks and fasten aggradation of the gully bed (Harvey, 1992; Martín-Moreno *et al.*, 2014).

Topographic factors such as catchment area, slope gradient and gully cross-sectional shape and size exert an important control over the potential failure of gully control techniques, as they strongly influence the flow erosivity. Catchment size and slope gradient are considered good proxies of runoff volume and energy. In interaction with other driving factors, catchment size also influences the micro-environments of gullies. For example, soil moisture conditions in gullies draining small catchments may indeed be very different from those draining larger catchments, which is important for vegetation establishment and survival (See section 5.2.2.), but also for the stability of bank gullies (See section 5.2.3.).

Climate controls precipitation characteristics that have an impact on the flow volumes and velocities in gullies. Areas exposed to high rainfall intensities are likely to exhibit large peak flow discharges in gullies, making the latter hard to control. Where low temperatures prevail, snowmelt (Øygarden, 2003) or freeze-thaw cycles (Wu *et al.*, 2008; Barnes, Luffman and Nandi, 2016) can contribute to gullying. Also the micro-climatic conditions of gullies and especially gully banks also play their role, especially when vegetation is being used to control gully development (Section 5.2.2.). For example, both slope gradient and slope aspect strongly control vegetation cover and plant species diversity in dry climates (Bochet, García-Fayos and Poesen, 2009; Nadal-Romero *et al.*, 2014).

The bio-physical environment and its management largely determine the runoff mechanisms of catchments, and thus what enters the gully. Their impact on failure rates is thus mainly indirect. Degraded catchments exposing shallow and rocky slopes may produce large runoff volumes carrying coarse bedload that scours the gully channel as well as the gully control structures (See section 5.2.1.). The characteristics of soils exposed along gullies may also require specific attention. Soils which are

susceptible to soil piping may for example cause flows to bypass check dams (Section 5.2.1.).

5.2.1. Check dam failure and its prevention

As the construction of check dams requires considerable effort and investment, several authors have investigated the stability of the structures following their implementation. As sediment retention structures in (ephemeral) rivers, check dams are generally reported to remain stable, even decades after their implementation (Ran *et al.*, 2008). In mountain torrents where debris flows can occur, check dam breaching is more frequent (Cucchiaro *et al.*, 2019). For gullies, the failure of check dams is also considerable. According to this review, with data on fourteen reported cases of dam stability, a median of 24% of the implemented check dams breached after 1 to 45 years (Error! Reference source not found.). Lucas-Borja *et al.* (2018) and Nyssen *et al.* (2004), who evaluated the short-term stability of numerous check dams in, respectively, Mexico and Ethiopia found that about one third of the check dams breach within 5 years after their construction. Similar results were reported for the USA (Gellis *et al.*, 1995; Pederson, Petersen and Dierker, 2006) and China (Zeng *et al.*, 2009). Worse, Xiang-zhou *et al.* (2004) estimated that a decade after the construction of hundreds of thousands of check dams in Shanbei (China), about 80% had failed.

Failures have mainly been attributed to poor design and construction (**Table 3**) (Zeng *et al.*, 2009). However, the failure of check dams is also largely controlled by discharge characteristics and the stability of gully cross-sections. In this regard, the area draining to the gully, the channel steepness as well as the channel morphology (channel dimension, gully bed gradient) are important characteristics (Gellis *et al.*, 1995;

Nyssen *et al.*, 2004; Lucas-Borja *et al.*, 2018). In the SE USA, Pederson *et al.* (2006) identified a slope – area threshold for check dam failure (**Error! Reference source not found.**). This work showed that check dam failure was mainly controlled by slope steepness. This may be because, in the studied dryland environment, runoff discharge did not increase much with catchment area and because larger gullies mostly have larger width to depth ratios. The latter reduces basal flow shear stress, leading to less check dam failures (Pederson, Petersen and Dierker, 2006). In areas with exposed rock, abrasive flows (by coarse bed load) may erode dam crests and chute steps (Nyssen *et al.*, 2017). Where dispersive or cracking soils occur, bypassing of check dams by soil piping is a frequent reason of failure (Gellis *et al.*, 1995; Nyssen *et al.*, 2004) (**Error! Reference source not found.**).

Several studies found that installing check dams can also lead to an increased erosion (clear water effect) of the channel bed downstream of the dam (Boix-Fayos *et al.*, 2008; Polyakov *et al.*, 2014). In Spain, channel incision was observed at 81% of the surveyed check dams in the Cárcavo catchment (Castillo *et al.*, 2007).

