7.6 Gully erosion

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State of knowledge of the "Gully erosion" attribute: between Medium / unresolved and Good / established but incomplete

Medium-good state of knowledge because we understand the process, there are some studies, and there is agreement on what gullies are, how they are treated, and the effectiveness of treatment. But there is limited to no spatial coverage of either gully location or 'areas' of gully erosion (other than general noted presence within a polygon in the NZLRI) which limits this as a national attribute.

In practical terms the 'gully erosion protection' attribute would aim to reduce gully erosion from the processes that contribute to its development or enlargement. This would require councils to define areas where gullies and/or gully erosion exists or has a high likelihood of developing. Councils would then plan and monitor relevant mitigation towards reducing the activity or severity of erosion within a gully, or the prevention of gullies developing or enlarging.

Part A—Attribute and method

A1. How does the attribute relate to ecological integrity or human health?

Soil erosion is a wide-spread and long-standing issue in New Zealand (Basher 2013; and many others). Gully erosion (including tunnel gully erosion) is not as ubiquitous as some other erosion processes in many regions of New Zealand, though it is significant in some, e.g., East Coast, Manawatu-Wanganui, Taupoūhō, Marlborough, Banks Peninsula (Basher 2013) (See Figure 1). Gully erosion is caused by runoff and seepage from rainfall and storms and is thus 'episodic'. The activity and severity of erosion within gullies is generally related to the intensity and duration of rainfall as is their initial development, though land disturbance is also important. Gullies are usually local features in the landscape and may be restricted in terms of size, severity and spatial extent (Basher 2013; Marden et al., 2017).

The protection of land with existing gully erosion and/or land in which gullies are likely to develop is largely achieved with vegetation and runoff controls. It, like other erosion process control, benefits the ecological integrity of waterbodies by reducing sediment generation and transport (Frankl et al., 2021).

Gully erosion, like other erosion processes, also affects ecological integrity through reducing soil depth and integrity at source locations (reduction of soils fertility, decreases in water-holding capacity, and decline in ecosystem function) resulting in making land more challenging to manage (Rosser & Ross 2011; Walsh et al., 2021). Gully erosion, like other erosion, can have adverse effects on the environment, including habitat destruction, loss of biodiversity, and degradation of water quality (Larned et al., 2019). Sediment runoff from erosion, including gully erosion, can smother aquatic habitats, disrupt stream ecosystems, and contribute to algal blooms in water bodies (Ryan 1991). It can affect human health indirectly via mental well-being, being a recurring and permanent feature in the landscape that can impact farming and some infrastructure. Knowledge and understanding of these impacts are not well correlated other than in a general sense with erosion and sedimentation and their impacts on freshwater and marine ecosystems (e.g., Cavanagh et al., 2014).

A2. What is the evidence of impact on (a) ecological integrity or (b) human health? What is the spatial extent and magnitude of degradation?

A gully is a landform created by running water, mass movement, or commonly a combination of both eroding into soil or other relatively erodible material, typically on a hillside or in river floodplains or terraces (e.g., Poesen et al., 1998; Day & Shepherd 2019).

Gully erosion is predominantly driven by fluvial processes, i.e., removal of material by channelised running water. Sheet or surface erosion may lead to rills which in turn may develop into gullies. Tunnel gullies are a special form in which subsurface flow or piping leads to collapse at the surface. Gullies may be small linear features of a few 10s of square metres up to large 'amphitheatre-like' 'badass' gullies of 10s of hectares (Marden et al., 2017).

Gullies are characterised by a distinct headscarp or headwall, generally have steep sides, and tend to enlarge headward or upstream rather than laterally.

Gully erosion is a significant issue in New Zealand affecting both rural and urban areas and is but one of a suite of erosion processes (Figure 1). It is more common in some regions than others, e.g., in the soft rock hill country of the East Coast North Island, on crushed argillite and mudstone, and in the North and South Island mountainlands (Basher 2013). Human activities such as deforestation, agriculture, urbanization, and improper land management practices can exacerbate erosion, including gully erosion, by increasing surface runoff and soil disturbance (Dotterweich 2013; Stats NZ 2018)

Gullies are landscape features resulting from erosion. Geology (including rock type and faulting and fracturing), steepness, vegetation cover, historical and current land use, and the exposure to rainfall may determine where a gully is formed and how big it becomes (Basher 2013). Gully erosion is often combined with other erosion processes in reference to erosion, i.e., the term 'erosion' is generally used as an umbrella term to describe multiple erosion processes. The evidence is strong that gullies, as but one of several erosion processes, through the production of sediment impacts ecological integrity (Larned et al. 2019). The evidence is also strong regarding how to treat them, though effectiveness is largely qualitative and anecdotal (Phillips et al., 2020).

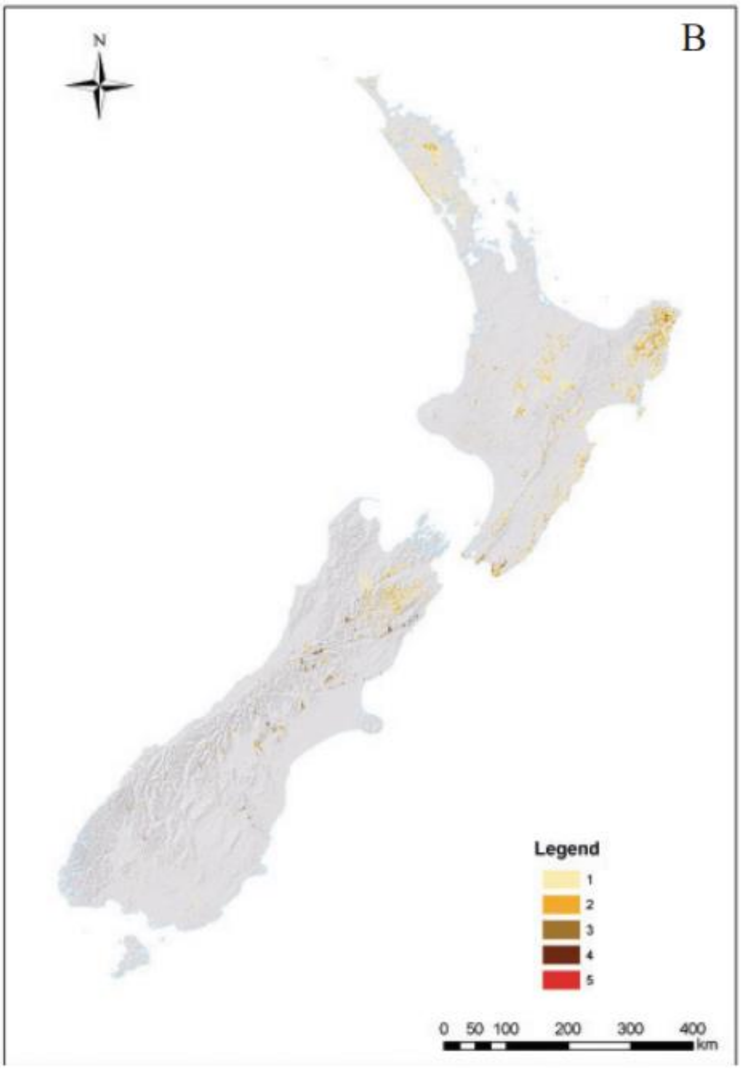

Figure 1. Distribution and severity of gully erosion in New Zealand derived from the New Zealand Land Resource Inventory (from Basher 2013). The lighter colours represent lower severity.

Mapping (on the ground, aerial photography or remote sensing) is used to identify gullies in the landscape. These may be mapped in terms of spatial extent, counted and their activity/severity assessed. There is no national nor regional inventories of gullies. Land in which gullying is present and/or has a high potential to develop will be recorded in the Land Use Inventory underpinning the national Land Use Capability mapping (Lynn et al., 2021) (see Figure 1). Gully inventories developed as part of science projects exist for some places like the Gisborne-East Coast region (Michael Marden pers. comm), though these are not publicly accessible.

Techniques such as soil conservation planting, afforestation, and retirement/reversion or other effective land management techniques are used to reduce or limit gully erosion (Basher 2013; Thompson & Luckman 1993; Phillips et al., 2008). Structural measures to lessen scouring such as drop structures, debris dams, rock chutes and some vegetative techniques can also be used.

Gullies can be assessed by number, size, severity, likelihood of stabilisation, and types of land prone to gullying.

A3. What has been the pace and trajectory of change in this attribute, and what do we expect in the future 10 - 30 years under the status quo? Are impacts reversible or irreversible (within a generation)?

In some localities and regions, gully erosion has reduced in the last 50 years as steep pasture covered slopes have been treated with soil conservation plantings, allowed to revert, or afforested (Marden et al., 2011; 2014). In other areas the opposite has occurred as new gullies have developed, and others have enlarged (Marden et al., 2017). Apart from local knowledge, there is unlikely to be any quantitative data on the pace and trajectory of change in this attribute.

Climate change projections suggest increasing storminess in many regions indicating a concomitant increase in erosion is likely. How this will preference gully erosion over other erosion processes is unknown. As rainfall is a key driver of gullying, gully erosion, where it exists, is likely to increase with increases in rainfall (Basher et al., 2020; Neverman et al., 2023).