Several strategies have been proposed to reduce the risk of check dam failure (**Error! Reference source not found.**). The most important ones rely on revegetation (Heede, 1982; Polyakov *et al.*, 2014; Lucas-Borja *et al.*, 2018). Vegetation is a key explanatory variable to understand check dams stability (Lucas-Borja *et al.*, 2018), and more generally, the overall stability of the entire gully network (Zeng *et al.*, 2009).

Given the variability of controlling factors, designing a ‘one size fits all’ check dam is hardly feasible. Therefore, several authors have explored the applicability of alternative check dam designs. For small gullies, permeable check dams made of

brushwood appear to be more stable than loose rock check dams (Pederson, Petersen and Dierker, 2006). To make check dams more resistant to abrasive flows, Nyssen *et al.* (2017) proposed boulder-faced log dams that dissipate flow energy across the channel width. Although results were promising, 37.9% of the log dams still failed after a high magnitude runoff event. In other areas, constructing check dams with downstream energy dissipation aprons proved to work very well (Polyakov *et al.*, 2014). To block subsurface flow where soil piping causes check dam failure, Frankl *et al.* (2016) inserted a geomembrane in the soil at both sides of a gabion check dam. To maintain the ecological functioning of lower reaches, Schwindt *et al.* (2018) proposed a hybrid check dam that blocks high sediment discharges but allows small flows and corresponding sediment fluxes to pass.

5.2.2. Vegetation

The establishment of vegetation in gullies is usually preceded by channel reshaping or the installation of check dams to stabilize the eroding channels (**Error! Reference source not found.**). When check dams are used, favourable (i.e. moist and nutrient-rich) conditions are created to foster vegetation establishment and growth (Reubens *et al.*, 2009; Nichols, McReynolds and Reed, 2012). Vegetation, in return, can fix the morphology of the engineered channel and increase sediment trapping efficiency (Thompson and Luckman, 1993; Stokes *et al.*, 2014; Ehrensperger *et al.*, 2015; Lira-Caballero *et al.*, 2018; Rey *et al.*, 2019). In addition, as check dams reduce gully depth through sediment deposition, they also reduce the risk of undercutting the root-reinforced soil horizons. Such undercutting processes can be frequently observed where gullies obtain large depths (Archibold *et al.*, 2003). As such, check dams can also increase the effectiveness of measure taken on gully banks.

The application of vegetation is especially useful when the absence of nearby vegetation (on the gully banks) limits the possibility of natural colonization of the gully floor. Establishment and survival is also influenced by topographic, (micro-)climatic and pedological conditions.

Another key element is of course that the applied vegetation can resist the concentrated flow shear stresses that may develop during strong runoff events. Often, flash food regimes in large gullies hamper seedling establishment and survival (Reubens et al., 2009). Plant cuttings (e.g. of willow or jatropha) may therefore be more appropriate for early vegetation establishment in gullies (Hooke and Sandercock, 2012; Reubens et al. 2011a, Rey, 2009). Alternatively, planting stiff grass hedges has also been proposed (Dabney et al., 2004).

The gully cross-sectional shape can also be significantly affect the potential for revegetation. For example, Marden et al. (2011) report that the establishment of vegetation is easier in gullies with large top width to depth ratios because such gullies are more easily accessed by practitioners. In other socio-economic contexts, with high grazing pressures or firewood needs, the opposite may be true, and vegetation may establish more easily in steep, deep and inaccessible gullies (Frankl et al., 2019).

Slope aspect can also play an important role. For instance, in semi-arid conditions, south-facing slopes are generally drier, have a higher water stress and are, therefore, less favourable for vegetation establishment (Bochet et al. 2009, Rey and Burylo, 2014). However, under more humid and cold badland conditions, north-facing slopes may have poorer plant growth conditions than south-facing ones (Nadal-Romero et al., 2014).

After initial establishment, the effects of vegetation on soil water retention, aggregate stability, soil organic matter and nutrient content as well as on sheltering and

microclimatic conditions may further facilitate natural colonization (Carlson and Olyphant, 1996; Reubens *et al.*, 2009; Zhang, Xu and Wang, 2009; Xu *et al.*, 2014; Erktan *et al.*, 2015; Rey and Labonne, 2015).

Reported survival rates of vegetation applied in a bioengineering structure range from 0 to 100%. For example, from studying 336 bioengineering structures applied in the Southern French Alps, Rey and Labonne (2015) noted a survival rate of 45% after 3-4 years (**Error! Reference source not found.A**). Plant survival was mainly correlated to the presence of vegetation on gully banks (which improved micro-climatical and pedological conditions). The studied gullies had contributing catchments areas of less than 1 ha, so large flood events did not negatively affect plant survival. Nonetheless, when contributing areas became too small (<0.1 ha) this had a negative impact on plant survival rates. Gullies with such small catchments typically have dryer gully floors and thus present a harsher environment where plant survival may drop to 0% (Rey and Burylo, 2014) (**Error! Reference source not found.B**).

5.2.3. The case of valley-bottom gullies

Valley-bottom gullies are a subject of great concern for land managers and scientists, who observe that rehabilitation attempts for such gullies often fail or even have aggravating effects. The issue has been recently raised in subhumid NW Ethiopia, where intensive soil and water conservation activities are not paying off in terms of gully stabilization (Zegeye *et al.*, 2016; Dagnaw *et al.*, 2017; Addisie *et al.*, 2018; Zegeye, Dessalegn, *et al.*, 2018; Mhiret *et al.*, 2020). This has been related to the adaptation of methods developed for the largely semi-arid NE-part of Ethiopia (Tebebu *et al.*, 2010). In this dryer area, the focus has been on improving soil infiltration (as Horton overland flow dominates). Adopting a similar strategy in subhumid areas could

accelerate gully erosion instead of reducing it. The problem of valley-bottom gullying is, however, not restricted to NW Ethiopia, but has been reported for other areas as well: e.g. S Africa (Boardman, Parsons and Holland, 2003), N and SE Australia (Prosser and Slade, 1994; Brooks *et al.*, 2009), Europe (Vandekerckhove *et al.*, 2000; Poesen *et al.*, 2006), SW USA (Miller, 2017).

The particularity of valley-bottom gullies is that they act as efficient groundwater drains. Consequent seepage erosion can undercut gully banks, making them very susceptible to slumping (Desmyttere, 2004; Brooks *et al.*, 2009; Mhiret *et al.*, 2020). Furthermore, clay soils often prevail in valley bottoms. When these clays are dispersive, they can be very prone to soil piping, which in turns aggravates gullying and complicates stabilization (Imeson and Kwaad, 1980; Ding *et al.*, 2017; Bernatek-Jakiel and Poesen, 2018). Controlling valley-bottom gullying through the use of check dams may thus prove to be difficult, unless potential risks of bypass flow are addressed (Frankl *et al.*, 2016).

Often, the loss of vegetation on valley floors (e.g. due to increased grazing pressure) has played a key role in increasing the sensitivity to gully development (Boardman *et al.*, 2017; Miller, 2017; Wilkinson *et al.*, 2018). For example, Prosser and Slade (1994) indicated that critical flow shear stresses for scour in valley floors reduced with a factor 4 to 11, following 19th Century vegetation degradation in SE Australia.

Given the role of (lack of) vegetation, several authors also point to vegetation as a key solution to address gully erosion in valley bottoms (Miller, Lord and Germanoski, 2011; Ayele *et al.*, 2016; Shellberg *et al.*, 2016; Frankl *et al.*, 2019). Reducing grazing pressures (by fencing) and allowing natural vegetation regrowth may be a first approach, but must be applied in both the gullies as well as their upslope contributing areas (Shellberg and Brooks, 2013). As indicated by Frankl *et al.* (2019), indigenous

knowledge systems in Ethiopia in the past may have already incorporated such strategies to control erosion in thalwegs, as they appear as dense vegetation corridors on 1930-40s aerial photographs. A key requirement, however, is to apply vegetation that develops dense and resistant stems and roots (increasing soil cohesion; De Baets *et al.* 2007). In particular shrubs and grasses are typically suited for this (Shellberg and Brooks, 2013). It is equally important to create homogeneous vegetation covers across the valley floor that is susceptible to gully erosion. This is well demonstrated by Grellier *et al.* (2012), who noticed that the transformation of a grassland into a savanna with sparse woody vegetation patches increased gully erosion. By draining valley bottoms using Willows (Miller, Lord and Germanoski, 2011) or Eucalyptus (Mhired *et al.*, 2020), groundwater levels can be lowered and consequently reduce the susceptibility of gully banks to slumping.