Impacts are only partially or temporarily reversible. In short timescales (years to decades), closed canopy woody vegetation will reduce and "shut down" some gullies as will treatment with soil conservation (Marden et al., 2014; 2017). At decadal to century timescales and in the most severe rain events (e.g., cyclones like Gabrielle, Bola, etc) geomorphic thresholds are crossed and new gullies will be initiated, existing gullies may be enlarged, and old 'stable' gullies may be re-activated including those under a woody vegetation cover (Marden et al., 2017).

A4-(i) What monitoring is currently done and how is it reported? (e.g., is there a standard, and how consistently is it used, who is monitoring for what purpose)? Is there a consensus on the most appropriate measurement method?

This attribute (*sensu stricto*) is not routinely monitored either nationally or regionally. In regions where it might be monitored, it is usually combined with other erosion processes such as 'highly erodible land', 'erosion susceptibility' or other proxies such as 'bare land'.

Gullies have been mapped in the Gisborne-East Coast region (Marden pers. comm) and recently re-mapped post Cyclone Gabrielle (for MPI). However, this is not monitoring *per se* but two snapshots in time of gully distribution in this region.

Where it could be monitored, the metric would be the number of gullies or the spatial extent of gullies (area). In terms of treatment monitoring, it would be the number of gullies whose activity status changed from active to inactive, or a spatial measure of land with or prone to gullying being treated. Frequency of monitoring less than 5 yearly would not be warranted as the changes are time dependent.

There is no consistent methodology in use and no nationally agreed monitoring methodology. Some Councils assess 'bare ground', or the proportion of LUC classes that have changing vegetation coverage, or similar approaches as part of SOE monitoring. Others may report how much is invested annually in soil conservation programmes, or poles planted, or the number of farm plans +/- works, etc. None of these approaches are focused <u>specifically</u> on gullies or land susceptible to gully erosion.

A4-(ii) Are there any implementation issues such as accessing privately owned land to collect repeat samples for regulatory informing purposes?

There do not appear to be any major impediments or implementation issues for this attribute. While there is no consistent approach to assessment of gullies, gully erosion, and gully erosion mitigation, remote sensing is likely to be the most suitable and cost-effective method for determining gully numbers, land susceptible to gully processes, or treated areas relative to a baseline state. As the baseline state does not exist, it is somewhat moot.

There is unlikely to be issues accessing private land unless there was a requirement for validation of remote-sensed information. Many remote sensing tools can provide resolution down to individual trees or sub-metre. The main barrier will be the cost of acquiring imagery and setting up automated processes to enable change comparisons. As with other 'erosion monitoring', another barrier will be the development of consistent and standardized data reporting, including systems and infrastructure to manage, store and report on monitored data.

A4-(iii) What are the costs associated with monitoring the attribute? This includes up-front costs to set up for monitoring (e.g., purchase of equipment) and on-going operational costs (e.g., analysis of samples).

To our knowledge, monitoring of this attribute is not being done routinely anywhere, therefore it is hard to assess costs.

At least one region (East Coast) has whole or partial spatial coverage of gully distribution (snapshot in time of gully locations), though this information is not easily accessible (M. Marden pers. comm).

Some councils report on how many farms are treated with soil conservation works (which would include treatment of active gullies if present), others on the number of poles planted, etc.

If high resolution, cloud-free satellite imagery was regularly and cheaply available, algorithms could be developed to routinely assess gully distribution and their treatment such as areas planted, counts of individual trees, 'activity' of gullies, etc., between one time period and another. Given issues around change detection, assessment of change in less than 5 years would not be warranted or practical.

To date, most assessment of gullies (similar to other erosion features) is manually done using aerial photography/satellite imagery and field mapping and is therefore costly. Semi-and fully-automated approaches such as OBIA (Object based image analysis) utilising satellite imagery for mapping gullies are not yet commonly used in NZ, though have been tried (Hölbling et al., 2016; Hölbling et al., 2022; Abad et al 2023). Separating gully erosion from other erosion types and the proportion of land treated or not, will be problematic. Bare ground has been used as a proxy for erosion and/or erosion risk (North et al., 2022; Norris & Wyatt 2023) the corollary of which would be a reduction in bare ground.

The attribute would need to be monitored by consistent, spatial and standardised reporting of numbers of gullies, areal extent of those gullies, activity status, and the amount of soil conservation work and treatment by regional councils and/or central government to progress the evidence base that work is being done towards environmental improvement and gully erosion was reducing.

Some councils already report on assessments of erosion 'proxies' and the kinds and area of land treated with soil conservation plantings and are well positioned with data systems in place. Data standardisation across regional councils is likely to be achievable with direction, coordination, and funding and/or using a platform such as LAWA (https://www.lawa.org.nz/).

A5. Are there examples of this being monitored by Iwi/Māori? If so, by who and how?

I am not aware of any monitoring being carried out by representatives of iwi/hapū/rūnanga.

However, erosion is of very high interest to Māori and various hapū/iwi are focused on monitoring erosion and mitigating risk. See for example, the Waiapu River Restoration project (Led by Te Rūnanganui o Ngāti Porou) that focuses on erosion in the Waiapu catchment https://www.ngatiporou.com/nati-news/the-waiapu-river-restoration. See also the Waiapu Koka Huhua initiative https://ourlandandwater.nz/wp-content/uploads/2022/02/TMOTW-Case-Study-Waiapu-Kokahuhua.pdf

Successful erosion control within the catchment is required to achieve the cultural aspirations of Ngāti Porou (Scion, 2012). Measures of erosion (including visual observations and drone aerial measurements) are just parts of a holistic approach to assessing the state of the catchment.

A6. Are there known correlations or relationships between this attribute and other attribute(s), and what are the nature of these relationships?

Gully erosion is usually grouped with other erosion processes in a "general erosion assessment".

During rain events that initiate shallow landslides, gully processes are likely to be exacerbated particularly where shallow landslides transform into debris flows and are channelised within a gully or stream. In this situation, toe slope removal may initiate mass failure. Alternatively, in the absence of landslides being connected to gullies, concentrated runoff in the gully may scour the toe slopes resulting in 'streambank' failure (mass failure), i.e., in certain conditions there is a feedback loop between channel and slope (Ionita et al., 2015). However, gully processes operate whenever it rains rather than only in extreme events.

Gully erosion is usually lumped with other erosion processes, e.g., shallow landslide erosion, surface erosion, and even bank erosion in assessments of erosion (e.g., New Zealand Empirical Erosion Model (NZEEM), Highly Erodible Land (HEL)). In the Land Use Capability (LUC)/Land Resource Inventory the key/dominant erosion process for that polygon is described along with its severity, e.g., in LUC as G gully erosion (Lynn et al., 2021), along with secondary erosion processes. Severity is rated in 6 classes based on area, i.e., size of gully with 'slight' being < 0.05 ha, and extreme being > 5 ha (Lynn et al., 2021). A special form of gully erosion – tunnel gully is referred to as T and its severity is ranked based on the percentage of the mapping polygon that has this erosion process.

In the National Environmental Standards for Commercial Forestry (NES-CF) Erosion Susceptibility Classification (ESC), all erosion processes are combined within one of 4 erosion susceptibility classes (the ESC is based on the national LUC).

Part B—Current state and allocation options

B1. What is the current state of the attribute?

Current state of gully erosion is not well understood at the national scale (the process is well understood and locally/regionally its distribution might be). Understanding is not advanced enough for this to be used as a national indicator, though it has potential in some regions where it is more prevalent, e.g., Gisborne–East Coast. At the regional scale, some regional councils will have a good idea where the large gullies are, but they may not monitor the development of new gullies or the activity of existing gullies.

To be used as an indicator would require establishment of a baseline state for each region of gully number, their area (individually and/or collectively), their activity status and their treatment. Once a national layer was available, the numbers/areas could be monitored (5-yearly) to reduction in gully area (treated) relative to the starting baseline.

B2. Are there known natural reference states described for New Zealand that could inform management or allocation options?

I am unsure of the existence of natural reference states for this attribute. A pre-European reference state, while potentially attractive as a natural reference state, would be difficult to quantify and would not be attainable in contemporary New Zealand. Gully erosion would have existed in New Zealand pre-Europeans, but it was the clearance of indigenous forest from 'hill country' in both islands for farming that exacerbated all erosion types, including gully erosion (Basher 2013).

B3. Are there any existing numeric or narrative bands described for this attribute? Are there any levels used in other jurisdictions that could inform bands? (e.g., US EPA, Biodiversity Convention, ANZECC, Regional Council set limit)

I do not know of any existing numeric or narrative bands for this attribute.

Globally, gully erosion is a problem in some countries more than others. For example, it is a key erosion process in many parts of Australia, China, Spain etc., (Boardman et al., 2022). However, our understanding on spatial patterns and rates of gully erosion remain little understood (Poesen et al., 2003).

Gully erosion, if it is monitored, is usually monitored using change quantification techniques (Aber et al., 2010). In Europe, attempts have been made to integrate a soil erosion module into the Land Use/Cover Area frame statistical Survey (LUCAS) Topsoil Survey (Borrelli et al., 2022).

B4. Are there any known thresholds or tipping points that relate to specific effects on ecological integrity or human health?

I do not know of any thresholds or tipping points, but there are some "rules of thumb" which relate to the size of gullies in some regions and whether they can be treated or not (Marden et al., 2011; 2017; Marden & Seymour 2022).