5.3. Impact on gully development

5.3.1. Headcut retreat and network development

One of the most visible impacts of gully control is the effect it has on channel network development. Direct measurements of headcut retreat rates following stabilization are, however, rare. This is because, on the one hand, most studies on headcut retreat mainly focus on rapidly expanding channels (Vandekerckhove *et al.* 2001, Frankl *et al.* 2012, Vanmaercke *et al.*, 2016). On the other hand, poor results associated with headcut stabilization are rarely reported.

Nevertheless, runoff reduction in the catchment upstream of the gully head has proven to strongly reduce headcut retreat in areas without intense precipitation (He *et al.*, 2010) or even render gully heads inactive (Oostwoud Wijdenes *et al.* 2000).

Likewise, several experiments with headcut reshaping, filling and strengthening demonstrate that such an approach can yield good results with gully erosion often stopping immediately and permanently (Heede, 1979; Ayele *et al.*, 2018). However, when the filling is done by plugging loose rock or other inert material into the channel, intense erosion at the contact between the plug and the soil can cause further headcut retreat, making the effort ineffective (Poesen, 1989). As reported by the latter, this may be solved by intercepting the overland flow upslope of the headcut with a geomembrane (polyethylene sheet) and transferring the flow over the plug some distance downslope. Plugging by cornstalk mulching has also shown to yield positive results on small gullies in laboratory experiments (Xu *et al.*, 2015). Similarly, Higaki *et al.* (2005) found that the rate of gully head retreat reduced by 14-73% after planting bamboo or Napier grass.

While localized morphological changes can often be directly related to stabilization measures, assessing the overall effect of measures on gully network development is overall much harder. Gully channel stabilization measures that prevent gully network expansion are generally applied in combination with the application of soil and water conservation measures within the catchment. As a result, the relative contribution of both to gully rehabilitation often remains unclear (Frankl *et al.*, 2011; Ehrensperger *et al.*, 2015; Guyassa *et al.*, 2018). In addition, gully network development also depends on the geomorphic context and its long term development. The examples presented here, therefore, have to be carefully interpreted (**Error! Reference source not found.**).

5.3.2. Gully aggradation and morphology

The most direct impact of gully control measures, and in particular check dams, is gully aggradation through trapping sediment in the channel. As such, they also reduce

sediment connectivity within catchments. We identified 14 studies that reported sediment deposition by check dams (**Table 2**). The median aggradation rate was 1.36 Mg yr⁻¹ per check dam. In very large gullies, aggradation rates behind newly built check dams may reach short-term maxima of up to 662.5 Mg yr⁻¹ per check dam (Ayele *et al.*, 2016). Check dams indeed typically fill in rapidly after their installation and show lower sedimentation rates later on (Polyakov *et al.*, 2014). Nonetheless, their effect may be prolonged. In Spain, for example, large check dams (lengths 10-20 m) acted as significant sediment traps up to 30 years after their implementation (Quiñonero-Rubio *et al.*, 2016).

When check dams are conceived as a bioengineering structure (e.g. Figure 4A), mean gully aggradation rates reached 4.0±2.2 cm yr⁻¹ per dam (or 0.21±0.08 m³ yr⁻¹ per dam) in small gullies in the French Alps (Rey, 2009; Rey and Burylo, 2014; Rey *et al.*, 2019). Reported channel floor aggradation rates when using only vegetation were 0.03±0.01 m³ yr⁻¹ per meter of gully length in the Andes (Molina *et al.*, 2009) and 0.03 to 0.10 m yr⁻¹ in Belgium (Vanwalleggem *et al.*, 2005). Studies in New Zealand show that reforestation of gullies can effectively stabilize gully channels (Thompson and Luckman, 1993; Marden, Herzig and Arnold, 2011).

As gullies fill in, the cross-sectional shape and longitudinal gradient of the channel are also affected. Top width to depth ratios of cross sections generally increase (Frankl, Poesen, Scholiers, *et al.*, 2013). Gully widening may also occur by the collapse of undercut gully banks. Where steep gully banks have been fixed by vegetation, they can remain 'inactive' channels for many years (Frankl *et al.*, 2011).

Studies report that, upon revegetation, longitudinal gully bed slopes can decrease by 2 to 36% (Polyakov *et al.*, 2014; Borja *et al.*, 2018; Mongil-Manso *et al.*, 2019). This, in combination with sediment infilling, can improve infiltration and aquifer recharge. It

also reduces hydrological and sediment connectivity, runoff discharge as well as velocity and energy (Frankl, Poesen, Haile, *et al.*, 2013; Guyassa *et al.*, 2017; Borja *et al.*, 2018; Mongil-Manso *et al.*, 2019). This can lead to further sediment deposition on gully floors.