B5. Are there lag times and legacy effects? What are the nature of these and how do they impact state and trend assessment? Furthermore, are there any naturally occurring processes, including long-term cycles, that may influence the state and trend assessments?

Yes, lag times and legacy effects are likely. Vegetation establishment in the margins or within a gully and/or its contributing catchment may take some years to become effective and shut down the gully, similar to other vegetative approaches. Once sufficient density of vegetation is established or canopy closure occurs, the effectiveness of rainfall will be reduced. Some gullies may only be partially shut down and continue to contribute small amounts of sediment even though they appear to be successfully treated. Non-vegetated measures may be immediately effective or not, i.e., there is likely to be variability in effectiveness of treatment depending on what is implemented and the activity of the gully itself. Hard engineered mitigations are not common in New Zealand.

B6. What tikanga Māori and mātauranga Māori could inform bands or allocation options? How? For example, by contributing to defining minimally disturbed conditions, or unacceptable degradation.

In addition to discussing this attribute directly with iwi/hapū/rūnanga, there is likely to be tikanga and mātauranga Māori relevant to informing bands, allocation options, minimally disturbed conditions and/or unacceptable degradation in treaty settlements, cultural impact assessments, environment court submissions, iwi environmental management and climate change plans etc.

I suspect that many iwi will see eroded gullies as being a scar on Papatūānuku. Continual on-going bleeding of sediment from the large gullies will not be acceptable. In terms of gully treatment, not all vegetation solutions, i.e., species, may be agreeable to iwi.

Part C—Management levers and context

C1. What is the relationship between the state of the environment and stresses on that state? Can this relationship be quantified?

The relationship between erosion-prone land (including land that is susceptible to gully processes or has gullies on it) and vegetation cover is moderately well understood (Basher 2013, etc). In the Gisborne - East Coast region gullies are characteristic of both forested and grassed landscapes (Parkner et al., 2006; 2007).

Various strategies and techniques are employed to avoid, manage and mitigate gully erosion in New Zealand (Basher 2013). These may include revegetation of gully margins (and/or contributing catchment area) with exotic or native plants to stabilize soil (Marden et al., 2011), construction of targeted erosion control structures such as check dams (Howie 1968), gabion baskets, rock riprap and rock bunds in concentrated flow zones to slow water flow, and trap sediment and implementation of sustainable land management practices to reduce surface runoff and soil disturbance (Phillips et al.,, 2020). The latter include measures that increase topsoil resistance and the use of vegetation barriers (Frankl et al., 2021). Once deeply incised, the development of gullies may be partially controlled by diverting runoff away from the channel, but this comes at the risk of relocating the problem (McIvor et al., 2017).

Terracing and contouring are also used to help reduce the speed and volume of water flow, allowing it to infiltrate the soil rather than causing erosion. This is not commonly done in NZ, though has been trialled in the past. It is more commonly related to significant earthworks associated with urban developments or roading (Leersnyder et al., 2018).

Prevention is much more effective than repair. New Zealand experience suggests that once erosion is into the bedrock it is very difficult to get trees (or any other plant material) established. If gullies are treated when they are small (< 1ha) the likelihood of treatment leading to reduced erosion and soil loss is high (see Figures2, 3, 4 – Marden et al., 2011; 2017; Marden & Seymour 2022). When they get larger (threshold > 10 ha in area, commonly called 'badass' gullies) they are much more difficult if not impossible to treat. Large gullies cannot be repaired, e.g., Tarndale Slip, Barton's Gully on the East Coast (Figure 4) (Marden et al., 2017).

The contributing catchment surrounding the gully needs to be retired from grazing and planted in closed canopy trees to reduce the effective runoff, or if the gully is small, soil conservation planting along the edge and within the gully may stabilise it. Eroding surfaces within the gully likely need to be repeatedly planted with willow wands to create a vegetated surface (McIvor et al., 2017). Structures such as debris and check dams in association with planting is another 'bioengineering' treatment commonly used in the past and but less so now (Phillips et al., 2020).

Figure 2. Typical East Coast linear gully showing untreated state (left) and treated state (right) with paired poplars and/or willows.

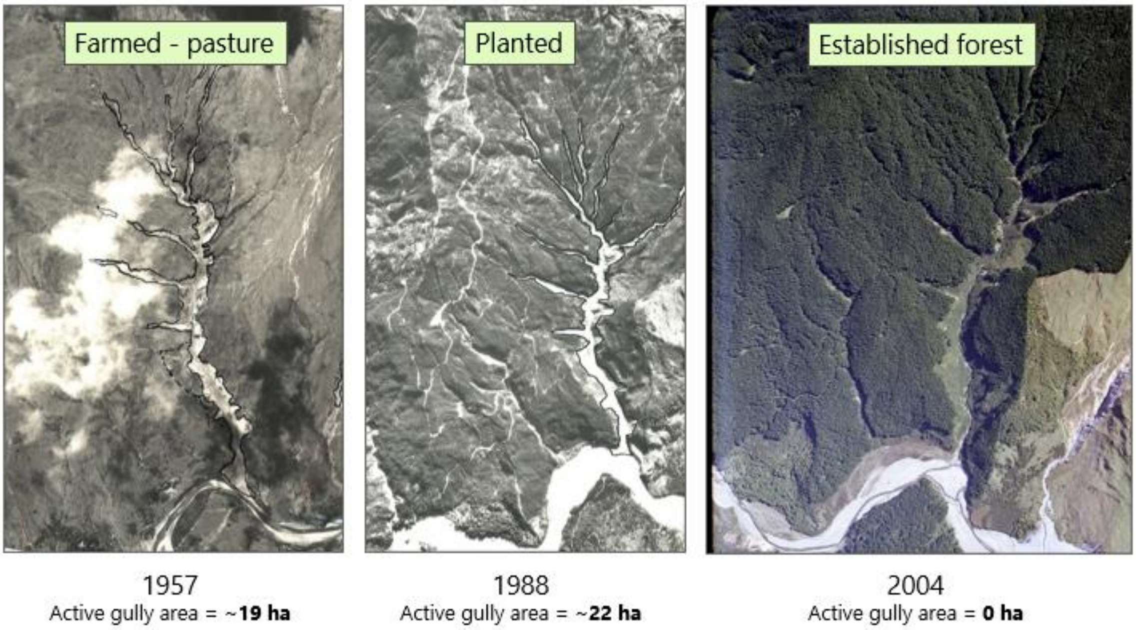

Figure 3. East Coast (Owhena, North Island, New Zealand) gully showing effective treatment with exotic forest (Marden pers. comm.).

Figure 4. Large amphitheatre or badass gullies from the East Coast region. Similar photos can be found in Marden et al. (2017).

Like other aspects of erosion control, gully treatment or protection is expected to improve the ecological integrity of land and water bodies as described in A2.

C2. Are there interventions/mechanisms being used to affect this attribute? What evidence is there to show that they are/are not being implemented and being effective?

C2-(i). Local government driven

All Regional Councils have soil conservation or land management programmes that aim to reduce the amount of erosion (and sediment) in their regions from different erosion processes including gullies. However, the size, scale and cost of these programmes varies widely. In some regions there is not enough resource available to treat the current state of erosion and therefore some gullies will go untreated.

Afforestation, soil conservation planting, and reversion are the primary treatment methods though gully treatment may involve a range of other methods (see C1 above).

C2-(ii). Central government driven

Current and past initiatives have been directed towards more general erosion control which includes gully erosion control, e.g., East Coast Forestry Project, One Billion Trees, Hill Country Erosion Fund. I am unaware of any funding specifically targeting gully erosion treatment.

C2-(iii). Iwi/hapū driven

Erosion risk and mitigations to prevent erosion are of high interest to iwi/hapū/rūnanga, especially in the areas severely impacted by Cyclone Gabrielle (for example). Iwi planning documents such as Environmental Management Plans and Climate Change Strategies/Plans may contain policies/objectives/methods seeking to influence erosion outcomes for the benefit of current and future generations.

C2-(iv). NGO, community driven

Unknown.

C2-(v). Internationally driven

Unknown.

Part D—Impact analysis

D1. What would be the environmental/human health impacts of not managing this attribute?

Not managing this attribute (or erosion in general) would result in further losses to ecological integrity (sedimentation in rivers, wetlands, hydro dams, estuaries and oceans), reduced clarity in freshwaters, etc., particularly in the areas where gully erosion is common. It would also result in the continuing degradation of hill country soils leading to reduced productivity, though unlike pasture production recovery on shallow landslides (Rosser & Ross 2011) no such information exists for gullies.

Not managing this attribute (and erosion in general) may lead to the further demise of rural communities and those who live in highly susceptible/erosion-prone areas, particularly East Coast Māori communities. It might be seen as an affront not to treat this type of erosion, as unlike other erosion forms, it can be identified, is specific to a location, and its severity can be assessed.

D2. Where and on who would the economic impacts likely be felt? (e.g., Horticulture in Hawke's Bay, Electricity generation, Housing availability and supply in Auckland)

North Island hill country farming communities are the most likely to be affected. Farming is marginal on many hill country properties, including those where gullies exist. If there were further requirements to plant more trees on farms it could make some pastoral properties uneconomic and lead to further rural decline. The Beef & Lamb and forestry sectors are linked with soil loss and erosion and their management, particularly on steeplands and hill country in North Island.