5.3.3. Catchment sediment yield

As check dams are designed to be sediment sinks and can trap significant volumes of sediment, their impact of catchment sediment yield has also been studied. Overall, our data compilation indicated that check dams can reduce catchment sediment yield by 0.1 to 203.8 Mg ha⁻¹ yr.⁻¹ (median 6.05 Mg ha⁻¹ yr.⁻¹, n=23), which represent a considerable reduction in sediment export by 20 to 98% (**Error! Reference source not found.**). As check dams mainly induce sediment deposition shortly after their installation (Ayele *et al.*, 2016), a decrease of their effectiveness over time may be expected. A reduction of catchment sediment yield is especially observed for the smaller catchments reported in **Error! Reference source not found.**. However, when peak flow events cause check dam failures, the rapid release of stored sediments can result in unprecedented sediment yield peaks from 'restored' catchments (Pederson, Petersen and Dierker, 2006). Also bioengineering works applied in small gullies found in eroding catchments have proven to be often very efficient. For example, when bioengineering works result in a gully floor vegetation cover of 20-33%, catchment sediment yields reduced to nearly zero (Rey, 2003, 2009).

6. Conclusions

Once a gully forms, its stabilization is a difficult and often a lengthy process. Preventive action is therefore suggested (Kirkby and Bracken, 2009). Several prevention

strategies exist and especially those for cropland and ephemeral gullying have been considered in this paper (e.g. vegetation barriers). Although some measures as improving topsoil resistance have demonstrated positive effects, reducing gullying from vegetation barriers is not straightforward. Once a deep (permanent) gully is formed, the cost of doing nothing is high, both in terms of local environmental degradation and downstream impacts. Controlling already developed gullies relies on both 'hard' and 'soft' engineering techniques which consist runoff diversion, gully reshaping and/or reinforcing, implementing check dams and/or growing vegetation. Their applicability and failure rates depend on two main factors, i.e. the (i) runoff and sediment characteristics and (ii) cross-sectional stability and micro-environment of the gully. Both are driven by a number of external forcing factors that can be grouped in three categories (i) geomorphology and topography, (ii) climate (iii) and bio-physical environment. As check dams are conceived as temporary structures, the establishment of vegetation is often the best long-term strategy to secure the channel from degradation. This is especially true since failures rates of check dams are high; based on 14 studies we concluded that a median of 24% of the implemented check dams breached after 1 to 45 years. Vegetation can improve the failure rate but needs to be adapted to harsh and unstable gully environments (such the co-design approach of bioengineering check dams). Vegetation also plays an important role in treating valley-bottom gullies. Gully control measures showed positive effects on network development, gully aggradation and morphology and sediment yield. Check dams caused a median gully aggradation rate of 1.36 Mg yr^{-1} per check dam for 14 studies and sediment yield reduced by a median of $6.05 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ following check dam implementation ($n = 23$). In the long term, natural revegetation can transform gullies into linear oases that become biodiversity and carbon sequestration hotspots.

Conflict of Interest: None.

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Table 1: Common types of vegetation barriers to prevent gully development and their characteristics

Type	Material	Fixation	Impact and life-expectancy	Examples
Bales of plant residues	Straw, coconut	Not fixed or by using posts (and mesh wire)	Short term impact is high; Life-expectancy is short (ca. 2 years)	(Morgan, 2005; Degré and Bièlders, 2016)
Filter socks	Compost (+ shrub seeds) in a tubular mesh	Not fixed or by using posts	Short term impact is high; Life-expectancy is short (ca. 2 years)	(NRCS, 2011)
Wood chip barriers	Chipped branches and roots	Filled in-between mesh wire fences, fixed by posts	Short term impact is high; Life-expectancy is medium (ca. 4 years) but may be extended when replenished frequently	(LNE, 2015)
Fascines of plant residues	Bundles of brushwood cuttings (fagots)	In-between posts	Short term impact is high; Life-expectancy is medium (ca. 4 years)	(Dégré and Bièlders, 2016; Frankl <i>et al.</i> , 2018)
Narrow stiff grass hedges	Grasses	Rooting	Short term impact is high; Life-expectancy is long, depending on survival and maintenance	(Ritchie, Kemper and Englert, 1997; Cao <i>et al.</i> , 2015)
Fascines of live vegetation	Bundles of brushwood cuttings (fagots)	In-between rooting plant stakes	Short term impact is high; Life-expectancy is long as the growth and branching of the live vegetation functionally replaces the fagots (after ca. 4 years)	(Richet, Ouvry and Saunier, 2017; Frankl <i>et al.</i> , 2018)
Herbaceous hedges	Shrubs	Rooting shrubs	Short term impact is low (can take 10 years to be functional); Life-expectancy is long	(Richet, Ouvry and Saunier, 2017)

Table 2: Common plant species reported in case studies used for gully control works in the eroding channels

Bioclimate	Plants species	Reference
Mediterranean	<i>Lygeum spartum</i> Loeft. ex L.(esparto grass)	Hooke and Sandercock (2012)
Mediterranean (mountainous)	<i>Salix alba</i> L. (willow)	Burylo <i>et al.</i> (2007), Erktan and Rey (2013), Erktan <i>et al.</i> (2013), Rey and Labonne (2015), Rey and Burylo (2014)
Subtropical	<i>Acacia etbaica</i> Schweinf. (acacia)	Reubens <i>et al.</i> , (2009)
Subtropical	<i>Dodonaea angustifolia</i> L.f. (sand olive)	Reubens <i>et al.</i> (2009)
Subtropical	<i>Guadua angustifolia</i> Kunth (guadua bamboo)	Calle <i>et al.</i> (2013)
Subtropical	<i>Jatropha curcas</i> L.(Jatropha)	Ehrensperger <i>et al.</i> (2015)
Subtropical	<i>Pennisetum purpureum</i> Schumacher. 1827 (elephant grass)	Addisie <i>et al.</i> (2018), Ayele <i>et al.</i> (2016)
Subtropical	<i>Sesbania sesban</i> (L.) Merr. (river hemp)	Addisie <i>et al.</i> (2018); Ayele <i>et al.</i> ,(2016); Reubens <i>et al.</i> , (2009)
Subtropical, tropical	<i>Chrysopogon zizanioides</i> L. (Vetiver grass)	Addisie <i>et al.</i> (2018); Ndona and Truong (2006)
Warm temperate	<i>Dodonaea viscosa</i> Jacq. (jarilla)	Marden <i>et al.</i> (2011)
Warm temperate	<i>Erythrina americana</i> Mill (colorin)	Lira-Caballero <i>et al.</i> (2018)
Warm temperate	<i>Panicum virgatum</i> L. (switchgrass)	Dabney <i>et al.</i> (2004)

Table 3: Gully control by check dams and its effectiveness

	Country	Location (catchm.)	Cath. area (ha)	# Check dams	Gully width (m)*	Implement -ed since	Monitoring interval (yr.)	Breach -ed (%)	Total sediment retent. per check dam (Mg)*	Annual sediment retent. per check dam (Mg yr ⁻¹)	Catchment sediment yield reduct. (Mg ha ⁻¹ yr ⁻¹)	Reference
Africa	Ethiopia	Amhara (Ene-Chilala)	26	4	3	2013	2	0.0	5300.00	662.50	203.8	<i>Ayele et al. (2016)</i>
	Ethiopia	Tigray	ca. 200	29	4.6	2014	1	37.9	x	x	x	<i>Nyssen et al. (2017)</i>
	Ethiopia	Tigray (Geba)	647	400	5	1998	2	39.0	x	x	x	<i>Nyssen et al. (2004)</i>
America	Ecuador	Cuenca (Loreto)	0.42	12	1.5	2011	1	x	2.85	2.85	81.5 (-77%)	<i>Borja et al. (2018)</i>
	Ecuador	Cuenca (Loreto)	2.4	35	1.5	2011	1	x	16.90	16.90	15.7 (-86%)	<i>Borja et al. (2018)</i>
	Mexico	Sinaloa (Culiacan)	x	273	6.5	2011	3-5	27.1	32.04	8.01	x	<i>Lucas-Borja et al. (2018)</i>
	Mexico	Sierra Madre del Sur	x	x	small	2015	x	x	x	x	4.1 (-39%)	<i>Lira-Caballero et al. (2018)</i>
	USA	Arizona	4	27	ca. 1 - 3	2008	5	3.7	2.75	0.92	6.2 (-48%)	<i>Polyakov et al. (2014)</i>