Horticulture on floodplains in Gisborne, Hawkes Bay and other regions are also impacted by erosion in catchments expressed as increased flood risk and sedimentation on flood plains, of which gully erosion is a part, and in some localities can be significant.

D3. How will this attribute be affected by climate change? What will that require in terms of management response to mitigate this?

Many hill country areas currently under pasture with or without active gullies will require more trees. Better classes of land under agriculture could consider a change to silvopastoral systems (Mackay-Smith et al. 2024), while the most susceptible parts of the landscape will require a permanent tree cover. The challenge will be to embrace the diversity in NZ's landscapes and match land-use to both land capability and susceptibility to provide a mosaic of use and cover at a finer spatial scale than is seen today (PCE 2024).

Large-scale afforestation with exotic species on the most susceptible terrain will merely repeat the failures of the past, and could give rise to future unintended consequences, e.g., slash issue on steep Tertiary hill country on the East Coast.

The pace of transition needs to increase faster than the perceived, modelled, or real changes arising from climate change (Neverman et al., 2023).

References:

Abad L, Hölbling D, Smith H, Neverman A, Betts H, Spiekermann R 2023. Expert-based and data-driven gully and cliff erosion feature detection in New Zealand. Poster presented at 28th IUGG General Assembly, Berlin.

Aber JS, Marzolff I, Ries JB 2010. Chapter 13 - Gully Erosion Monitoring. In: Aber JS, Marzolff I, Ries JB ed. Small-Format Aerial Photography. Amsterdam, Elsevier. Pp. 193-200.Borrelli P, Poesen J, Vanmaercke M, Ballabio C, Hervás J, Maerker M, Scarpa S, Panagos P 2022. Monitoring gully erosion in the European Union: A novel approach based on the Land Use/Cover Area frame survey (LUCAS). International Soil and Water Conservation Research 10(1): 17-28.

Boardman J, Poesen J, Evans M 2022. Slopes: soil erosion. In: Burt TP, Goudie AS, Viles HA ed. The History of the Study of Landforms or the Development of Geomorphology. Volume 5: Geomorphology in the Second Half of the Twentieth Century, Geological Society, London, Memoirs.

Cavanagh JE, Hogsden KL, Harding JS 2014. Effects of suspended sediment on freshwater fish. Envirolink Advice Grant 1335-WCRC129.

Day J, Shepherd R 2019. Gully erosion. Options for prevention and rehabilitation. Experiences from the Burnett and Mary River Catchments, Queensland. Published by Burnett Mary Regional Group.

Dotterweich M 2013. The history of human-induced soil erosion: Geomorphic legacies, early descriptions and research, and the development of soil conservation—A global synopsis. Geomorphology 201: 1-34.

Frankl A, Nyssen J, Vanmaercke M, Poesen J 2021. Gully prevention and control: Techniques, failures and effectiveness. Earth Surface Processes and Landforms 46(1): 220-238.

Hölbling D, Betts H, Spiekermann R, Phillips C 2016. Identifying Spatio-Temporal Landslide Hotspots on North Island, New Zealand, by Analyzing Historical and Recent Aerial Photography. Geosciences 6: 48.

Hölbling, D., Abad, L., Spiekermann, R., Smith, H., Neverman, A., and Betts, H.: Exploring knowledge-based and data-driven approaches to map earthflow and gully erosion features in New Zealand, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-1013, https://doi.org/10.5194/egusphere-egu22-1013, 2022.

Howie WR 1968. A design procedure for gully control by check dams. Water and Soil Division Ministry of Works. https://docs.niwa.co.nz/library/public/HowWRDesi.pdf

Ionita I, Fullen MA, Zgłobicki W, Poesen J 2015. Gully erosion as a natural and human-induced hazard. Natural Hazards 79(1): 1-5.

Larned ST, Moores J, Gadd J, Baillie B, Schallenberg M 2019. Evidence for the effects of land use on freshwater ecosystems in New Zealand. New Zealand Journal of Marine and Freshwater Research: 1-41.

Leersnyder H, Bunting K, Parsonson M, Stewart C 2018. Erosion and sediment control guide for land disturbing activities in the Auckland region. Auckland Council Guideline Document D2016/005. Incorporating amendment 1. Prepared by Beca Ltd and SouthernSkies Environmental for Auckland Council.

Lynn IH, Manderson AK, Page MJ, Harmsworth GR, Eyles GO, Douglas GB, Mackay AD, Newsome PJF 2021. Land Use Capability Survey Handbook - a New Zealand handbook for the classification of land. Hamilton, Lincoln, Lower Hutt, AgResearch, Manaaki Whenua - Landcare Research New Zealand Ltd, GNS Science.