Asia	USA	Arizona	3.1	10	ca. 1 - 3	2008	5	0.0	0.11	0.04	0.1 (-82%)	<i>Polyakov et al. (2014)</i>
	USA	Arizona (Colorado)	769	2000	x	1983	3	0	0.32	0.11	0.3 (-50%)	<i>Norman and Niraula (2016)</i>
	USA	Arizona (Colorado)	x	116	x	1980s	1	45	x	x	x	<i>Pederson et al. (2006)</i>
	USA	Colorado (Alkali Creek)	260	132	x	1963	7-11	x	2694.90	2.27	sediment load -92%	<i>Heede et al. (1979)</i>
	USA	Mississippi (Topashaw)	3700	x	x	1985	x	x	x	x	0.1 - 11.5	<i>Wilson et al. (2008)</i>
	USA	New Mexico (Rio Nutria)	?	70	?	1930s	ca. 60	35.4	x	x	x	<i>Gellis et al. (1995)</i>
	China	Yunnan (Mengqian)	1480	117	1	1965-67	8	100	x	x	x	<i>Zeng et al. (2009)</i>
	China	Yunnan (Mengqian)	1320	44	1	1979-82	2-5	29.5	x	x	x	<i>Zeng et al. (2009)</i>
	India	Shiwalik	?	?	?	2000	6	?	?	?	3.04 (-20%)	<i>Sran et al. (2012)</i>
Europe	France	Southern French Alps (Saignon)	40	101	x	2002	3	x	0.08-0.18**	0.22-2.5**	x	<i>Rey and Burylo (2014)</i>
	France	Southern French Alps	x	x	x	x	1	x	0.276-0.42**	0.28-0.42**	x	<i>Rey 2005 in Rey (2009)</i>
	France	Southern French Alps (Saignon)		29	1.2	2002	0.5	x	0.072	x	x	<i>Rey et al. (2005)</i>

Greece	Cassandra (Chanioti and N. Skioni)	953	x	small	2006	1.5	5.9	x	x	sediment load -11 to 25%	<i>Aristeidis and Vasiliki (2015)</i>
Spain	Almeria (Betic Cordillera)	2890	36	x	1960s	16-39	x	x	x	10.1 (-72%)	<i>Bellin et al. (2011)</i>
Spain	Ávila (Tórtolos)	ca. 200	113	11	1966	48	x	65.65	1.37	5.6 (-91%)	<i>Díaz-Gutiérrez et al. (2019)</i>
Spain	Palencia (Saldaña)	ca. 37.5	25	9.3	1930s	ca. 80	x	x	x	10.9 (-91%)	<i>Ramos-Díez et al. (2016)</i>
Spain	Ávila (Tórtolos)	ca. 200	25	14	1966	48	x	x	x	9 (-98%)	<i>Ramos-Díez et al. (2016)</i>
Spain	Ávila (Corneja)	428	30	11	1960s	ca. 53	x	x	x	5.9 (-92%)	<i>Mongil-Manso et al. (2019)</i>
Spain	Iberian Range (Ribagorda)	9.23	3	20.7	2008	6	x	1266.67	211.11	114	<i>Martín-Moreno et al. (2014)</i>
Spain	Murcia (Cárcavo)	2732	36	13.6	1970-80s	35-45	5.6	34.33	0.86	0.01	<i>Castillo et al. (2007)</i>
Spain	Murcia/Albacete (Taibilla)	32000	120	large	1973	27	22	16.37	0.61	3.3 (-30%)	<i>Quiñonero-Rubio et al. (2016)</i>
							n=	14	15	14	23
							median=	24.39	16.37	1.36	6.05

* When reported in m³, an average bulk density was used for conversion.

** Average used from range for median calculation

Table 4: Check dam failure and its solution (references and explanation see text)

Key reasons of check dam failures

- Inappropriate design
- Poor construction and/or implementation
- Excessive height (unstable, plunge pool erosion)
- Steep gully bed slope (high flow energy)
- Dam abrasion by sediment-laden runoff
- Bypass flow (due to soil piping)
- Catchment area increasing runoff volume
- Gully is in a 'cut' phase

Main solutions to improve the sustainability of check dams

Adjust design

- More permeable structures using brushwood, loose rocks, etc. (Pederson, Petersen and Dierker, 2006; Schwindt *et al.*, 2018; Nichols and Polyakov, 2019);
- Structures dissipating runoff energy such as log dams (Böll *et al.*, 2009; Aristeidis and Vasiliki, 2015; Nyssen *et al.*, 2017);
- Structures which intercept subsurface flow when soil piping may cause dam bypass flow (Frankl *et al.*, 2016);
- Structures more resistant to abrasive flows (boulder-faced) (Nyssen *et al.*, 2017).