Mackay-Smith TH, Spiekermann RI, Richards DR, Harcourt N, Burkitt LL 2024. An integrative approach to silvopastoral system design: perspectives, potentials and principles. New Zealand journal of agricultural research. DOI: 10.1080/00288233.2023.2298922

Marden M, Herzig A, Arnold G 2011. Gully degradation, stabilisation and effectiveness of reforestation in reducing gully-derived sediment, East Coast region, North Island. Journal of Hydrology (NZ) 50(1): 19-36.

Marden M, Herzig A, Basher L 2014. Erosion process contribution to sediment yield before and after the establishment of exotic forest: Waipaoa catchment, New Zealand. Geomorphology 226(0): 162-174.

Marden M, Fuller IC, Herzig A, Betts HD 2017. Badass gullies: Fluvio-mass-movement gully complexes in New Zealand's East Coast region, and potential for remediation. Geomorphology 307: 12-23.

Marden M, Seymour A 2022. Effectiveness of vegetative mitigation strategies in the restoration of fluvial and fluvio-mass movement gully complexes over 60 years, East Coast region, North Island, New Zealand. New Zealand journal of forestry science 52.

McIvor I, Youjun H, Daoping L, Eyles G, Pu Z 2017. Agroforestry: Conservation Trees and Erosion Prevention. Encyclopedia of Agriculture and Food Systems, Pages 208-221. Reference Module in Food Science, Elsevier.

Neverman AJ, Donovan M, Smith HG, Ausseil A-G, Zammit C 2023. Climate change impacts on erosion and suspended sediment loads in New Zealand. Geomorphology: 108607.

Norris T, Wyatt J 2023. Soil stability in the Waikato region, 2007-2017. Waikato Regional Council Technical Report. 56 p.

North H, Amies A, Dymond J, Belliss S, Pairman D, Drewry J, Schindler J, Shepherd J 2022. Mapping bare ground in New Zealand hill-country agriculture and forestry for soil erosion risk assessment: An automated satellite remote-sensing method. Journal of Environmental Management 301: 113812.

Parkner T, Page MJ, Marutani T, Trustrum NA 2006. Development and controlling factors of gullies and gully complexes, East Coast, New Zealand. Earth Surface Processes and Landforms 31: 187–199.

Parkner T, Page M, Marden M, Marutani T 2007. Gully systems under undisturbed indigenous forest, East Coast Region, New Zealand. Geomorphology 84: 241–253.

Parliamentary Commissioner for the Environment 2024. Going with the grain. Changing land uses to fit a changing landscape. 84 p.

Phillips CJ, Marden M, Douglas G, Ekanayake J 2008. Decision support for sustainable land management: effectiveness of wide-spaced trees. Landcare Research Contract Report LC0708/126 for Ministry of Agriculture and Forestry.

Phillips CJ, Basher L, Spiekermann R 2020. Biophysical performance of erosion and sediment control techniques in New Zealand: a review LC3761. 122p.

Poesen J, Vandaele K, van Wesemael B 1998. Gully Erosion: Importance and Model Implications. In: Boardman, J., Favis-Mortlock, D. (eds) Modelling Soil Erosion by Water. NATO ASI Series, vol 55. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-58913-3_22

Poesen J, Nachtergaele J, Verstraeten G, Valentin C 2003. Gully erosion and environmental change: Importance and research needs. Catena, 50 (2–4): 91-133.

Rosser BJ, Ross CW 2011. Recovery of pasture production and soil properties on soil slip scars in erodible siltstone hill country, Wairarapa, New Zealand. New Zealand Journal of Agricultural Research 54(1): 23-44.

Ryan PA 1991. Environmental effects of sediment on New Zealand streams: a review. New Zealand Journal of Marine and Freshwater Research 25: 207-221.

Scion 2012. Waiapu River Catchment Study –Final Report. Scion Confidential Client Report No. 15201. Rotorua, New Zealand: Scion

StatsNZ 2018. Estimated long-term soil erosion – published April 2018. https://www.stats.govt.nz/indicators/estimated-long-term-soil-erosion/

Thompson RC, Luckman PG 1993. Performance of biological erosion control in New Zealand soft rock hill terrain. Agroforestry Systems 21: 191-211.

Trustrum NA, Lambert MG, Thomas VJ 1983. The impact of soil slip erosion on hill country pasture production in New Zealand. Proceedings of the second International Conference on Soil Erosion and Conservation, Honolulu, Hawaii, January 1983, edited by SA El-Swaify, WC Moldenhauer and A Lo. Ankerly, Iowa, Soil Conservation Society of America, 1985. 793p.