Use vegetation

- As a bioengineering structure in which vegetation is an integral part of the check dam, and thus part of the rehabilitation strategy (Rey, 2004, 2018);
- To stabilize the gully in-between check dams, in combination with additional measures such as channel reshaping and protection against, for example, gazing (Reubens *et al.*, 2009);
- To stabilize the gully head, in combination with additional measures such as flow diversion (in a forest) or head reshaping (into cropland) and applying a protective ground cover (Poesen, 1989; Sheng and Liao, 1997; Addisie *et al.*, 2018).

Table 5: Case studies that demonstrate the positive effects of control measures on gully network development.

Country	Reduction in gully length	Time span	Comments	Reference
New Zealand	42%	10-30 years	mainly for gullies less than 5 m deep	Thompson and Luckman (1993)
N Ethiopia	25%	ca. 20 years	mainly effective on first-order reaches	Frankl <i>et al.</i> (2013)
Tunisia	9%	52 years	compared to a marked increase of gully length by 66% in untreated zones	(Rebai, Raclot and Ouezdou (2013)

Gully prevention and control technique: 1. Soil and water conservation (soil bund in cropland), 2. Land use change (from cropland to forest), 3. Topsoil resistance in concentrated flow zone (grassed waterway), 4. Vegetation barrier at recurrent ephemeral gully site (fascine made of live vegetation), 5. Runoff diversion into forest, 6. Gully reshaping and filling, 7. Gully channel vegetation, 8. Brushwood check dams, 9. Bioengineered check dams (log dam + live vegetation), 10. Log dams, 11. Loose rock / gabion check dam (showing channel aggradation), 12. Subsurface geomembrane dam to block bypassing of check dams caused by soil mining

Figure 1: Overview of gully prevention and control techniques discussed in this paper.

Figure 2: Examples of vegetation barriers made of plant residues, A: straw bale (Belgium), B: filter socket (U.K.), C: woodchip (Belgium), D: fascine made of plant residues (France), and made of life vegetation, E: live fascine (France), F: hedgerow (France). Photographs A, C-F © A. Frankl, B © SteelNation.com.

Figure 3: Effectiveness of vegetation barriers in controlling ephemeral gully erosion
(modified from Ouvry et al., 2012)

Figure 4: Examples of gully rehabilitation methods combining check dams and vegetation. A: Bioengineered check dams made of woods logs that dissipate the flow energy across the channel width, and planted with a brush layer of *Salix alba* L. (willow) cuttings, B: Loose rock check dam which facilitates spontaneous bush growth (Ethiopia). C: Loose rock check dam, reinforced with Aloe plants, in gully channel cut in vertisol (Ethiopia). (A: © <https://blogs.egu.eu/>, B: © A. Frankl. C: ©J. Poesen).

Figure 5: Factors controlling success or failure rates of gully control and their driving forces.

Gully 'cut-and-fill' cycle:

Cut —————> Fill

Degradation

Degradation/Aggradation

Aggradation

Success rate and value for money of control measures:

Low —————> High

Check dams ('hard' engineering)

Vegetation ('soft' engineering)

Figure 6: Illustration of the relationship between gully channel development and the application of gully control measures

Figure 7: Slope – area threshold for check dams (ECS, erosion control structures) developed for a dryland environment (Grand Canyon) in the USA. Reprinted from Pederson et al. (2006).

Figure 8: Dispersive soils are a main reason for check dam failure. The check dam allowed the establishment of *Nicotiana glauca* shrubs (a woody weed) on the gully bank, but because the flow bypassed the gabions at a Vertisol lens, the gully re-incised. The gully banks are now steep and undercut, ready to collapse. (Ethiopia, © A. Frankl).

Figure 9: Willow cuttings survival rates at bioengineering works in the Southern French Alps. For A and B, cuttings are applied as brush layers (BL) (+ brush mat BLM) on wooden sills (see figure Figure 7B). In both cases, survival rates stabilize from the third year onwards. In B, the gully catchment size (S= small, M = moderate, L = large), negatively affects survival rates. A: reprinted from Rey and Labonne (Rey and Labonne, 2015), B: reprinted from Rey and Burylo (2014)